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Review

Potential Role of Technology Innovation in Transformation of Sustainable Food Systems: A Review

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Abstract: Advanced technologies and innovation are essential for promoting sustainable food systems (SFSs) because these technologies can be used to answer some of the critical questions needed to transform SFSs and help us better understand global food security and nutrition. The main objective of this study is to address the question of whether technological innovations have an impact on the transformation of SFSs. There are certain innovations including agricultural land utilization, food processing, production systems, improvement in diets according to people's needs, and management of waste products. This study provides an overview of new technologies and innovations being used with potential to transform SFSs. Applications of emerging technologies in digital agriculture, including the Internet of Things (IoT), artificial intelligence and machine learning, drones, use of new physical systems (e.g., advanced robotics, autonomous vehicles, advanced materials), and gene technology (e.g., biofortified crops, genome-wide selection, genome editing), are discussed in this study. Additionally, we suggest eight action initiatives, which are transforming mindsets, enabling social licensing, changing policies and regulations, designing market incentives, safeguarding against undesirable effects, ensuring stable finance, building trust, and developing transition pathways that can hasten the transition to more SFSs. We conclude that appropriate incentives, regulations, and social permits play a critical role in enhancing the adoption of modern technologies to promote SFSs.

Keywords: technology innovation; food processing; transition pathways; sustainable food systems; digital agriculture; transformation

1. Introduction

Food sustainability is directly linked with sustainable agriculture. Sustainable agriculture is an integrated system of plant and animal production practices that can provide sufficient human food and fiber needs, enhance environmental quality and natural resources, use resources efficiently, sustain farm operations, and enhance the quality of human life for the long term [1]. The critical factors for a sustainable food system (SFS) are fertile land, water, fertilizers, favorable climate conditions, and energy [1]. However, currently, the sustainability of food and agricultural systems is under stress due to the positive global demographic change, including rapid global population growth, increases in food demands, climate change effects, limited water supplies, and the transition from conventional energy sources (oil and gas) to new energy sources. Social, economic, and environmental sustainability are closely interlinked and critical for sustainable agriculture. However, an integrated approach that includes proper use of advanced technology is equally important for sustainable agriculture. Therefore, it is important to use an integrated approach that includes ecosystem services, human capital, and new technologies to produce food sustainably [2].

The population of the world is now more than 7.7 billion, and it is increasing at an annual rate of around 1.07%. Hence, by 2050, the world's population is projected to increase by more than 30% of the current population and reach 10 billion [3–8]. Given the projected growth of the population and income, as well as the headwinds of the climate, meeting the total demand for food in the future will place unprecedented pressure on limited water, fertile land, energy, and potential climate change. The risk of huge and potentially irreversible ecological damage caused by unprecedented pressure is subject to serious academic debate. In addition to the long-term pressure from the inevitable increase in the food demand, several other factors have raised concerns about the sustainability of the agricultural food system to adapt to climate change and environmental stresses. The frequency and/or intensity of such stresses appear to be increasing, and they usually respond in a cascade, with one triggering the other [3,9–12]. Stresses to the agri-food system seem to be increasing due to the growing demand for high-quality nutritional food around the world [11,13]. The projected demographic change will negatively impact agricultural productivity and agricultural expansion, which will stress natural resources by increasing deforestation, water consumption, and greenhouse gas emissions, thus contributing to ecological insufficiency and climate change [3,14]. For example, it is projected that the consumption of meat and dairy products will be increased by 173% and 158%, respectively, between 2010 and 2050 globally [6,15]. The continued increase in demand for animal protein and the corresponding expansion of food production are causing serious concerns.

Efficient resources are required to convert vegetable matter into animal-derived proteins (e.g., meat or milk protein). For example, eight kilograms of vegetable food is required to increase one kilogram of weight in beef cattle [3,16]. Since April 2016, the main goal of the United Nations Decade of Nutrition Action has been to "eliminate all forms of malnutrition". However, some important key points (e.g., economic aspects, nutrition and health, environmental, social, and food security) that were agreed at the Second International Nutrition Conference also focus on developing a "sustainable, resilient and healthy diet food system" [3,17]. For this reason, people have discussed food alternatives including all aspects of integrating food safety and sustainability concepts.

Moreover, it is necessary to adopt emerging technologies (Internet, mobile phones, computers, IoT, etc.) for sustainable agriculture, including food productions with high protein. It is also important to optimize the protein contributions from animals and plants. While this will help promote the sustainability of food systems and biodiversity, it will ultimately provide effective distribution of high-quality protein for the global population [18–21]. In the global context, government and non-government policies and consumers' current intentions to include more plant-based protein in their daily diets [3,22] motivate the use of alternative protein sources for better human health. Some examples of emerging and sustainable protein sources include grains (e.g., wheat and zein), seeds (e.g., chia seeds), leaves (e.g., moringa), legumes (e.g., beans, lentils, peas), microalgae, fungi (e.g., bacteria protein), milk (e.g., whey protein), and insects.

Until now, the future sustainability of food systems, changing diet's role, reducing waste, and increasing agricultural productivity have mainly been studied through existing technologies. For example, a common research question concerns what level of yield increase can be achieved through the spread of new crop varieties, livestock species, animal feed, or changes in agricultural practices, as well as the spread of irrigation and improved management techniques [23,24]. However, as research has shown, even if existing agricultural technologies are widely adopted, flexible diets are fully implemented, and food waste is reduced by half, it will still be a challenge to feed the growing world population while ensuring the well-being of the planet [2,23,25,26]. Thus far, few studies have explored whether the world is adopting more destructive, "wild", game-changing options [6,27,28] that can affect the progress of many required dimensions of food systems simultaneously. Some of these game changers are no longer the realm of imagination; they are already being developed fairly rapidly, reshaping the viability of different sectors. Investment data on agriculture show that several companies are focusing on digital agriculture [29–31]. Digital agriculture includes applications of advanced technologies such as the Internet of Things (IoT), artificial intelligence and machine learning, drones and use of new physical systems (e.g., advanced robotics, autonomous vehicles, advanced materials), and gene technology (e.g., biofortified crops, genome-wide selection, genome editing).

