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Digitalization of the agro-food sector for achieving sustainable development goals: a review

Increasing food demand, inequality, climate change, and pandemics threaten global food security. Digital technologies are aligned with the UN's sustainable development goals and are poised to play a crucial role in modernizing agriculture, with advancements from AI, precision farming, and data analytics. Digitalization in food safety and e-commerce is increasing, while future trends include blockchains for traceability and personalized foods improving health and nutrition. These approaches boost yield, reduce waste, and promote widespread sustainability.

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Digitalization of the agro-food sector for achieving sustainable development goals: a review

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Food security and agricultural sustainability are essential for an equitable and healthy society. Increasing food demand, growing inequalities, climate change and pandemics are converging to undermine food security. These factors are contributing to an impending global food crisis, with 30% of people worldwide lacking regular access to adequate food. Digital technologies offer unique opportunities to address techno-economic challenges in the agro-food sector by improving food production, quality, supply chain management and commerce. The innovations offered by digitalization in agricultural and food systems can help attain the 2030 United Nations sustainable development goals. Here, we review the importance and application of digitalization in the agriculture and food sectors. The modernization of agriculture through technological advancements such as artificial intelligence, precision farming, and big data analytics has been emphasized. The integration of these techniques would significantly increase yield with minimal human interference, leading to environmental, social and economic sustainability. The adoption of digital technologies in agriculture allows for at least a 23% reduction in costs and a nearly 5% decrease in the volume of medium-level waste. Furthermore, digitalization in food safety and electronic commerce is increasingly being adopted. Future trends lie in blockchain technology for improving traceability and personalized foods catering to individual consumer needs for better health and nutrition.

Sustainability spotlight

The food crisis is a major global concern that is closely related to sustainable development. The second United Nations Sustainable Development Goal focuses on achieving zero hunger and food security and promoting sustainable agriculture. Despite the advancements, food insecurity has been rising since 2018. The unprecedented challenge requires innovative research efforts on an urgent basis. The purpose of this work is to emphasize the importance of digitalization technologies in the agro-food sector as well as their potential for addressing several complex challenges for sustainable development. The findings reveal that digitalization of the agro-food sector can play a crucial role in achieving sustainability by improving automation, process efficiency, food safety, traceability, and optimizing resource management. Digital technologies such as sensors, drones, and data analytics can help farmers optimize their use of resources, such as water and fertilizers, and reduce waste. This can lead to increased food security as well as lower greenhouse gas emissions and reduced environmental impacts. Food safety can be ensured through real-time food quality monitoring. The review presented here elucidates the contribution of digital technologies to improving the sustainability of the food and agricultural industries. In spite of the rapid advances of digital technologies, their benefits have yet to be fully realized in the agro-food sector on a global level. Future research should be focused on increasing the adoption of digital technologies in food and agriculture. Smart packaging and IoT-enabled sensors would allow monitoring of food conditions during storage and transportation, thus minimizing food spoilage and wastage. Non-invasive analytical techniques would be useful for analyzing the chemical composition of food products. Advances in big data, artificial intelligence, and computational tools would aid in predictive modeling for ascertaining food quality based on molecular compositions and chemical reactions. This work should pave the way for incorporating digital tools into existing technologies to improve their capabilities, as well as exploring emerging applications such as personalized food formulations, with the ultimate goal of developing sustainable agro-food systems.

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1. Introduction

Early developments in the agro-food industry started centuries ago with small but creative innovations with respect to processing. The transition from simple tools to huge machinery marked a significant leap towards bulk production and processing. Agriculture and food processing industries have pioneered various technological breakthroughs and innovations.[1,2] The large-scale mechanization has paved the way for improved farm machinery, efficient production and boost in the economy. A survey of agricultural machinery in Bangladesh up to 2019 indicated that about 80% of land tilling was done by power tillers whereas 15% of land was tilled by tractors. About 1.57 million of low lift pumps, shallow tube wells and deep tube wells were used for irrigation of 95% of farmland.[3] A study conducted in 2020 at five smallholder rice farms in Nasarawa, Nigeria explored the outcome of shifting from manual to mechanized harvesting and threshing. The mechanization of farming reduced greenhouse gas emissions by 1696 kg CO_2 equivalent per hectare, decreased paddy losses from 9.6% to 0.9% and improved threshing efficiency from 31.1% to 33.1%.[4] The agro-economic benefits arising due to switchover from manual to mechanized farming has potential to outweigh the investment involved and lead to sustainable practices.

The positive transformation induced by agricultural mechanization needs further expansion to address broader challenges regarding food security. Rapidly changing lifestyles and socioeconomic factors have contributed to many food commodities and packaging materials getting wasted worldwide. Research done in China reported that about 15% of the total food produced and 10% of the water used for foods got wasted or discarded.[5] A consumer habits and attitude study conducted in 2016 analyzed that nearly 90% of the consumers claimed to throw away some food after every meal. Common foods included leftovers, bakery, fruit and vegetable peels and other foods left for many days in the refrigerator.[6,7] Food wastage was also found to have a tremendous impact on the environment and carbon footprint. A study conducted in Daegu, South Korea on the basis of food waste collected from 218 households in 2019–20 inferred that the average daily contribution of food waste was 0.73 kg per household, 0.71 CO_2 equivalent of greenhouse gas emissions, 0.46 m^3 of water footprint and 3855.93 Korean won of economic loss.[8]

Recently, a comprehensive global food emission database was developed that analyzed emissions from each stage of the food chain on a yearly basis for the duration 1990–2015. The findings revealed that agro-food sector activities accounted for nearly 34% of the total global anthropogenic greenhouse gas emissions.[9] The global demand of food is projected to rise by 35% to 56% between 2010 and 2050, leading to the intensified use of natural resources, specifically land, water and energy.[10] Thus, a paradigm shift is required in making the current food production ecosystem more efficient by new technological improvements that can address food safety concerns in an environmentally sustainable manner.

The sustainable development goals (SDGs) adopted by the United Nations in 2015 are a set of 17 global objectives for attainment of a sustainable future for all by 2030.[11] These are: (1) no poverty, (2) zero hunger, (3) good health and wellbeing, (4) quality education, (5) gender equality, (6) clean water and sanitation, (7) affordable and clean energy, (8) decent work and economic growth, (9) industry, innovation and infrastructure, (10) reduced inequalities, (11) sustainable cities and communities, (12) responsible consumption and production, (13) climate action, (14) life below water, (15) life on land, (16) peace,

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[1]justice and strong institutions, and (17) partnership for the goals. These goals encompass social, economic and environmental dimensions of sustainability. Importantly, these goals are interconnected, with progress in one often influencing outcomes in the others.

Specifically, the second sustainable development goal specifically aims to end hunger, achieve food security and improved nutrition and promote sustainable agriculture.[12] The hunger problem has aggravated in recent years with nearly 9.8% of global population affected by hunger in 2021 in comparison to 8% in 2019 and 9.3% in 2020. About 11.7% of people worldwide confronted severe food insecurity.[13] The trends suggest that the world remains far from the ultimate target of eliminating hunger and malnutrition-related issues. The pandemic crisis not only exacerbated the existent challenges but also exposed vulnerabilities in the agro-food supply chain.

The coronavirus pandemic hugely impacted all sectors worldwide bringing out infrastructure and management-related inefficiencies and challenges. The restrictive measures taken by the government in almost all countries led to interruption in supply chains, production, tourism, transportation and sales. The stoppage of international trade and transportation caused an imbalance in supplies indirectly impacting the economy. A study done in India in May 2020 revealed that more than 80% of farms had a decline in sales, and farm income decreased for nearly 90% of farms in the dataset.[14] Additionally, 62% of surveyed households reported disruptions in dietary patterns. The pandemic also brought about immense changes in the lifestyles, healthcare facilities and services leading to improvements in these areas.

One of the unprecedented developments triggered by the pandemic has been in the context of digitalization. Invariably, almost all sectors have experienced the incorporation of digital technologies for various purposes.[11] The development of novel applications based on these technologies has enabled efficient operation and control of systems in agricultural and food systems. The smart systems allow highly effective storage, transmission and retrieval of electronic data. The amalgamation of these technologies in the agricultural and food sectors is likely to have enormous favorable consequences in improving productivity and output. Meta-analyses suggested that the dissemination of agricultural information using mobile devices in sub-Saharan Africa and India improved yields by 4% and the likelihood of adopting agrochemical inputs by 22%.[15] These developments represent a significant leap in the direction of attaining the sustainable development goals.

While the primary focus of digitalization in the agro-food sector is indeed related to SDG 2, which centers on eradicating hunger and achieving food security, it is vital to recognize its broader implications encompassing other relevant SDGs. Digitalization contributes to SDG 1 (no poverty) by enhancing the livelihoods of smallholder farmers and marginalized communities through improved access to markets, financial services, and valuable agronomic information. In the context of SDG 3 (good health and well-being), digital technologies contribute to safer, healthier food by enabling real-time monitoring and traceability, thereby reducing foodborne illnesses. The efficient use of digital technologies in agriculture leads to improved water resource management and conservation, aligning with SDG 6 (clean water and sanitation). Moreover, digitalization plays a role in SDG 8 (decent work and economic growth) by generating employment opportunities within the agro-food tech sector, promoting sustainable economic growth. SDG 9 (industry, innovation, and infrastructure) benefits from innovative agro-food technologies that improve production and distribution infrastructure.

Furthermore, digitalization supports SDG 12 (responsible consumption and production) by promoting resource-efficient farming practices, reducing food waste, and enhancing traceability in supply chains. SDG 13 (climate action) gains momentum as digital technologies enable precision agriculture and resource optimization, contributing to climate resilience and mitigation efforts. Moreover, SDG 14 (life below water) benefits from digitalization as it pertains to marine ecosystems. Precision aquaculture, reliant on digital technologies, can optimize seafood farming practices, thereby reducing the strain on marine resources and aiding the conservation of aquatic life. Additionally, digitalization aligns with SDG 15 (life on land) by promoting sustainable land use and agriculture. Technologies like data analytics minimize the use of harmful agrochemicals, reduce soil erosion, and encourage sustainable land management, contributing to the conservation of terrestrial ecosystems and biodiversity. Hence, the far-reaching impacts of digitalization extend to various SDGs in a holistic manner.