Technology itself is not always transformative. However, if it is applied/used appropriately to address critical issues of any field, including agriculture, it can be crucial for developing innovative solutions. The transformative power of technology depends on economic and administrative strategies, social needs, and socioeconomic status [32]. However, few studies have been conducted on the elements that can promote the transformation of food systems through system innovation [21,33–41]. This study contributes to the extant literature by filling the underlying gap, especially discussing and summarizing how to achieve a positive transformation of SFSs. Specifically, this study provides insights on emerging technologies that can be used to achieve sustainability in food systems.

The rest of this review article is organized as follows: Section 2 describes the methodology and framework of the study. Section 3 elaborates on the technology change and innovations in food systems and transformation accelerators. Section 4 provides key factors of sustainable food systems, and Section 5 presents the conclusion of this study.

2. Methodology and Framework of the Study

In recent decades, several studies have been conducted to solve key issues in agriculture to improve agricultural production and achieve SFSs. With recent advancements in technologies to increase the potential of agricultural development and SFSs, some researchers have made great efforts to promote SFSs. The scientific community's interest in advanced technology has grown exponentially. However, it is always challenging for stakeholders and users to select and implement appropriate technologies to increase agricultural production. Recently, some studies have reviewed articles focusing on the implementation, application, challenges, potential, and prospects of the IoT in smart agriculture, and agricultural and food production systems. However, they mainly focused on research based on the IoT. We reviewed the most important research based on advanced technologies essential to SFSs. Our strategy was to review articles based on advanced technologies used in agriculture. We have reviewed articles that focus on the application of sustainable food, precision agriculture, food safety and nutrition, digital technology, the IoT, and smartphone technology in food.

A tentative framework was designed to assess the contribution of recent innovations towards the current technological transformation process and innovations within food systems which help improve food sustainability. It is purely a qualitative process of achieving the Sustainable Development Goals. The current innovations and future technologies are critical to support SFSs. Some innovations including agricultural land use, food processing and production systems, improved diets according to people's needs, and waste management can play a significant role for SFSs. This study discusses how advanced technologies applied to food systems can be transformed into SFSs (Figure 1). Additionally, eight action initiatives, including changing mindsets, enabling social licensing, changing policies and regulations, designing market incentives, preventing adverse effects, ensuring stable finance, building trust, and developing transitional pathways, are discussed. For this review article, we conducted an intensive literature review to collect the information and fill the underlying gaps to better understand the role of innovative technology in transforming SFSs.

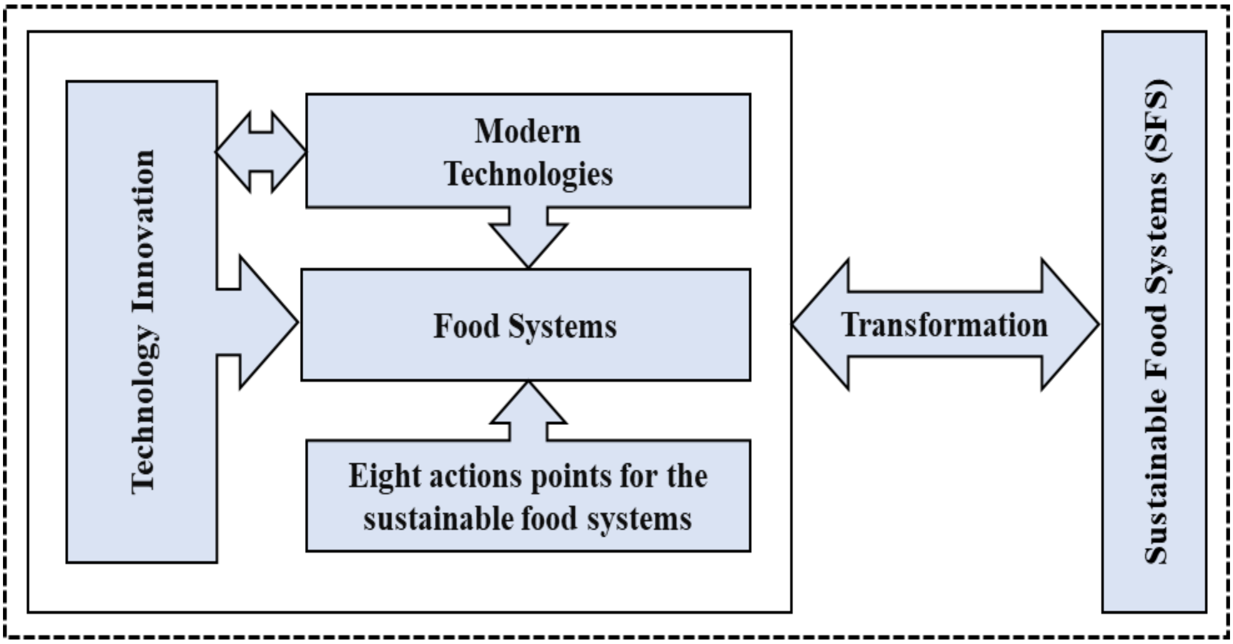

Figure 1. The framework of this study.

3. Technological Transformation and Innovations in Food Systems

Historically, activities dedicated to agri-food production have undergone many technological changes. The changes that have occurred in the past two centuries have been extensively examined [42]. Through the 19th century, the major technological innovations were the bearing, which introduced crucial mechanical modernizations, for instance, lawnmowers, mechanical harvesters, and threshers. With the first canned food entering the market, the increased industrial agriculture, and the gradual demise of household farms in more advanced countries, agricultural marketing had also undergone major changes. At the beginning of the 20th century, animal power was slowly substituted by innovative fuel-based energy sources [43,44].

In 1892, the prototype of the first gasoline tractor was constructed. Simultaneously, there have been numerous technological advances in marketing and food processing, including introduction of innovative packaging forms, expansion of long-distance trade, emergence of new food retail systems, and ongoing urbanization process. The main and lasting technological change of the past century is called the Green Revolution, which was based on the use of new high-yielding wheat varieties and the widespread use of chemical fertilizers and insecticides [43]. The Green Revolution, considered by capital-intensive production processes, led to a significant increase in agricultural productivity. In the United States in 1860, one farm job could feed 4–5 people, and in 1957, this number became 22.8 people [43,45]. At the end of the past century, biotechnology brought major technological variations to the agricultural food sector, followed by nanotechnology and digital technology.

Technological advances in several indicators of human well-being, including hunger, life expectance, and disease prevention, have played a significant role since Neolithic times [46]. Table 1 provides a detailed list of modern technologies such as digital agriculture, cellular agriculture, food processing and safety, gene technology, health, inputs, intensification, replacement food and feed, resource use efficiency, and other technologies and also an explanation of each technology's contribution to the technical advances of food systems. Despite the benefits to humanity of these food and agriculture advances, certain environmental and health indices are continuously declining, particularly in the 21st century. For instance, the conversion of forest land into agricultural land or pastureland has increased air and water pollution and greenhouse gas emissions. In addition, nitrogen and phosphorus usage has been multifarious, and their consumption is continuously increasing [47,48]. Excessive use of nitrogen and phosphorus in agriculture has a significant negative impact on the environment and human health. For example, runoff from agricultural watersheds causes eutrophication of waterbodies. On the other hand, excess nitrogen in the air can impair our ability to breathe and limit visibility [26,49]. The development of inexpensive, fast, or discretionary foods has also contributed to significant malnutrition in many parts of the world [49].

Table 1. Future technology with transformative potential. Modern technologies are divided into (10) categories, covering the entire food system. Table 1 presents a complete explanation of each technology.

Modern Technologies	**Explanation of each Technology**	**Production**	**Processing**	**Packaging**	**Distribution**	**Consumption**	**Waste**	**References**
Digital agriculture (DA)	Drones	✓			✓	✓	✓	[50,51]
	Innovative sensors		✓	✓	✓	✓	✓	
	Big data	✓	✓	✓	✓	✓	✓	
	Artificial intelligence	✓	✓	✓	✓	✓	✓	
	Data integration	✓						
	Assistive exoskeletons	✓	✓		✓			
	Disease/pest early warning	✓					✓	
	Robotics	✓	✓	✓	✓		✓	
	On-field robots	✓					✓	
	Sensors for soil		✓	✓	✓		✓	
	Tracking tech for livestock	✓			✓			
	Farm-to-farm virtual market		✓	✓	✓	✓	✓	
	Internet of Things	✓	✓	✓	✓	✓	✓	
	Improved climate forecasts	✓					✓	
	Nano-drones	✓			✓	✓	✓	
	SERS sensors		✓	✓	✓		✓	
	Pest control robotics	✓					✓	
	Nanotechnology		✓	✓	✓		✓	
	Intelligent food packaging		✓	✓	✓		✓	
	Pre-birth sex determination	✓						
	Smartphone food diagnostics		✓		✓	✓		
	Omics data use	✓						
	Traceability technologies		✓	✓	✓	✓		
Cellular agriculture (CA)	Artificial products	✓	✓			✓		[21,52]
	Artificial meat/fish	✓	✓			✓		
	Molecular printing	✓	✓	✓	✓	✓	✓	
Food processing and safety (FPS)	Nanocomposites			✓	✓		✓	[50]
	Food safety tech		✓	✓			✓	
	Whole-genome sequencing	✓	✓				✓	
	Biodegradable coatings			✓	✓		✓	

	Technologies for sustainability		✓	✓	✓		✓	
	Drying/stabilization tech		✓	✓	✓		✓	
	Microorganism coatings			✓	✓		✓	
Gene technology (GT)	Genome editing	✓						[53]
	GM-assisted domestication	✓						
	Biofortified crops	✓				✓		
	Plant phenomics	✓						
	Synthetic biology	✓						
	Novel perennials	✓						
	Weed-competitive crops	✓					✓	
	RNAi gene silencing	✓						
	Genome-wide selection	✓					✓	
	Apomixis	✓						
	Oils crops	✓						
	Reconfiguring photosynthesis	✓						
	Disease/pest resistance	✓					✓	
	Novel nitrogen-fixing crops	✓					✓	
	Genome selection	✓						
Health (H)	Personalized crops		✓	✓	✓	✓	✓	[54]
Inputs (I)	Soil additives	✓					✓	
	Holobiomics	✓					✓	
	Nano-enhancers	✓					✓	
	Enhanced efficiency fertilizers	✓					✓	
	Nano-fertilizer	✓					✓	
	Micro-irrigation	✓					✓	
	Botanicals	✓					✓	
	Nano-pesticides	✓					✓	
	Macrobials	✓					✓	
	Microbials	✓					✓	
Intensification (In)	Vertical agriculture	✓			✓			[54]
	Electro-culture	✓						
	Irrigation expansion	✓					✓	
Other (O)	Ecological biocontrol	✓					✓	
	3D printing	✓	✓	✓	✓	✓	✓	
	Resurrection plants	✓						
	Battery technologies	✓	✓		✓		✓	
Replacement food and feed (RFF)	Microalgae and cyanobacteria for food	✓	✓			✓	✓	[55,56]
	Seaweed for food	✓	✓			✓	✓	
	Insects for food	✓	✓			✓	✓	
	Omega-3 products for aquaculture	✓						
	Innovation aquaculture feed	✓	✓				✓	
	Microbial protein	✓	✓			✓	✓	
	Dietary additives for livestock	✓					✓	
	Livestock/sea substitutes	✓	✓			✓	✓	
Resource use efficiency (RE)	Circular economy	✓	✓	✓	✓	✓	✓	[55]