This work provides a critical perspective on the digitalization of agriculture and food sectors in the context of sustainability. The direct and spillover effects of the pandemic on the economy, food production, logistics and consumer behavior have been discussed. Future technologies such as smart farms and foods, artificial intelligence, machine learning, precision farming, big data storage and food safety digitalization in the agro-food sector have been the prime foci of this work. Adequate importance has also been given to the future outlook in blockchain and food personalization. The review has been written after critically evaluating various research papers, review articles and online reports from the Google Scholar database over the past ten years. The work could pave the way for a paradigm shift in agricultural practices and food production systems to move towards a sustainable future.

2. Effect of the pandemic on the agro-food sector and environment

The novel coronavirus (2019-nCoV) constituted a class of enveloped, single stranded ribonucleic acid viruses responsible for the Middle East respiratory syndrome (MERS-CoV) and severe acute respiratory syndrome coronavirus (SARS-CoV).[16] The virus reportedly emerged in 2019 from a wet market in the Wuhan province of China and rapidly spread globally.[17] The coronavirus disease (COVID-19) pandemic situation led to severe global disruption in the systems ranging from transportation and logistics to agricultural and food production. The International Monetary Fund and World Bank estimated a global contraction in the gross domestic product by 3–7% in 2020.[18] Many parts of North America and Canada experienced huge issues in transporting frozen foods in container ships due to restrictions in other countries and lack of migrant laborers. The reduction in overall freight services caused a massive hit in sales.[19] Various countries with limited agricultural production such as those from the sub-Saharan region import about 75–90% of the food they consume. The trade and supply chain imbalances were aggravated due to the pandemic and many nations faced a huge food shortage crisis. Kenya, for example, faced massive losses in international trade with the European Union as its fruits, vegetables and herbs rotted on farms.

Additionally, due to the local travel restrictions, the sales of perishable food commodities also became challenging.[20] The reverberations of the pandemic were significant in China and India, the most populous nations in the world, and prompted the authorities to initiate the countermeasures. Manufacturing industries in India including the food sector noticed a major disruption in the supply chain as workers returned to their hometowns and many lost their jobs.[21] China initiated a Clean Your Plate campaign in 2020 to address the food shortage issues during the pandemic crisis.[22,23]

Although the virus created a catastrophic situation for everyone, the lockdown also prompted some positive changes. Industrial waste emissions and discharges decreased considerably. Due to the imposition of a worldwide travel ban and with forced public confinements, vehicular movement was restricted leading to a reduction in toxic emissions. The daily global fossil CO_2 emissions declined by nearly 17% in April 2020 relative to the mean emission levels in 2019.[24] These lessons from positive transformations highlight the potential for controlled measures to have a positive impact on the environment.

2.1 Global economy

Agriculture is the foundation of growth for many agrarian countries, accounting for a sizable portion of their gross domestic product.[25] The sector meets the food consumption needs and also constitutes one of the major export segments in such countries. Due to the sudden outbreak of the pandemic, farmers all over the world faced severe issues related to price volatility, rising debts and job losses. The announcement of lockdown was tough for farmers across different countries, with several implications including (i) dearth of labor supply, (ii) deficiency of fertilizers, (iii) stoppage of import and export of raw materials, (iv) extreme climatic conditions, (v) sudden shutting down of factories, and (vi) post-harvesting issues.

The concerns also escalated in various countries due to transportation issues leading to obstruction in the conveyance of various commodities to their destinations. A survey conducted among farmers in Tamil Nadu and Kerala states of India for the study period January–December 2020 revealed that 46% shortage was observed for chemical fertilizers. The maximum shortage among the pesticides was found to be 52% for insecticides, whereas 25% shortage was seen for herbicides.[26] The insufficiency of fertilizers and pesticides has an adverse impact on agrarian output. The encountered challenges necessitate pertinent actions to enhance the overall agro-food supply chain for sustainable development.

2.2 Food production

The disruptions in food and agricultural production have an immense impact on the global food demand leading to poverty, hunger and malnutrition. Although the current influence of food security is minimal, more challenges may arise in the countries with limited assets. In the least developed countries, production is very labor-intensive and requires many workers for processing staple crops such as rice, wheat, maize and soybeans.[27] In contrast, the production operations are highly mechanized in developed countries managed by limited workforce. The concerning issues in agro-food production units during the pandemic mainly arose due to social distancing norms and shortage of workers. An imbalance manifested between demand and supply with the main effect on population with low income. The demand for emergency food supplies also increased as the global food processing facilities were affected for a prolonged period. A survey conducted among the recipients of meal assistance program in Kentucky, USA during September 2020–February 2021 indicated that more than 71% respondents utilized the meal assistance services more frequently in the pandemic situation.[28] In another study, researchers estimated that the number of people facing acute hunger could surge by 130 million as a consequence of the pandemic.[29] Thus, farmers must strike a balance between crop production and conservation in order to ensure food supply in the event of a future pandemic.

2.3 Supply chain

Another area greatly hit by the pandemic was the overall food and agricultural supply chain with strict global scale restrictions. The interruptions in food supply posed challenges in processing, harvesting, transport, packaging and distribution. The sudden announcement of lockdowns led to huge risks and imbalances in the supply chain. The closure of international borders and strict constraints on the movement had consequences with respect to (i) transportation delays, (ii) shortage of workers, (iii) shutting down of processing units, and (iv) inventory buildup, leading to enormous wastage and spoilage of food.

In various countries, farmers were forced to dump the produced food due to lack of vehicles and workers. The disruptions in the supply chain compelled dairy farmers in the United States to dump 7% of milk produced during the first week of April 2020.[30] About 350 acres of lettuce crops with an estimated value of $1.46 million were reportedly plowed under during the same period in California.[31] Due to mobility restrictions, air freight was often the only option for the trade of high-value foods. However, there were challenges associated with the cost and shortage of trained workforce. The resultant disruptions could have long-term implications regarding food accessibility.

2.4 Consumer behavior

The pandemic led to discernible changes in the social behavior. The restrictions imposed during the pandemic situation

Table 1 Major changes and trends observed in the agro-food sector based on the short-term and long-term impacts during a crisis or pandemic[11,19,26,35]

Areas impacted	Short-term impact	Long-term impact	Changes and trends to meet the demand
Food and agricultural commodities	Increase in global food demand	Rise in the consumption of staple foods	Rise in the number of online-transactions and cashless trading
	Human population loss due to food shortage	Increase in the number of consumers cooking at home leading to losses in restaurants	Increase in automation of food production and processing thus reducing the risk of contamination of foods
	Piling and stocking of essential food commodities leading to decrease in supplies	Stocking raw materials and ingredients	More investment in post-harvest technologies and supply chain management for better speed to market
Trade relations	Issues in the import–export of food commodities between countries due to lockdown	Start in usage of local food commodities and products with an aim to decrease the amount of infection and ultimately achieve self-sufficiency in food production	Advent of vertical farming and hydroponics technology to increase sustainability in agricultural production
		Reduction in the export of food commodities	Accelerated deployment of different cross-bred crops using genetic technologies for improved productivity
Employment	Closing of borders limiting the availability of migrant workers	Unemployment and job loss surge	Protected cropping to address unpredictable climate change
	Salary cuts or no-salary and sudden variation in pay-rates	Rise in poverty worldwide	Use of controlled environments, increase in nutritional values and food product innovations to address food security
Transportation	Transportation issues due to different rules and restrictions being followed worldwide	Segregation and shipment of only high valued and emergency foods by air	Adoption of digital tools to ensure a better connect from farm to fork
Consumer behavior	Prioritization in food purchase	Increase in consumption of plant-based foods and immunity-boosting foods	

prompted consumers to indulge in panic shopping and stocking essential food commodities. The demand for staple and canned foods rose as restaurants shut and home cooking increased. Rapid spread of the virus compelled people to transition to a work from home environment. The health concerns of consumers resulted in an increased consumption of packaged foods. Studies revealed that the sales of pre-processed and packaged food commodities grew by 20–54% during the pandemic.[32] An increase in the amount of plastic waste was seen as consumers began ordering more food online.[33] An increase in the consumption of readily consumable foods that required less cooking also surged during the pandemic.[34] In addition, precautions with respect to health and a diet-changed behavior with immunity boosting foods became more popular during the lockdown phases. Table 1 summarizes various changes observed in the agro-food sector in the context of the pandemic situation.

The emergence of the COVID-19 pandemic significantly reshaped the landscape of the agro-food sector, prompting a rapid adaptation to digital technologies. This global crisis accelerated the adoption of digital solutions and emphasized their crucial role in ensuring the resilience and sustainability of food systems. The pandemic disrupted supply chains, causing logistical challenges, labor shortages, and supply–demand imbalances. In response, digital technologies played a pivotal role in mitigating these disruptions. Digital innovations enabled food producers, distributors, and consumers to navigate the challenges posed by the pandemic. For instance, online platforms facilitated direct-to-consumer sales, reducing the reliance on traditional distribution channels. Additionally, advanced data analytics and remote monitoring helped optimize resource management, ensuring efficient food production while minimizing waste. These digital tools not only improved the sector's resilience to external shocks but also enhanced food safety, transparency, and traceability. Furthermore, the pandemic underscored the importance of leveraging digital technologies for sustainable agricultural practices. The adoption of data analytics allowed farmers to optimize resource use, minimize environmental impacts, and increase productivity. These advancements align with the goals of sustainable agriculture and environmental stewardship, contributing to the broader objectives of the SDGs.

3. Transition technologies in industrial revolution

3.1 Evolutionary transformations

A plethora of changes have been noticed through the years in the agro-food sector with respect to specialization, automation, chemical and fertilizer dosages and market analytics. Fig. 1 shows the evolution of industry over the years. In the primitive stages, humans used stones to produce fire. The first industrial revolution involved the usage of coal, stones and mechanical production facilities. Equipment and machines were run either

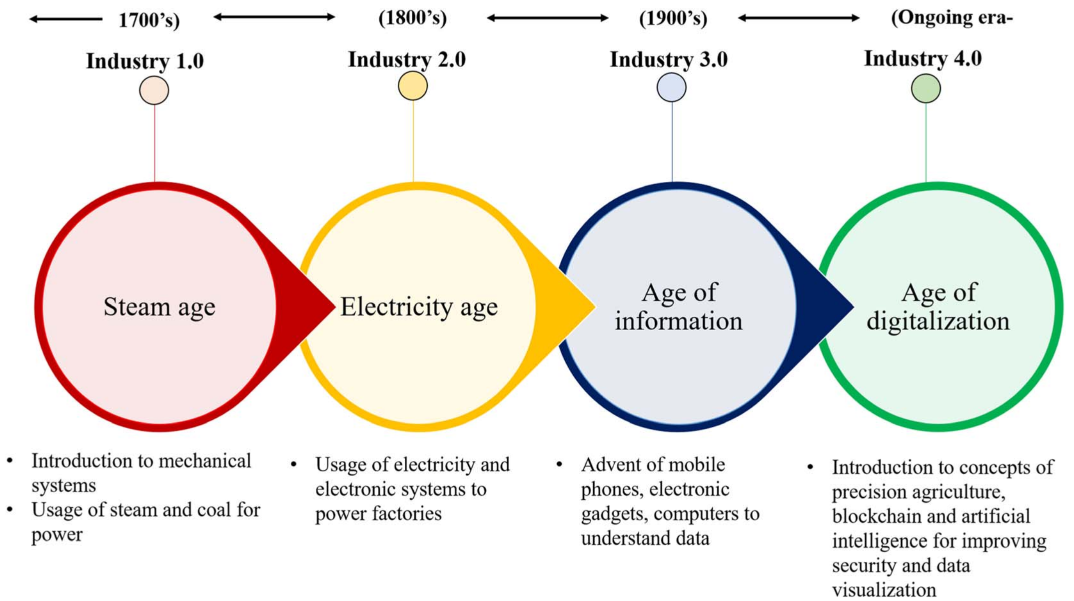

Fig. 1 Evolution of industry through the years. The transformation to Industry 4.0 represents immense growth in manufacturing industries. Cost, quality, feasibility and safety are important aspects for consideration while implementing digital technologies.

on heat, coal, water, or steam. Humans gradually began to find ways to make processes more efficient.[36] The switch from heat to electrical energy usage for production was marked as the start of the second industrial revolution. Heavy machines used electricity and power for getting outputs as they required less energy and gave better efficiency. The usage of electrical energy and power supply gave rise to Industry 3.0, the third industrial revolution, involving development of electronic devices such as laptops, mobile phones and hi-tech gadgets. The adoption of electronic devices facilitated storage and processing of huge volumes of data.

The late 20th century witnessed gradual progress with the advent of Industry 4.0, the fourth industrial revolution. An increased emphasis was placed on data analysis and optimization for improved supply chain.[37] Apart from the technological innovation, the organization structure underwent a major shift to face markets with a strict division of labor and standardization. Production was done considering the product varieties and effectiveness and analyzing bottlenecks. The demand for customized products for better lifestyle and consumer satisfaction had considerable impact on the global industry.[38] Additionally, security and traceability issues gained importance in the context of fraud reduction.

3.2 Industry 4.0: a focus on digitalization

In recent years, Industry 4.0 has emerged as the current technology framework for integrating various dynamic technical concepts. The model provides an appropriate bond for linking advances in the manufacturing industry with digitalization. The incorporation of digital tools and technologies such as artificial intelligence, the internet of things, cloud computing and machine learning has been cited as the possible future prospect for innovation and transformation towards sustainable food systems.[39–41] The applications of digital systems, simulations and navigation tools have increasingly grown in food production and agriculture. The agricultural artificial intelligence market is expected to increase to $312.4 billion by 2027, up from $518.7 million in 2017.[42]

Rapid advances are predicted with enhanced automation and integration of artificial intelligence in food systems. For instance, drones could be used for monitoring environmental conditions such as pH, soil, weather and moisture. The machine learning concept could be used to predict the sensorial characteristics for improving the physicochemical properties of food. In a recent study, the application of a hybrid machine learning and mechanistic modeling strategy was demonstrated to design reduced-fat chocolate chip cookies. The overall mean average percentage error of 5.7% in 10-fold cross validation suggested the accuracy of the model.[43] In the context of food safety, blockchain technology could be applied for easing out the traceability in the food supply chain. Such technologies could aid in reducing the physical contact among people in pandemic or similar situations. Digitalization would also provide advantages in terms of (i) improved connectivity, (ii) digital analytics, (iii) better transportation, trade and logistics, (iv) increased automation, and (v) the development of sustainable foods. The multifarious advances would help in transforming the operations, improving productivity and enabling the efficient supply of high quality products to the market.

4. Global agro-food perspectives: industry 4.0

The stakeholders in the agro-food sector have taken steps toward transformation from producing staple crops for daily meals to confectionaries and fortified foods for improved taste and enhanced lifestyle. Modern agricultural practices and urbanization involve advanced technologies easing out the overall process. Enhanced productivity has been observed with the advent of novel automated systems, genetically modified crops, fertilizers, pesticides and preservation techniques.[44] Agricultural developments have enabled farmers to efficiently manage fields, understand topography, soil chemistry and appropriate nutrient requirements for the crops and improve overall productivity.[45] Nanopesticides have been demonstrated to exhibit nearly 32% more efficiency than non-scale analogues against targeted pest species, including 19% improved performance in field studies. Nanopesticides have also manifested other environmental benefits such as 43% reduction in toxicity toward non-target species and about 22% decrease in the leaching potential of pesticidal active ingredients in soils.[46] These emerging developments have brought about substantial changes in agricultural and food processing industries.

4.1 Smart farms and foods

The objectives of developing smart farms and foods are to increase global food production, address food security, and contribute to novel products for a healthier lifestyle. Steps taken in this direction should contribute to the achievement of the second, third and twelfth sustainable development goals of zero hunger, good health and well-being, and responsible production and consumption, respectively. The modernization of agriculture and the advent of sensors are likely to provide a huge impetus for a digital future.

4.1.1 Modernizing agriculture. According to the Food and Agriculture Organization, the majority of worldwide land has been degraded completely or partially due to various environmental impacts, causing difficulties in crop cultivation. Moreover, the current business models have also not given desired outputs. Traditional methods relying on the usage of manpower have not been sufficient to meet the growing demands of the consumers. Although efforts have been made to improve crop yield by using fertilizers, the overuse of chemical fertilizers has had an undesirable impact on the environment. With increasing population and the crisis in the wake of the pandemic, scientists need to develop new ways of producing foods such that the environment is minimally affected. Fig. 2 provides a brief overview of the agricultural transformation.

Significant developments are being made in agro-food systems in terms of technology and policies. Several studies have inferred that biofortification could be a prospect due to the inclination towards diet, health and nutrition.[47] Biofortification, which enhances the nutritional content of crops, directly aligns with SDG target 2.2 of ending all forms of malnutrition. Farmer-driven innovations have also garnered immense interest on a global scale. These measures can contribute to attainment of SDG target 2.3 of improving agricultural productivity and target 2.4 of ensuring sustainable food production systems and implementing resilient agricultural practices. A study conducted in rural Italy explored the emergence of innovative young farmers who introduced novel developments into farming practices. Approximately, 58% of such farmers intended to pursue the innovative trajectory during the ensuing five years.[48]

However, the scalability and financial sustainability of farmer-led innovations are primary concerns.[49] The verification and validation processes involve a collaboration among the local people, farmers, stakeholders and concerned scientists. The approach allows improvements in innovations as well as reducing the gap between knowledge and practice. Steps can be taken to improve the land and water usage by land cover transitions. Studies conducted in East African catchment areas showed that grassland to cropland transformation contributed to rise in evapotranspiration by 12%, whereas reversed transformation decreased evapotranspiration by nearly 4%.[50] A clear framework needs to be set regarding policy-based innovations in order to understand the productivity and sustainability. A

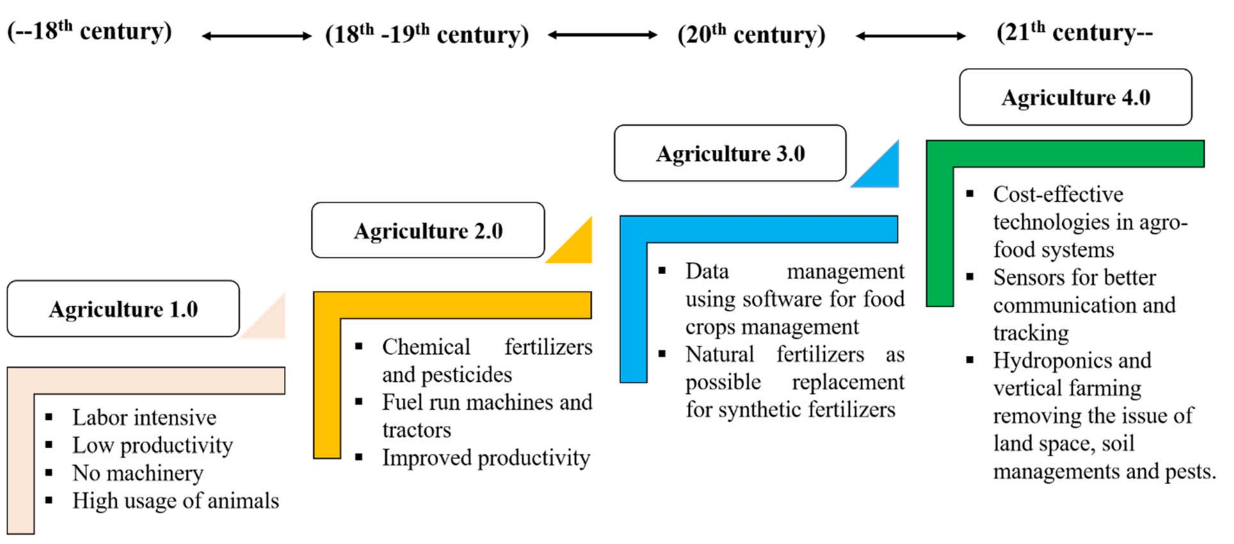

Fig. 2 Transformation to a modernized agriculture. Agricultural acceleration in terms of sustainability, usage of land, biofertilizers and effective data management will be given more importance towards building a digital agro-food ecosystem.

balanced supply chain is very critical with a close link between the stakeholders for sustainable food value chain development. Enough funds should also be provided by the governments making agro-food systems a priority. A collaborative effort could reduce problems such as land degradation and water shortage as well as preserving natural resources.