Food management technology (e.g., food production, handling supply, and delivery) should be based on hazard analysis, and a critical control point (HACCP) is emerging at an incredible pace, which can be applied for SFSs in the future. According to comprehensive literature reviews, we offer a stock of nearby and potential innovations that can contribute towards the development of SFSs. Each technology is graded corresponding to its role in the value chain (such as manufacturing, production, storage, delivery, usage, and waste) and ready-to-mind ranking [57–59].

The nine technology readiness levels (TRL) include (i) basic principles observed and reported, (ii) technology concept and/or application formulated, (iii) characteristic proof of concept, (iv) component and/or breadboard validation in a laboratory environment, (v) breadboard validation in a relevant environment, (vi) system/subsystem model or prototype demonstration in a relevant environment, (vii) system prototype demonstration in a space environment, (viii) actual system completed and "flight qualified" through test and demonstration, and (ix) actual system "flight proven" through successful mission operations. These technology readiness levels contain the established application of technology on a real-world basis, including fundamental study, concepts discovered, and technology experiments applied [57,58].

This work exercise leads to a few insights. Firstly, as apparent in Table 1, technology covers the whole food chain (production, processing, packaging, distribution, consumption, and waste management). Therefore, various technical solutions can be adapted to tackle particular food system challenges in multiple structural and administrative settings. This complex conduit involving artificial meat, 3D printing, consumers' readiness, nano-drones, smart packaging, etc., provides a genuine chance for structural change. New technology mixes might differ widely based on a country's or region's level of socioeconomic growth and other governmental and institutional constraints.

Secondly, many concerns with digital and smart farming and the substitution of feed and food for fish and livestock are comparatively similar to the vast number of near-ready and advanced technologies, considering the massive size of the industry classes. This is not surprising given the pace of innovation and cost savings due to emerging technology, accompanied by the universal acceptance of these innovations across countries with medium, middle, and high incomes [54]. Additionally, efforts are underway to reduce the demand for livestock goods by offering alternate protein sources and disconnecting animal production with substituted circular feed from the ground, reducing its environmental effects. Increasing the demand for fish relies on decreasing the share of the complete amount of fish captured for livestock feed, which presently is about twelve percent [54].

Thirdly, some near-mature technologies have great capability to be adopted, thereby promoting strategic investments in their dissemination and implementation. There is an urgent need to study how to provide options with minimal disturbance in the current food systems and better understand the factors that may affect their absorption of the scale of transformation. This also highlights the potential contribution of the private sector in promoting the adoption of these technologies and the need to establish a regulatory framework and market structure to ensure that these advancements are fully aligned with public policy goals. Crucially, at least in the medium term, the affordability of these new options will increase, which is more likely to happen as demand becomes clearer and manufacturing processes and supply chains are better established. Finally, the simultaneous implementation of variations of these technologies can drastically accelerate achieving SFSs. This may simultaneously improve sustainable food production and reduce waste while improving human well-being and creating new local business opportunities, as resources are reassessed as part of the process. In addition, this is consistent with the current efforts to revitalize the bioeconomy in many parts of the world [60,61].

Transformation Accelerators

A mode of innovation that requires significant changes in food systems (infrastructure, technology, expertise, and capabilities) and structural reforms of principles, legislation, policy, economies, and governance around them is essential to this process (Table 2). This vision of transformations as a dynamic and integrated mechanism suggests that modern technology alone is not enough to force changes in the food system; instead, it should be supported through a broad spectrum of societal and structural forces that empower its use [32].

Table 2. Technical preparations for future food system technology. The technology readiness score is a (ten-step stage system) evaluation system that helps to assess the maturity of specific technologies. Detailed information about each step, score estimates, technical groups, and initials is provided for each technology.

Food System Technology	Research Initiated	Experimental Proof	Prototype	Implemented	References
Microalgae and cyanobacteria for food				H	
Innovative aquaculture feed				H	
Microbial protein				H	
Insects for food				H	
Seaweed for food				H	
Disease pest resistance				FPS	
Biofortified crops				FPS	
Vertical agriculture				I	
Drying/stabilizing methods				I	
Drones			O		
Battery technologies			O		
Tracking and confinement techniques for livestock			DA		
3D printing			DA		
Improved climate forecasts			DA		
Traceability technologies			DA		
Farm-to-farm virtual marketplace			DA		[11,33,52,62,63]
Robotics			DA		
Disease/pest early warning			DA		
Microbials			H		
Micro-irrigation/fertigation			H		
Dietary additives for livestock			H		
Soil additives			H		
Microbial			H		
Circular economy			H		
Omega-3 products for aquaculture			H		
Irrigation expansion			I		
Oil crops			GT		
Genomic selection			GT		
Genome editing			FPS		
Sustainable processing technologies			FPS		

Biodegradable coatings			FPS
Food safety techniques			FPS
RNAi gene silencing			FPS
Plant phenomics			FPS
Big data			DA
Smartphone food diagnostics			DA
Intelligent food packaging			DA
Internet of Things			DA
Soil sensors			DA
Advanced sensors			DA
Holobiomics		H	
Botanicals		H	
Weed-competitive crops		GT	
GM-assisted domestication		GT	
Nano-enhancers		H	
Enhancing efficiency fertilizers		H	
Personalized food		H	
Omic data usage		DA	
Data integration		DA	
Pre-birth sex determination		DA	
On-field robots		DA	
Artificial phenomics		DA	
SERS sensor devices		DA	
Assistive exoskeletons		DA	
Pest control robotics		DA	
Whole-genome sequencing		I	
Microorganism coatings		I	
Nanocomposites		I	
Electro-culture		I	
Artificial meat/fish		CA	
Molecular printing		CA	
Genome-wide selection		FPS	
Resurrection plants	FPS		
Apomixis	FPS		
Nano-drones	DA		
Nanotechnology	DA		
Nano-pesticides	H		
Artificial products	CA		
Nano-fertilizers	RE		
Ecological biocontrol	O		
Reconfiguring photosynthesis	GT		
Novel perennials	GT		
Novel nitrogen-fixing crops	GT		
Synthetic biology	GT		

Note: digital agriculture (DA), cellular agriculture (CA), food processing and safety (FPS), gene technology (GT), health (H), inputs (I), intensification (In), other (O), replacement food and feed (RFF), and resource use efficiency (RE).

Transformation is also a deeply political process with winners and losers, which involves choices, consensus, and compromise regarding new directions and pathways.

Powerful food system actors provide the right motivations for the continuation of the current status and market share. In comparison, new consumers are much more likely to behave as device disrupters and use it as a means of generating fresh products and appeal (e.g., replacement of meat). Efforts to drive beneficial structural progress and transition must also be compatible with social and political mechanisms that obstruct or catalyze creativity in the sector [50,55].

In reality, this involves creating relationships, dialogue, and faith in the pathway for improving food systems, maintaining governance and regulatory systems to preserve the expected effects of food systems, all necessary conditions for the implementation of modern technologies (Table 2). Emerging innovations benefiting from such improvements include insects for food, meat-generated animal alternatives, food system circularity, and vertical agriculture [11,43,55].

The new device developments (e.g., molecular printing, biodegradables, and customized nutrition) can catalyze technology by incorporating additional devices and tools (e.g., drones) into system developments resulting from extensive social and political shifts that drive transformation [32,61,64]. Technology can also raise undesired lock-ins (e.g., a grower who has practiced and invested heavily in grain production cannot turn quickly to diversified agriculture) [50,65]. To avoid these lock-ins, it is essential to recognize the mechanisms of transition.

4. Eight Action Initiatives for Sustainable Food Systems (SFSs)

We summarize eight action initiatives (e.g., building trust, emerging transition pathways, transforming mindsets, empowering social licensing, changing policies, designing market incentives, safeguarding against undesirable effects, and ensuring stable finance) closely related to technological and structural progress in food systems (Figure 2, Table 3).

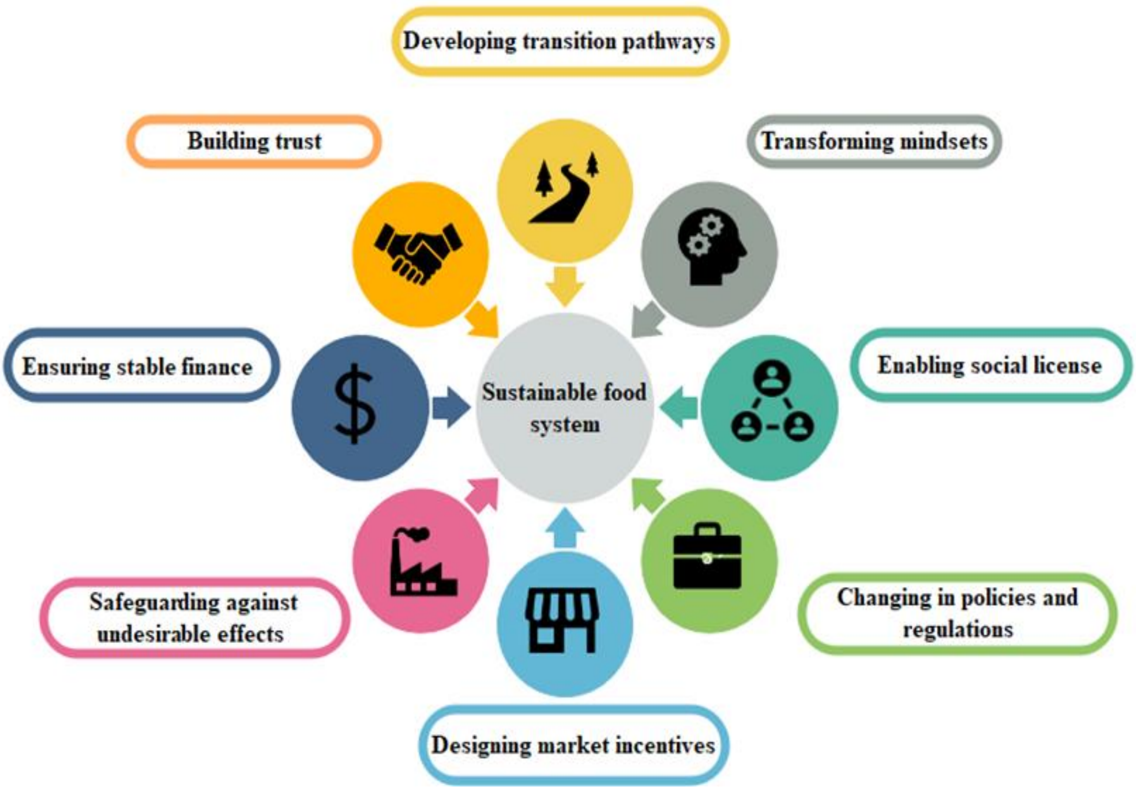

Figure 2. The crucial elements of hastening the transformation of food systems. These elements improve sustainable and healthy diets, productive agri-food systems, and waste management, these three outcomes being essential to achieving SFSs, modified from [11,33].