4.1.2 Sensor-based technologies. Sensor-based systems have been widely explored in the agriculture and food sectors in recent years. Table 2 shows different types of sensors and sensor-based technologies developed for agro-food applications. The pioneering developments in sensors belonged to the electronics and communications industry. The rapid growth in multidisciplinary research has expanded the scope of sensing techniques to various areas. Sensors have found diverse applications in food processing and quality control. Electrochemical immunosensors for the detection of foodborne pathogens have achieved excellent detection limits of nearly 5 colony forming units per mL.[51] Conventional methods of food quality evaluation relied on detailed sensory analysis by an experienced panel of food experts. However, the procedure required trained professionals and involved considerable costs. Analytical techniques such as gas chromatography-mass spectrometry and high performance liquid chromatography (HPLC) are currently being used in the industry for food quality assessment. Although such techniques are well-established, they pose practical challenges in terms of maintenance, scalability and affordability. Researchers are aiming to find innovative ways to enhance the sensor technology in order to reduce the human intervention and cost.

A significant advancement in the food sensor industry has been the development of a novel scientific approach of electronic nose (e-nose) testing.[56,57] The method uses a high frequency quartz crystal (HF-QC) material for detection purposes. The technique is based on the principle of piezoelectricity, in which molecules are adsorbed on a chemically coated surface, generating variations in the weight of the HF-QC sensor. The advanced sensors process data within seconds by using special algorithms. Recently, the technology has also been investigated in food sample analysis. A study examined the volatile profile of carrot samples using e-nose and gas chromatography-mass spectrometry.[58] The variations in the aroma profiles of carrots stored at temperatures of −18 °C, 4 °C, 25 °C and 40 °C were examined till 26 days and the results obtained were comparable by both methods. Another recent study explored the capability of an e-nose to estimate the shelf life of different types of meat.[59] The e-nose technique has also

Table 2 Sensors used in agriculture and food processing

Types of sensors	Working mechanism	Sensor advantages	Sample	Inferences	References
Acoustic wave sensor	Monitoring change in oscillation frequency that creates a response wave from the input stimulus followed by conversion into an electric field for measurement	Easy to use with a fast response time	Maize	ZnO acoustic wave sensor built on zein protein served as an intelligent food packaging wrap used for monitoring the freshness of corn. Sensor had 687.38 MHz operating frequency and a sensitivity of 3151.22 parts per million by volume	52
Microbial whole cell biosensor	Usage of living cells as recognition elements for conversion of inputs into cellular responses	Long lifetime and environmental compatibility	*Pseudomonas syringae*	Sensor enabled the measurement of the biological oxygen demand in water with a response time of 3–5 minutes and a linearity range of 5–100 mg L^{-1} at a flow rate of 0.6 mL min^{-1}	53
Electrochemical biosensor	Conversion of interaction between the biorecognition element and target analyte into an electrical signal	Rapid analysis and high sensitivity	Listeria monocytogenes cells	Detection of foodborne pathogens was achieved with a minimal assay time of around 15 minutes	51
Nucleic acid sensor	Detection of nucleic acid target material through a selective hybridization reaction	High specificity	Zein gene from maize	Pyrrolidinyl peptide nucleic acid immobilized on a magnetic solid support was used for deoxyribonucleic acid enrichment. About 80% nucleic acid adsorption efficiency was obtained for optimal loading conditions	54
Fiber optic biosensor	Usage of an optical field to measure biological species such as cells and proteins	Good accuracy, low cost and convenience	Ready-to-eat meat products	Multiplex detection of *Listeria monocytogenes, Escherichia coli O157:H7* and *Salmonella enterica* was demonstrated. Limit of detection was 10^3 colony forming unit/mL	55

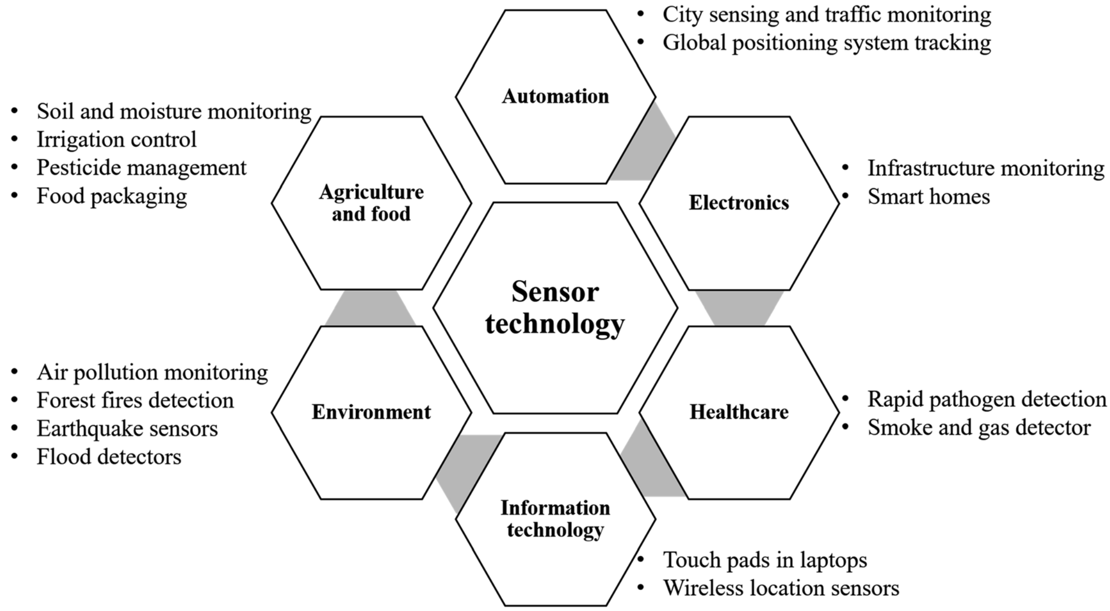

Fig. 3 Application of sensor technology in the fields of computers, electronics, agro-food and mechanical, environment and healthcare. Sensors can be used to gather enormous amounts of data within seconds. Data generated by sensors can be fed into algorithms for decision making and planning in any sector.

been successfully demonstrated for the assessment of the flavor profile of various volatile compounds.[60] In all the above studies conducted, the e-nose proved advantageous in terms of ease of usage, rapid testing and cost-effectiveness. The adoption of e-nose technology aligns with SDG target 9.5 of enhancing scientific research and technological capabilities.

Remarkable advancements have been made in sensor technology in various sectors. Fig. 3 illustrates the versatile applications of sensors. Significant progress has been witnessed in the healthcare sector for diagnosis of infection and prevention of epidemics by rapid pathogen identification.[61] The utilization of biosensors in agriculture has huge potential in ascertaining the amount of pesticides by transforming the analyte into measurable signals.[62,63] Cost-effective technologies such as paper-based chips have also been developed for the analysis of adulterants in food samples. A colorimetric paper-based sensor was demonstrated for the detection of starch contamination in milk in the concentration range of 0 to 10% (w/v).[64] A linear calibration equation was obtained using regression analysis as $y = 5.2634x - 0.9089$, where y denotes the grey scale intensity and x denotes the starch concentration in the milk sample. The coefficient of determination was 0.9965, suggesting the goodness of fit of the experimental data to the mathematical model.

Lab-on-a-chip (LOC) devices offer promise to overcome several challenges associated with conventional analytical methods, including sample storage, handling and conveyance to lab facilities. The efficient and rapid analysis offered by LOC technology aligns with SDG target 2.1 of ensuring accessibility to safe and nutritious food. The early detection of diseases or health-related issues by such portable devices can be valuable in contributing towards SDG targets 3.3 and 3.4 concerning ending epidemics and reducing mortality from non-communicable diseases, respectively. Low-cost ultrasonic sensors have shown their potential towards effective monitoring of the craft beer fermentation process.[65] In recent years, nanosensors have revolutionized the sensing capabilities in the food and agriculture sectors.[66] The applications of nanotechnology and smart materials have shown promising prospects in measuring the bacterial growth and shelf life of packaged foods as well as in the detection of heavy metals and organic compounds in agricultural ecosystems.[67–70]

The advent of the digital age has spurred a reevaluation of the diagnostic test criteria recommended by the World Health Organization, evolving from ASSURED (Affordable, Sensitive, Specific, User-friendly, Rapid and robust, Equipment-free and Deliverable to end-users) to the more comprehensive REASSURED framework.[71] This revised framework encompasses real-time connectivity, ease of specimen collection, affordable cost, sensitivity, specificity, user-friendliness, rapid and robust performance, equipment-free operation or simplicity or environmental friendliness, and deliverability to end-users.[72]

Within this context, digital food sensing technologies have made remarkable progress. The integration of microfluidic lab-on-a-chip devices with smartphones has revolutionized our approach to food safety and quality while aligning with the REASSURED criteria. These miniaturized sensors enable rapid and precise detection of various foodborne pathogens, allergens, and contaminants. When coupled with smartphones, they empower consumers, producers, and regulators with real-time data accessibility for on-site determination of food contaminants.[73] For example, consumers can utilize their smartphones to scan product barcodes, obtaining instant insights into a product's origin, ingredients, and potential allergens, making it user-friendly and easily deliverable to end-users. Moreover, these technologies facilitate on-site food safety testing in diverse settings, from farms and processing plants to restaurants and households. Their rapid and robust performance, combined with equipment-free or simplified operation, ensures affordability and efficiency. The state-of-the-art sensors could be advantageous for real-world applications as they allow rapid and accurate detection in an affordable manner.