Table 3. Basic elements of developing and scaling up beneficial effects, and examples from four case study technologies.

Action Initiatives	Examples	References
Developing transition pathways	For all case studies Establish a transition path based on all the above elements. Ensure that everyone, involving those at a disadvantage, can benefit from innovation. Apply adaptive methods to acclimate to changing environments and unintended consequences. Focus on attaining overall goals, not explicit technologies. Local, national, and international pledges and suitable resource apportionment. Case studies dedicated to automation and robotics in agriculture. Endorse health and safety and create employment to attain fair production.	[11,33,50]
Transforming mindsets	For all case studies Boost the acceptance of high-tech products and the handling of nourishment and feed. Case studies specific to microbial proteins in organic waste streams. Treating all types of waste as by-products can be used as valuable inputs for other processes. Accept feed production from organic waste streams, counting human and animal waste.	[11,33,66]
Enabling social licensing and stakeholder dialogue	For all case studies Interact with stakeholders across humanity (comprising consumers, workers, and producers) to ensure transparent development and technology implementation. Case studies specific to grain nitrogen fixation. Focus on food quality to ensure that new crops are as good even if they do not substitute crops. Indications and enhanced environmental footprint, reduction in input usage and waste. Evade vertical integration models that cause industry conspiracy concerns.	[11,50]
Changing policies and regulations expected support	For all case studies Improve and simplify coherent strategies and regulations to ensure proper supervision and enforcement of environmental, social, health, and safety standards throughout food systems. Reduce economic and organizational limitations on technology adoption and dissemination. Case studies specific to personalized nutrition. Apply strong standards on nutrition and health labeling. Develop supervision of the food environment, which will affect personal consumption choices.	[11,33]
Designing market incentives	For all case studies Formulate fiscal and trade policies to cultivate initial markets to achieve economies of scale. Invest in plans to increase awareness of new technologies and their appropriate use. Case studies specific to microbial proteins in organic waste streams. Increase waste costs to encourage alternative uses (for example, enhance waste disposal fees). Provide price help for main inputs to decrease production expenses. Provide support to the traditional feed industry to transition to alternative production.	[11,33]
Safeguarding against undesirable effects Monitor and correct	For all case studies Independent, transparent, and competent regulatory agencies oversee and enforce standards. Establish global eco-friendly, worker, and trade standards to evade offshore external factors. Entail investment to improve the usage of influence valuation and further assurance principles. Case studies specific to grain nitrogen fixation. Monitor land usage to ensure the adoption of tech-	[33,50]

	nology aids lessen the food system footprint. Monitor the wider adverse effects of extensive adoption of new crops. Monitor the nitrogen concentration in the soil to inform the taxation of excess nitrogen to avoid overuse.	
Ensuring stable finance Explore and pilot	For all case studies A clear commitment to long-term objectives to support stakeholders in reorienting their assets. Encourage the use of other funding mechanisms to support liable improvement. Persuade long-term funding and approve the extension of the investment timetable to obtain a total return on investments. Case studies dedicated to robotics and automation in agriculture. Promote the application of verified robotics machinery in modern agricultural environments to enhance the visibility and perceivable viability of agricultural food systems.	[11,33]
Build trust vision and values among participants in food systems	For all case studies Establish trust in so-called profits with reason or so-called progressive benefits of the system. Promote transparent production, supply, and management procedures. Develop trust in regulatory agencies that describe and enforce ecological, health, and safety standards. Case studies specific to personalized nutrition. Increase a health-centric machinery platform that equalizes short- and long-term goals.	[11,50]

4.1. Building Trust among Stakeholders of the Food Sector

Every change in the agricultural sector demands the general opinion and support to build new developmental pathways. Technology, cooperation, and a set of collective values regarding the agreement of the results of various food systems are the key factors. These results include the durability, socioeconomic effects, and provenance of the developed food system. Development of trust occupies the central position in this process. Many social and economic networks provide the connecting resources between the food producers or farmers and food consumers or food companies. For the absorbance of technology and a systemic change, many steps are necessary for the actors of food systems, i.e., identification of business opportunity by private companies, identification of systemic change requirement by the government for public welfare, initiation of a dialogue with the mass/public to modify their attitudes, and innovation in policy and market shifts by investments (public or institutional) [32,67]. The Green Revolution in Asia provides an excellent example of these types of systemic variations, which has resulted in increased crop production and utilization and diminishing malnutrition in a little more than a decade [32].