4.2 Precision farming

Precision farming has emerged as a promising agricultural technology for enhancement of crop productivity in an environmentally sustainable manner. The site-specific farming concept relies on advanced information technologies to minimize cost and manpower and achieve higher efficiency. The main components of the precision farming approach include (i) collecting information from different zones from a specific field, (ii) decision-making based on the given inputs and information gathered about the zones, and (iii) precise implementation by applying the specific inputs. Precision farming practices can substantially reduce the negative impacts of agriculture on adjacent coastal ecosystems and water bodies. This includes minimizing runoff of agricultural chemicals and nutrients into rivers and oceans, thereby contributing to SDG target 14.2 concerning sustainable management and protection of marine and coastal ecosystems.

A study was conducted at the Federal Land Consolidation and Rehabilitation Authority Seberang Perak in Malaysia to assess the economic prospects of adopting precision farming in rice production. Cost–benefit analysis suggested that the use of precision farming technology packages could result in extra net income per hectare ranging from Malaysian Ringgit 1109 to 1133.[74] Precision farming technologies save time, effort and help farmers in harvesting, sales and pest management.

4.2.1 Artificial intelligence and machine learning powered approaches. Data analysis has garnered significant interest in the field of information technology, primarily due to the rapid growth of digital data and the capabilities of knowledge-based systems to address complex challenges. Inefficient crop cultivation, overuse of chemical pesticides and improper soil management can have detrimental impacts on the environment and food security.[75,76] For instance, inordinate utilization of pesticides in apple farms was evaluated based on the data gathered from 452 orchards in Shaanxi and Shandong provinces in 2017. The findings revealed that more than 70% of farms were involved in excessive use of pesticides.[77] Advanced digital technologies have the potential to address such challenges. Advanced digital technologies offer promising solutions to such agricultural challenges by enabling the modernization and increased efficiency of processes within the agro-food sector.

Artificial intelligence (AI), in simple terms, is the intelligence shown by machines to accomplish the tasks that typically entail human intelligence. Understanding data, languages and driving models are the major features of AI. The technology revolves around three interconnected subfields: machine learning, deep learning and neural networks. Machine learning employs algorithms for statistical predictions and inferences, as seen in applications like image recognition.[78] Deep learning involves the use of various datasets or nodes to process and connect information. Advances in computing *via* speech recognition have been achieved by deep learning. Neural networks leverage statistical models and algorithms for the prediction of data and the recognition of patterns.[79] The systems replicate the functioning of the network of interconnected neurons in the human body to adapt and find optimal solutions. While these digital technologies are still in their early stages of development within the agro-food sector, they hold immense potential for enhancing various aspects of the food value chain.

Traditionally, agriculture and food production have primarily focused on attaining better yields with minimal resources. A study conducted on a 121 hectare North Carolina vegetable farm inferred that nearly 65% of the unharvested crop that remained in the fields was of edible quality, but could not meet market specifications due to issues such as compromised appearance.[80] Addressing such losses is vital for improving crop production sustainability. The integration of artificial intelligence into agriculture, often referred to as digital agriculture, could be a groundbreaking step in this direction. Fig. 4 shows the working of artificial intelligence and machine learning empowered technologies in storing data and aiding the farmers for sustainable agriculture. These technologies utilize sensors, cameras, or robots that work in unison and are connected to a central motherboard or microcontroller. The primary sensor monitors soil pH, moisture levels, light exposure, and other factors influencing crop growth. The collected data are transmitted wirelessly to a server using sensors, where they are stored for future reference, analysis, and documentation. After efficient nutrient management and irrigation control, a message, an image or an audio is sent to the mobile phone of the farmer to communicate the output. The process is repeated for various tasks involved in agricultural practices. In addition, the application of AI and machine learning techniques plays a pivotal role in predictive modeling within food processing, enabling accurate forecasts and optimization in various stages of food production and distribution. The incorporation of such digitally enabled technologies can make a substantial contribution toward SDG target 9.4 by upgrading the infrastructure of agro-food processing industries.

Artificial intelligence and machine learning technologies have also been put into practical usage in diverse scenarios. An artificial intelligence-based mobile application was developed and detected nutrient deficiencies, ingredients and nutritional values.[81] The application encourages users to understand the crop qualities and fertilizer dosage needed for the plant. Another study was done to identify fruits and enable automatic harvesting using a robotic arm.[82] The method was based on the concept of deep learning, which proved to be fast and accurate. The learning model enabled successful fruit position detection with a 90% or higher success rate within 2 seconds. The fruit harvesting algorithm allowed the robot to harvest a fruit in about 16 seconds. These approaches hold the potential to reduce food quality defects and enhance food safety.

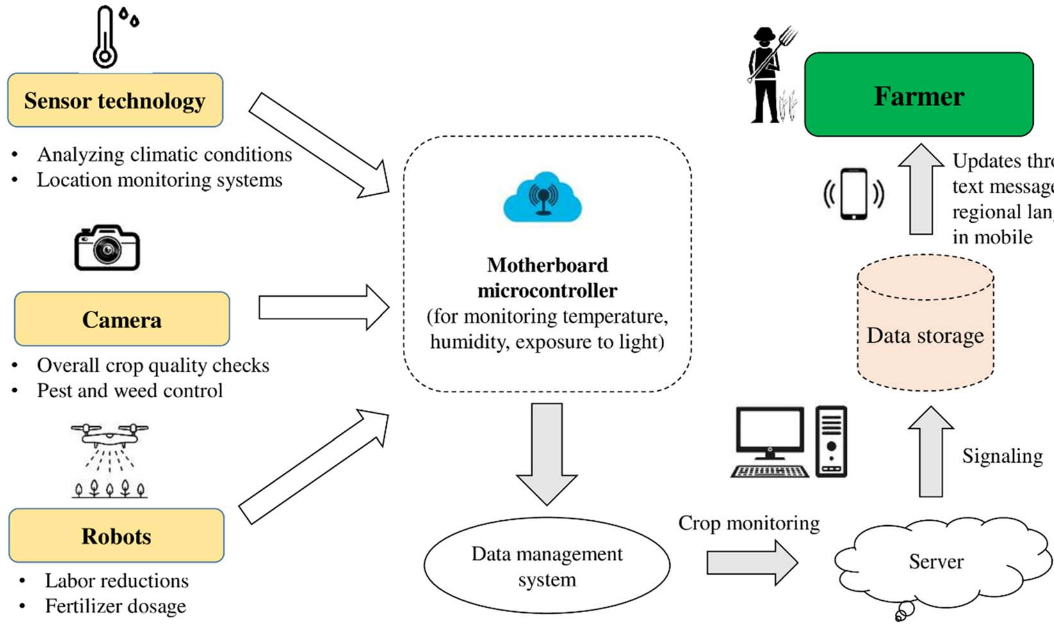

Fig. 4 Working of artificial intelligence and artificial intelligence-based concepts to create sustainable farming practices. Artificial intelligence-based technologies such as machine learning and deep learning allow farmers to understand data and crop managements as well as predicting weather conditions and soil patterns essential for the growth of crops.

4.2.2 Drones in the agro-food sector. Drone technology has found diverse applications in a wide variety of fields such as logistics, military, film industry, mining, search operations, wildlife monitoring and disaster management.[83,84] Drones have also been used in agriculture and food systems. The high-tech device is being used for scanning the overall health of crops using visible and infrared light. Drones have been deployed in various plantations for tree counting, terrace planning, forecasting, pest control and soil monitoring, thereby facilitating attainment of SDG target 15.1 regarding sustainable land management and conservation practices.[85] A comparative analysis of soil profiles for three types of soil, namely ploughed, harrowed and grassed, using drones and profilometer demonstrated similar trends in the obtained results.[86] The roughness reduction degree was 92.59 for the drone in comparison to 79.62 for the profilometer. The deviation in values could be due to the different types of sensors employed in the respective techniques. Drone technology offers a promising approach to enhance agricultural productivity and water use efficiency. By using drones to monitor crop health and optimize irrigation, water resources can be managed more efficiently, reducing water wastage and contributing to sustainable water use, as envisioned in SDG target 6.4. Apart from application in agriculture, drones also present various advantages in transportation and logistics of food products. A recent study reported that more than 30 delivery individuals die each year in South Korea due to accidents and the advent of drones can play a crucial role in reducing such incidents.[87] Moreover, drones can be used for climate-related data collection in the context of agricultural production and contribute to SDG target 13.3 by enhancing awareness and providing valuable data for climate change mitigation and adaptation.

Although drones have proved really beneficial for sustainable agriculture and food production, some limitations need to be considered. Firstly, affordability and lack of skills in understanding the controls could be of concern. The majority of farmers have neither the technical knowledge nor the income to use such hi-tech devices. Fundamental piloting skills and hardware knowledge are often considered mandatory prerequisites for handling the drones.[88] Secondly, the use of gadgets may cause wider ecosystem damage and be a surprise to various birds and animals.[89] The long-term perspectives of the utilization of drone technology in logistics with respect to device reliability and consumer behavior would be revealed in future.[90] Addressing such challenges would be crucial to move toward sustainable development goals of eradicating poverty and ensuring sustainable food consumption and production.

4.3 Big data in agro-foods

Big data is a widely used term for understanding large amounts of data that organizations and industries use for decision making, business insights and process optimization. As the database is growing exponentially, novel ways are being sought after to handle the voluminous data through advanced computing technologies.