The involvement of the government can remarkably introduce technology to the public. A high-level agreement can be critical in this regard because of ecological and ethical concerns from production to food utilization. For example, suppose the arrangements have a robust scientific base for the desired targets with the participation of public or private sectors for their opinions and discussions. In that case, mechanisms, innovative ideas, different products, incentives, and policies can be developed. The Paris Agreement on greenhouse gas emissions and the Sustainable Development Goals are excellent examples occupying the central position among national and international strategies in the public and private sectors. Managing the prospects of various stakeholders is necessary to gain legitimacy and trust. The best behavior may depend largely on the behavior expected by others. Suppose the benefits of adopting a particular behavior (e.g., using and/or investing in a specific technology) are considered a function of the behavior's popularity, among others. In that case, there may be a vicious or virtuous circle of self-fulfillment expectations, which ultimately accelerates or hinders change [68]. The Green Revolution of the 1960s provides an excellent example in this regard. If the expectation of acceptance of new adoption by other individuals is low, then the target individual would not adopt it; hence, temporary subsidies and incentives can play a crucial role in this regard [69].

4.2. Transforming Mindsets

The actors require an understanding that is ready to accept new information about food systems. There is also a requirement from a similar point of view of decision makers. Humans have a deep relationship with food regarding biological, psychological (especially around naturalness) [11,70], and cultural aspects [50,65], and thus it is still uncertain whether society would accept innovation or not. Hence, innovation's price and security are not the sole factors for innovation to be absorbed in the community. There is a tripartite relationship between people's attitudes to technology, the regulation that can change the market structure, and market actors that play out within a regulatory framework. The need to better understand the technology and transform mindsets arises particularly in the case of technologies whose advantages and disadvantages are still largely unknown (for example, gene editing, reconfiguring photosynthesis, novel nitrogen-fixing crops) [55].

4.3. Empowering Social Licensing and Stakeholder Discussion

There is a strong association between people's expenses on innovative development in social licensing and acceptance of innovation. The development of useful technology and public communication are critical factors in this regard [71,72]. It is possible to get pressure from users, workers, and capitalists to change the technologies being used (e.g., meat alternatives and nano-pesticides) after people become aware of specific issues in the existing technologies. It is compulsory to incorporate these actors. Otherwise, there are fewer chances of adopting innovation even if the invention has enough energy (e.g., genome editing). There may be a constraint to positive change by those who carry out trades routinely. Understanding the utilization of technology is very important for its proper use. Additionally, learning by action or practice is the critical factor in systems based on extensive knowledge [55,73,74], but it may be a loss for the smallholders (e.g., small farmers, suppliers, food processors, and growers) in developing countries.

4.4. Guaranteeing Variations in Strategies and Regulations toward Food System Sustainability

It is important to consider how all investors will respond to a new change in technology by keeping the investors' interests in mind. For example, currently, climate change has inducted a twist in carbon emission policies worldwide. Therefore, investors shall be keen to invest in any new technology possessing low-carbon emission abilities if they feel that this will be monetarily beneficial and rewarding. Once a technological change comes into play, it may become economically accessible, meaning it will have the social effects of being bought and changing policies. Besides this, if people start distrusting, the technology will never become a new product as few will be interested in adopting it. Others will stick towards myths of their own as the benefit of stable reward is their firsthand and selfish courage [68]. Therefore, only little effort is required to make policies favorable, such as subsidizing the projector by using public funds as this cause may attract several investors due to their self-interests [75–77].

4.5. Designing Market Incentives

Any technological change is successful only when all the investments and budgets are well planned and well directed. The hurdles toward a new technology and its application may vary. In a competitive environment, the big companies negate spending on knowledge and research-based technology as they solely intend to invest and make money. However, governments have come forward to play their roles to support such technologies. Governments have to propose a resolution to address this issue by tailoring appetizers such as subsidizing a company to produce on a mass scale, providing them with opportunities in the market, easing the procurement process, and even relaxing tax rates. This act of government is never confined to an old industry only. Instead, governments even try to offer all these helping tools to newly built companies because it is never understood who will eventually introduce better innovations [78]. The government's involvement in incubating innovation and accelerating technological enhancement can offer us new solutions in the market [11,79]. This has been the case with many technologies on our list (Table 1) across all technology groups (drones, algae for feed, plant-based meat substitutes, nano-enhancers, personalized food). Incentives that drive innovation also differ from those that encourage diffusion.

4.6. Safeguarding against Undesirable Effects

There are always hurdles when policymaking for transformation is needed because it is always challenging to correlate investment and technological changes. When the stage of public acceptance comes, it is still a complex situation, and regulating the whole operation is difficult and can even go overlooked [30,80,81]. For example, circular economic approaches in the food sector should always be in accordance with the strict laws which are established across North America and Europe about the re-use of organic waste as animal food (this law came into effect after the bovine spongiform encephalopathy and foot and mouth outbreaks) [82]. A mass-scale or widespread dialogue for a consensus may help more acceptably legitimize or better understand the grounds of disagreement. It may also help us understand how adoption or non-adoption happens, and how a whole struggle of innovation falls under the complexity and lack of social licensing due to not understanding the relevant issues. However, still, great technology cannot be accepted if it conflicts with the myths and traditions of a society deep rooted in the culture [65,70,83].

4.7. Ensuring Stable Finance

Technologies related to food and agricultural products undergo a production that is affected by seasons and regulations. This aspect makes the whole process more challenging. It becomes hard to relate investment and innovation because it favors any failed operation and then starts it again differently. Additionally, the transformational changes become more unpredictable, and their impacts are not easily measurable as accurate environment testing is needed to evaluate the effectiveness. Transformational change requires more creative investment solutions, steady and stable investment plans, and more extended time deployment of persistent investors to encourage a valuable output [55,84]. We need strong support for research and development for a longer time to develop a broader range of technologies for food sustainability (e.g., reconfiguration of photosynthesis, new vaccines for livestock, and genetically modified assisted breeding technologies) [43,66]. In addition, the application of digital knowledge and digital technologies in agriculture may tend towards better solutions, as happened in mobile banking during the mobile phone revolution in the 2000s.