4.3.1 Data storage advancements. Big data analytics refers to the process of gathering, organizing, analyzing and modeling data to discover new patterns and trends.[91] The approach enables users to comprehend data, use resources in an innovative manner, improve processes and implement solutions for a circular economy. The source of data is generally location-dependent, originating from websites, blogs, scientific articles and social media on the scale of terabytes, petabytes or

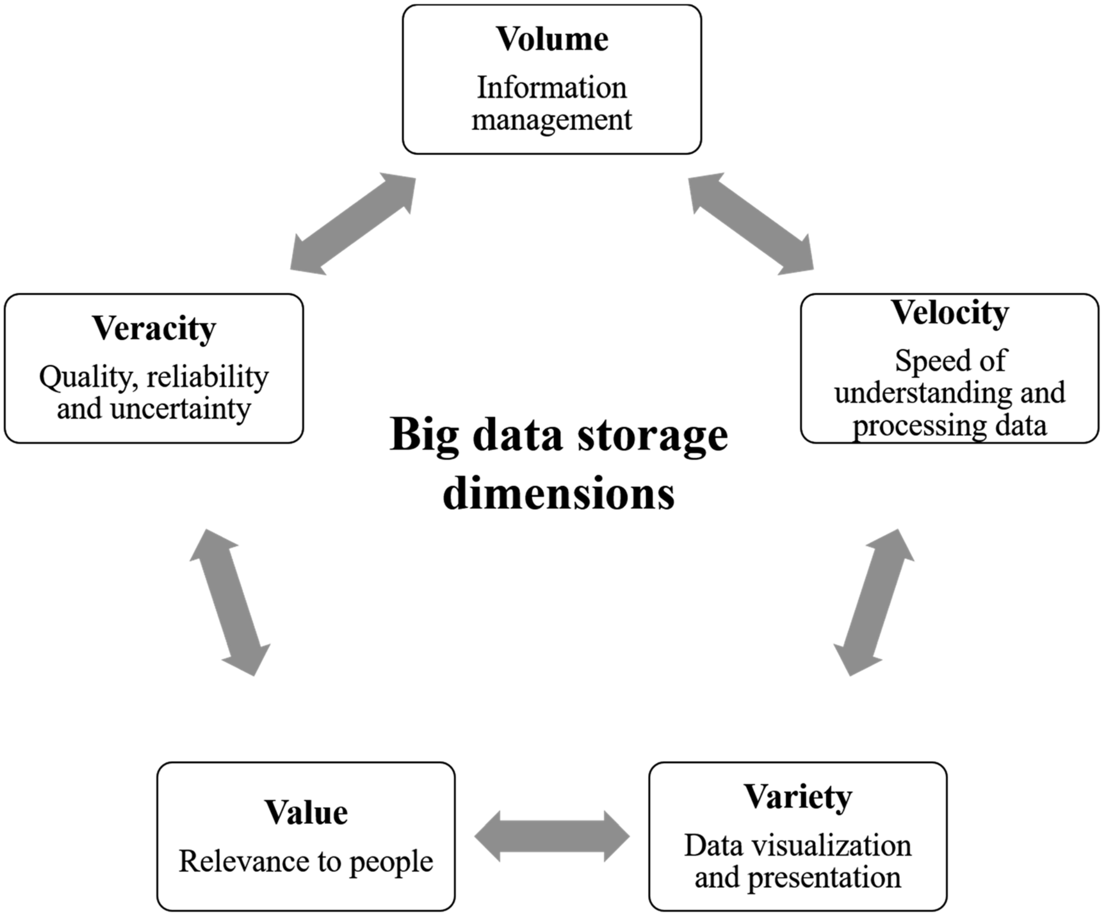

Fig. 5 Dimensions for processing, interpreting and executing big data. Big data consisted of 3 V's – volume, variety and velocity through advances of sensing, measuring and computing. However, value and veracity also became two important aspects for consideration. Value denotes understanding consumer expectations, relevance and knowledge, while veracity refers to accuracy and speed to market with good quality.

exabytes. Big data involves five V's, namely, volume, variety, velocity, veracity and value.[92] However, additional V's such as volatility, validity, visualization, variability, vulnerability, visibility and vagueness are also being considered.[93] Fig. 5 shows various dimensions of big data.

Big data analytics are gaining interest in the agro-food sector to address the huge food wastage issues and changing demands of consumers. Although the technology is in early stages, data analytics would enable industries and farmers to find solutions to complex agro-food systems. The approach can be applied to database generated from different sources including biosensors, weather stations, statistical year books, government reports, satellites, web services, regulations, social media and scientific literature. Big data analytics can play a crucial role in addressing SDG target 12.3 by helping to reduce food waste and optimize resource utilization in the agro-food sector. Approximately, 2.5 quintillion bytes of data are being generated on a daily basis.[94] Statistical datasets, satellite imaging, remote sensing and geospatial data are being used the most for understanding crops, land mapping and soil management. Due to the immense data production, techniques and tools are required for extracting data to reduce complexity and ease out the overall process. Table 3 lists the technical tools for big data analytics with their respective agricultural criteria. The implementation of data analytics should serve as a key enabler for realizing sustainable development goals of building resilient infrastructure, fostering innovation, combating climate change, and conserving natural resources.

4.3.2 Tracking systems. Food traceability offers a viable approach to ensure food safety and quality. With advancements in digital technologies and traceability systems, consumers are demanding comprehensive information on food products. Adopting digital tools could benefit the entire food supply chain. Precision agriculture enables farmers to improve productivity and resource efficiency and reduce management costs.[102] Tracking systems play a crucial role in coordinating with the farmers, production line and retail line for faster speed to market.

The usage of mobile applications has been of great interest to consumers in tracking the delivery process by merely switching on the navigation button.[103] Smartphone users can easily browse restaurants and menus, place food orders and make payments using mobile applications. Location-based services in smartphones have become highly beneficial as they

Table 3 Technical tools for big data analytics in agriculture

Area covered	Big data source	Technique	References
Land usage	Satellite data, radar sensing, historical data sets and camera mapping	Machine learning, image processing, and temperature calculations	95
Soil check	Ground sensors for salinity, moisture, and pH, as well as digital images	Machine learning	96
Weed control	Remote sensing using drones, digital libraries, plant-specific databases, and crop analysis	Neural networks and regression analysis	97
Weather forecast	Weather stations, surveys, earth observation data, and geospatial data	Statistical analysis, cloud platforms, and geospatial analysis	98
Biodiversity and animal usage	Species database, and geospatial data	Bayesian network	99
Robots	Remote sensing, historical datasets, drones, imaging, web services, radar-based data, and land data	Image processing, cloud computing, computer vision, and artificial intelligence	100 and 101

provide real-time updates on the exact location of the delivery personnel, order status and payment status. The service allows prevention of any physical contact and is useful in pandemic or similar situations. Online services allow consumers to order food products from their locations and reduce issues such as long waiting times in queues and miscommunication.[104] The market size of food delivery apps has been continuously expanding and is estimated to reach revenues of nearly $11.6 million by 2023.[105] Tracking systems have played an essential role in digital transformation.

4.3.3 Climate change mitigation and adaptation. Climate change poses significant challenges to agriculture, including shifting weather patterns and the need for sustainable resource management. Digital technologies offer promising solutions on multiple fronts. Precision agriculture optimizes resource usage, reducing emissions associated with excessive fertilizer and water application. Furthermore, advanced monitoring using AI and data analytics helps detect crop stress and diseases early, minimizing yield losses and decreasing emissions from inefficient livestock management. Digitalization also empowers data-driven decision-making, enhancing resilience by enabling farmers to anticipate weather-related risks and adjust practices accordingly. In supply chain management, digital technologies reduce food waste and improve traceability, contributing to sustainability. Moreover, renewable energy integration is facilitated by digital solutions, reducing reliance on fossil fuels. Digital techniques should be more actively employed for analyzing, forecasting, and making optimal management decisions.[106] Consequently, digitalization holds significant potential for mitigating greenhouse gas emissions and enhancing climate resilience within the agro-food sector, aligning with the global imperative to combat climate change.

4.4 Digitalization in food safety

The problem of food loss and wastage is a major concern throughout the supply chain. Studies have reported that agricultural production, post-harvest handling, retail stores and households are the major areas with high food losses and waste.[107] Approximately, 72% of overall food waste in the European Union is generated at the level of households and the processing sector. The pandemic situation disrupted the food supply chain, leading to unprecedented disruptions in the normal functioning of society. In the wake of the pandemic, the role of food safety and preservation has become crucial to ensuring effective resource management and protecting public health. One of the best ways to address the challenges is through the integration of digitalization into food safety practices.

Adequate care and attention are required while handling foods. Regular checks on the quality, authenticity, origin and packaging of the food products need to be carried out before the items reach retail stores and consumers. Good manufacturing practices along with hazard analysis and critical control points (HACCP) should be followed strictly in order to comply with the safety standards. Introduction to e-certifications by the specialized agencies, such as Food and Agriculture Organization and the utilization of food composition databases are some of the possible ways to reduce clearance costs and streamline the process. Quality and safety checklists with automated reports can be generated using computer software for daily production instead of filling binders, log books and datasheets. Food safety software tools can capture and store data in a structured format thus enabling simpler database search.

The United Nations has adopted two indicators, namely, the food loss index and the food waste index, to monitor the progress towards the twelfth sustainable development goal of ensuring sustainable consumption and production patterns.[107] Such parameters can aid in the quantitative estimation of food losses in various parts of the supply chain. The worldwide food losses estimated at 13% in 2016 and 13.3% in 2020 correspond to a food loss index of 98.7 and 101.2 in 2016 and 2020, respectively. Furthermore, external factors such as environmental conditions, food fraud and counterfeiting also need to be handled simultaneously in order to preserve the organizational identity.[108,109] Fig. 6 illustrates the significant aspects of food safety digitalization in the wake of the pandemic.

Food packaging also plays a crucial role in ensuring food safety. Proper packaging helps in protecting the food from external factors such as temperature, humidity, light, and pathogens and preserves the shelf life of the food items.[110] Intelligent packaging systems have been researched and

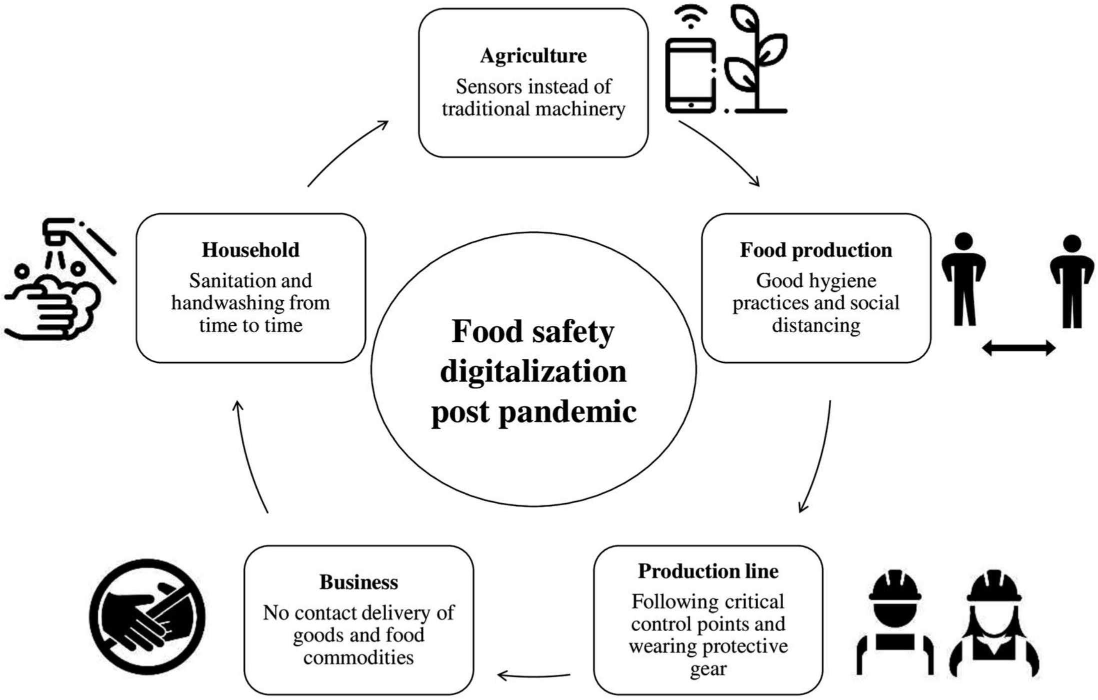

Fig. 6 Importance of food safety digitalization. Proper safety standards need to be maintained to ensure effectiveness and consistency in the system. The usage of personal protective equipment, maintaining social distancing, handwashing and application of sensors would ensure proper food safety.

implemented with an attempt to ensure better safety. Phytochemical loaded active edible electrospun coatings have been demonstrated to exhibit notable antibacterial efficacy with a reduction of approximately 2 logarithmic units of *L. monocytogenes* and *S. aureus* relative to the control samples, after 28 days at 4 °C.[111] Smart packaging can be classified into two broad categories. The first type incorporates data carriers such as barcode labels and radio frequency identification tags. Meanwhile the second type includes package indicators such as gas indicators, temperature–time indicators and freshness indicators.[112] Such temperature traceability systems could be mass-manufactured with an estimated cost of 2 Euros per device. The ability to monitor the condition of packaged foods can ensure the safety and quality of perishable food items during storage and supply. The adoption of smart technologies in food quality monitoring should help actualize SDG 3 of ensuring good health and well-being for all.

Furthermore, the Internet of Things (IoT) technology has emerged as a transformative force in the agro-food sector, reshaping the way food is produced, processed, and distributed.[113] Its relevance lies in its ability to connect physical devices and sensors to the internet, enabling real-time data collection and communication. This connectivity holds immense promise in revolutionizing the food supply chain. At the production level, IoT sensors monitor soil conditions, weather patterns, and crop health, providing farmers with valuable insights for precision agriculture. These insights lead to optimized resource allocation, reduced environmental impact, and increased yield. In livestock management, IoT-enabled wearable devices and monitoring systems ensure the well-being of animals while enhancing efficiency.

Moving along the supply chain, the IoT plays a pivotal role in logistics and cold chain management. Real-time tracking of products helps maintain the quality and safety of perishable goods. Additionally, temperature and humidity sensors in storage facilities prevent spoilage and reduce food waste, contributing to sustainability goals. IoT-driven data analytics offer supply chain stakeholders valuable insights for decision-making. Predictive maintenance of machinery and equipment minimizes downtime and ensures uninterrupted operations. Moreover, traceability is improved, allowing for rapid identification and mitigation of food safety issues.

4.5 New consumer interface: electronic commerce

With changing consumer demands, an efficient supply chain powered by digital innovation would be the pathway to success. The deployment of electronic commerce or e-commerce platforms offers promise in broadening product outreach to target consumers. Fig. 7 shows the business strategy followed by the e-commerce sector. An increase in the trust and security of digital transactions has prompted consumers to incline more towards online shopping instead of retail purchasing. An upsurge in e-commerce activities was witnessed due to the pandemic. An exploratory study conducted in France indicated that fast-moving consumer goods, healthcare products and household merchandise items witnessed a positive year-on-year growth of 55%, 49% and 46%, respectively, during the lockdown.[35] Two major profiles turn out to be well-suited in the post-pandemic situation for

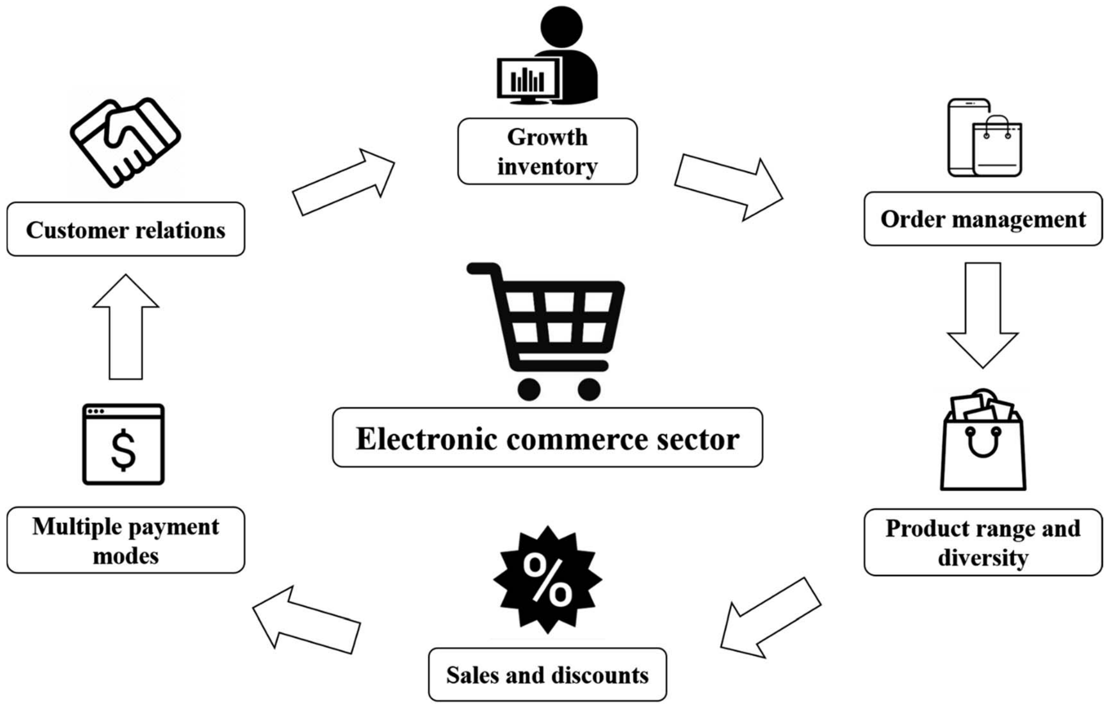

Fig. 7 Strategy followed for the growth of the electronic commerce sector. Product varieties, search engine optimization, constant offers and discounts, variations in pricing and understanding consumer perspectives are key areas for the growth of electronic commerce.

sustaining the changes. These include (i) the growth of startups based on the emerging market *via* digitalization, and (ii) e-commerce platforms for improving the supply chain and streamlining the purchase process. These align well with SDG target 1.1 by generating economic opportunities and reducing poverty. Additionally, these innovative developments contribute toward SDG target 8.2 of achieving higher levels of economic productivity through technological upgradation and market expansion.

The rise in e-commerce platforms has led to improved transparency and food traceability. These platforms have proved beneficial for the companies as well as the customers. Large multinational corporations are interested to invest in such digital technologies for faster speed to market. Global food corporations are utilizing e-commerce and blockchain technology to attract more customers and develop a reliable supplier base.[114] Alibaba, a multinational technology company, launched a digital market place in 2003 during the SARS epidemic. The e-commerce platform provides a convenient medium for farmers to sell their agricultural and food products in a transparent manner.[115] Internet-based commerce is an ideal platform to deliver consumer benefits, namely, (i) authorized and updated information of products, (ii) increased speed of raw and processed food to the market, (iii) improve the supply chains, (iv) expand the range of products, (v) door-to-door delivery system, and (vi) reliable customer service. The avenues offered by electronic commerce can facilitate the society to reach inclusive and sustainable economic growth.

In the ever-evolving landscape of technological advancements, the progression from Industry 4.0 to Industry 5.0 is an inevitable shift that extends its influence to the agro-food sector. While Industry 4.0 introduced the concept of smart, interconnected systems driven by data and automation, Industry 5.0 envisions a more harmonious collaboration between humans and machines, with a particular focus on enhancing the socio-economic aspects of various industries, including agriculture and food production.[116] Within the realm of agro-food technologies, this transition holds the potential to transform approaches to food production, distribution, and consumption. Industry 5.0 is poised to underscore the significance of the human element, recognizing that the fusion of human creativity, decision-making, and problem-solving skills with advanced technologies can lead to more sustainable and efficient agricultural practices.

5. Future outlook

Financial trading with transparency and consumer satisfaction as well as immunity boosting diets have promising future prospects in the agro-food sector in the post-pandemic era. In this section, two prospective technologies are presented, namely, blockchain and personalized foods along with a brief discussion on the evolving regulatory framework.