4.8. Emerging Transition Pathways

Most research for prospective food systems is about the effects of substituent models and many other parameters such as food alterations, minimizing waste, and elevated productivity [23,26,54,85]. However, such research has not discussed the mechanisms to convert them to address real-world issues. The term transition pathway is used to demonstrate how to convert these ideas into reality. However, the transition pathway demands a significant amount of information about digital innovation and its effects, goals, and improvement in the framework of public and private institutions, and a systemic path is necessary to obtain the desired results. Hence, accelerators and digital technology can be useful tools for developing these pathways. Digital technologies can provide an innovative solution to enhance the performance and sustainability of agricultural production systems [86,87], described as having economic, social, and ecological aspects [88,89]. Digital technologies can make the food sector more effective, inclusive, and ecologically sustainable, thereby increasing the interests of growers, customers, and society [90]. Moreover, digital technologies can help increase farm productivity, advance resource utilization efficiency, and support environment resilience [87,91]. If digital technologies are implemented/adopted, the improvement in main production, supply chain, and logistics performance and reductions in food loss and waste will be particularly significant. In addition, the COVID-19 pandemic has shown the importance and application of digital technologies in the food industry [92] and has promoted the introduction and adoption of digital technologies for sustainable agriculture and food systems [93]. Despite the numerous benefits promised, such as other major innovation breakthroughs, digital agriculture is not without challenges or risks [33,87,90,94,95]. As reported by the Food and Agriculture Organization (FAO), digital technologies can significantly address the challenges faced by the global agro-food systems at every level of the supply chain [96,97]. The FAO argued that digital technologies at the farm level, such as sensors, robots, and drones, can provide precise information to farmers and help them increase yields in a climate-friendly way. Blockchain technology can enhance traceability and sustainability by monitoring the food chain from the field to the final consumer [98]. The United Nations also explored the opportunities offered by digital technologies in the field of nutrition and concluded that they help provide tailored health advice but warned against their potential threats to the privacy of health information [99]. The FAO argued that "digital technologies can trigger major changes or "disruptions" in the sustainable food system that not only improve efficiency and speed but also redistribute information and power along the value chain" [100]. A similar approach was adopted by the European Commission, which, albeit recognizing the limited spread of digital technologies across the Union, considers them capable of increasing sustainability in the agro-food system [101], thus prioritizing digitalization in the Common Agricultural Policy (CAP) reform 2021–2027 [98,102].

5. Conclusions

Currently, food systems face enormous challenges such as a growing population, competition for resources, global food chain complexity, food consumption, climate change, increased biofuel production, limited food access, unsustainable agricultural practices, lack of farmers' and workers' rights, and food waste [95]. Since society is undergoing transformational progress in the use of telecommunications, including digital agriculture, new physical systems, and renewable energy, technological innovation is bound to play an essential role in the future of SFSs.

The inventory of potential technologies related to food systems has been extended. However, there is an urgent need for a more robust analysis of technological innovation and its potential impact on food security. This research is technically complex, especially in uncertainty and selecting new investment streams identified as funds for research organizations to work on. This research has been invented with a multicultural and socio-governmental perspective to ensure instant innovation where it is required the most, maintain fairness, and adopt diverse ideas.

The technological innovation and advancement in SFSs rely on sufficient investment in rudimentary study and improvement to maintain the research and development process. In the future, several modern techniques will significantly contribute to food systems worldwide. Therefore, there is a dire need to circumvent the bottleneck of the conducive ecosystem, particularly in developing nations, where the prospective influences (positive and negative) of the modernization of technology may be comparatively significant. History demonstrates that technology innovation produces winners and losers. In the short and long term, the considerable agenda in the sustainability of society and food systems is used to deal with several social and agricultural sectors.

Despite the numerous benefits of adopting innovative and advanced agriculture technologies, as with other major innovation breakthroughs, digital agriculture is not without challenges or risks. The major challenges to implement and adopt these technologies to support digital agriculture are the cost and appropriate training to use such technologies.

Finally, and perhaps most significantly, hastening food systems' transition to a positive, ideal state will have to entail social dialogue. Of the eight action initiatives proposed to hasten the systemic revolution of food systems, as a minimum, five revolve around building trust, obtaining a social license, changing mindsets, preventing adverse effects, and developing transitional pathways. Achievements in all these acts will lead to superior health, a better environment, and improved SFSs.

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Abbreviations

TI	Technology innovation
CA	Cellular agriculture
FPS	Food processing and safety
H	Health
DTP	Developing transition pathways
ICTs	Information communication technologies
GM	Genetically modified
AFS	Agri-food system
FP	Food policy
H	Health
RFF	Replacement food and feed
O	Other
TRLs	Technology readiness levels
ACI	Agri-food consulting
TLU	Tropical livestock unit
GDP	Gross domestic product
IFR	Institute of Food Research
FDA	Food and Drug Administration
MDGs	Millennium Development Goals
SFS	Sustainable food system
DA	Digital agriculture
GT	Gene technology
RUE	Resource use efficiency
TM	Transforming mindsets
PATs	Precision agriculture technologies
R&D	Research and development
FAO	Food and Agricultural Organization
AVC	Agri-food value chain
I	Inputs
In	Intensification

MT	Modern technologies
NASA	National Aeronautics and Space Administration
WHO	World Health Organization
SOFA	State of Food and Agriculture
LEAD	Livestock, Environment and Development
CAC	Codex Alimentarius Commission
FMS	Food management subsystem
MAFF	Ministry of Agriculture, Food and Fisheries

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