5.1 Blockchain

Traceability is very important for maintaining a concurrence between the production unit and consumers. The concept of blockchain has been known mainly in the trade and finance sector. However, rapid advancements with respect to transactions are being carried out in the agro-food industry. The blockchain technology is estimated to expand at a compound annual growth rate of 87% by 2023.[17]

Blockchain in the agro-food system refers to a series of data storage blocks or nodes where every action performed in the supply chain is recorded accordingly.[114] A record is maintained where all information is stored and processed in a computer. The network is considered to be reliable as there is no need of any confirmation from another intermediary to make the transaction. In blockchain, all nodes or blocks are connected to one another where information is transferred. In case if one of the users in the supply chain sends reports of fraudulent information, the network stops and resists the approval. The information must be approved and agreed by all involved parties to finally confirm the transaction. Such a decentralized ledger system reduces the cases of fraudulent transactions taking place in the supply chain thus improving the traceability in the system. The blockchain technology has proven to be 25% more advantageous and sustainable as compared to the traditional procedure.[117] Fig. 8 shows a descriptive blockchain network unit used in the food supply chain. The blockchain network in an agro-food supply chain is composed of the following:

(a) Farmer and distributor: the stakeholders obtain information regarding crops, fertilizers, pesticides and agricultural machinery using internet services. All transactions between the farmers and distributors get recorded in the form of blocks.

(b) Production line: food production and processing procedure, weather conditions, land mapping and soil management data are acquired with drone technology and sensors. (c) Retailer: post-packaging, shipment, inventory and schedule details are documented and supervised. Money transactions are done using blockchain.

(d) Consumer: food commodity reaches the consumer *via* e-commerce platforms or in the supermarket. Tag scanning of the food is processed and the information is associated with the whole logistics management.

The blockchain technology has significant utility in food product verification. The system can improve transparency, integrity, affordability and accessibility in the entire food value chain and possibly remove complex certification systems. A study investigated the application of radio frequency identification and blockchain technology in developing a traceability system for agriculture and the food supply chain. The proposed traceability system promised to offer a better building process in terms of warehousing, trading, distribution and selling in comparison to the centralized system.[118] The blockchain technology has also been used in bitcoin financial trading.[119] However, there have been a few challenges reported in terms of trust issues in storing data and data privacy.[120,121] Although blockchain technology proffers various benefits, challenges such as scalability and storage confidentiality should be addressed before blockchain can be fully adopted as a mainstream technology.

5.2 Personalized foods

Consumer preferences for fresh, tasty, nutritious, and healthy food products are driving innovation and growth in the food sector. One of the emerging trends in food processing and production is the concept of personalized foods, which involves tailoring food products to meet individual preferences and nutritional needs. This concept encompasses various aspects, including food printing, design, and innovative packaging.[122]

An exciting development within personalized foods is three-dimensional food printing, which offers distinct merits, including better ingredient utilization, reduced environmental

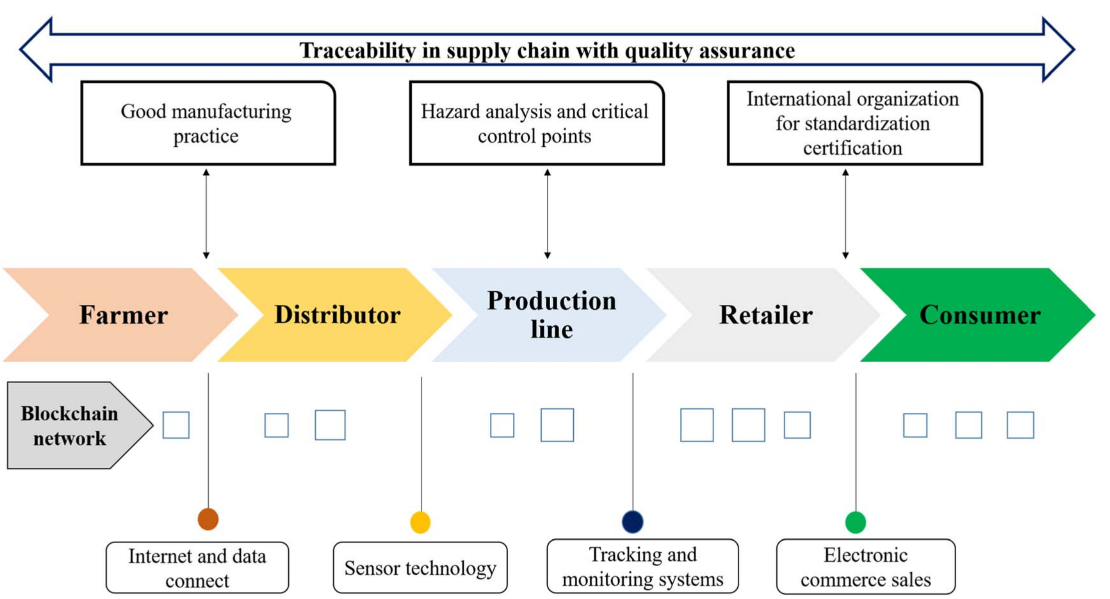

Fig. 8 Blockchain network used in the agro-food supply chain. Blockchain presents an innovative digital approach in the food system by decreasing the transparency gap between producers and consumers and reducing fraudulent activities. The boxes in the figure denote the amount of data being accumulated at each stage throughout the process. This enables the customer to understand the overall network of the food they consume.

impact, scalability, and minimized waste generation. Recent research in the Netherlands found that consumers have a preference for semi-solid foods and pastes, such as yogurts, due to factors like food texture, particle size and sensory characteristics. This preference was supported by a significant multivariate correlation between intake and liking, with a random variable coefficient of 0.64. However, individual differences were observed in the Pearson correlation between intake and liking, ranging from −0.98 and 0.92, with a mean value of 0.20. Overall, customers were satisfied because these food items matched their taste preferences and helped regulate their intake.[123]

Customizing foods based on nutrition, texture, design, shape, and taste represents a promising area for the development of healthy and sustainable food products.[124] This trend aligns with the growing consumer demand for more personalized and tailored food options. During the lockdown, there was a notable increase in the consumption of plant-based diets as a replacement for meat-based diets. This shift was driven by factors like convenience, accessibility, and health concerns. Plant protein-based alternatives and vegan diets are increasingly perceived as healthier options in terms of taste, health benefits and cost-effectiveness.[125] In the United States, more than 35% of consumers regularly choose vegetarian meals, thanks to the high proportion of natural fruits, vegetables, and whole grains in these diets, which offer various health benefits and contribute to immunity.[126] Innovative packaging also plays a role in making products more appealing, environmentally friendly, and sustainable. All these factors influence consumer behavior and are essential for targeting specific customer segments effectively.

Advertising is another underrated aspect that significantly contributes to personalized foods. Many websites display product reviews, which directly or indirectly influence customer choices.[127] Creative captions and visual illustrations can also persuade consumers to select food items associated with particular brands.[128,129] Additionally, the Delboeuf illusion is frequently employed in food packaging to make food portions appear 15–20% larger or smaller, subtly affecting consumer preferences.[130] Cognitive personalization is poised to play a vital role in advancing sustainable development in the agro-food sector.

5.3 Regulatory framework and policies

The successful implementation of digital technologies in the agro-food sector hinges not only on technological advancements but also on the presence of robust regulatory frameworks and policies governing their use. Governments and international organizations have acknowledged the necessity of specific guidelines and regulations to harness the benefits of digitalization, while addressing potential risks and challenges. Consequently, legal frameworks are being developed to strike a balance between the interests of farmers and service providers, ensuring the protection of personal and entrepreneurial data while facilitating innovative business models.

The proposed amendments of the European Commission to the Common Agricultural Policy underline the integration of technology as a means to enhance sustainability effects. This aligns with scenarios where digital technologies are expected to play a central role, reflecting the increasing recognition that digitalization can contribute significantly to sustainability objectives. In this digital era, data protection is paramount, with the principles of the General Data Protection Regulation (GDPR) highly relevant to data exchange processes within agriculture. Strategies like the Arable Farming Strategy 2035 emphasize farmers' data sovereignty, which aligns harmoniously with GDPR provisions. This establishes a robust foundation for data management, privacy, and governance. The increasing adoption of artificial intelligence (AI) in agriculture introduces evolving legal considerations. While specific safety requirements for AI in agriculture are presently lacking, general liability regulations, including the General Product Safety Directive and the Machinery Directive, are applicable.[131] The European Parliament approved its version of the draft European Union Artificial Intelligence Act on June 14, 2023, which could be the first comprehensive AI regulation at the international level. It incorporates enhanced legal requirements for AI use in critical infrastructures that should plausibly include agriculture due to its role in food security.[132] These requirements cover risk management, quality standards, transparency, and robustness.

Consequently, regulatory frameworks and policies in the digitalized agro-food sector are dynamic, aiming to strike a delicate balance between innovation, data protection, and cybersecurity. Collaboration among key stakeholders is imperative to navigate this evolving landscape and establish a supportive legal framework to facilitate and govern digital transformation in agriculture.

6. Conclusion

The global impact of the pandemic has created new pathways towards growing a digital world in the agriculture and food sectors. Digital technologies have huge potential to address the increasing concerns of consumers about the environment, sustainability and public health. Modern technologies based on precision farming could be promising to address the growing demand for food. Digital tools such as big data analytics could allow technologists to handle more data than ever and derive valuable insights for the benefit of farmers. Advancements in sensor technology and navigation controls using artificial intelligence could enable farmers, production units, retailers and customers to track and understand the steps involved in food processing. In the context of traceability and safety, blockchain technology could be the right platform for meeting consumer trust, improving trade and making the supply chain more efficient. The integration of information technology with agricultural production and food processing has the potential to improve overall food supply chain resilience. However, digitalization of the agriculture and food sectors is in the early stages of development. Infrastructural problems, resource constraints and staff imbalance issues are likely to be encountered. Thus, policymakers and governments across the world must play a vital role in taking charge of the digital industry to solve strategic problems, ensure food security and strengthen agricultural cooperation. Concerted efforts on multidisciplinary fronts would lead to green and sustainable agro-food systems.

Conflicts of interest

There are no conflicts to declare.

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