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Integrating Engineering and Technology for Sustainable Food Systems

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Abstract: The application of engineering to the production of sustainable food systems is examined more closely in this review. It deals with the important trifecta of the food system: issues such as food security, harnessing natural resources, and the catch-22 of sustainable economic development. Thus, it has shown very new innovations in food processing leading to an enhancement in the safety and shelf life of food by methods like high pressure preservation and bio preservation. It also addresses energy efficiency endeavours and disposal mechanisms particularly those revolving on the conversion of waste into energy. New technologies like Artificial Intelligence, the Internet of Things, and blockchain technology will also be covered as these if properly deployed can significantly reduce inputs because they will help in utilising all available resources in farming and help in providing traceability in the food chain. This review underscores the fact and necessity of technology adoption towards the realization of the sustainable development goals for food security, the environment, and climate change resilience. Combining these technologies the paper concludes that this would make a sustainable global food economy, efficient and capable of addressing some of the most dire contingencies of the future.

1. Introduction

1.1 Importance of Sustainable Food Systems:

There are growing demands on the world food system that affect economic and social results such as quality of life, availability of food, community integration, and financial growth, as well as greatly contributing to ecological deterioration (Tilman, Cassman, Matson, Naylor, & Polasky, 2002; Tukker & Jansen, 2006; Willett et al., 2019). Given these obstacles, it is imperative to completely restructure the food systems to accomplish the Sustainable Development Goals (SDGs), including reducing hunger, promoting sustainable consumption, mitigating climate change, and conserving biodiversity (Abraham & Pingali, 2020). Even though it is widely acknowledged that "the food system is broken," coming up with alternatives is a difficult and diverse task (Lawrence, Friel, Wingrove, James, & Candy, 2015; Schmidt-Traub, Obersteiner, & Mosnier, 2019). A number of approaches are recommended in recent publications, such as changing diets, creating international networks, increasing food production in a sustainable manner, and building community resilience (Mason & Lang, 2017; Willett et al., 2019). Nevertheless, these methods often ignore how different players in the food chain make decisions for themselves as well as how their actions might be affected (Benson, 2020; De Schutter, Goïta, & Frison, 2021).

Significant environmental, social, and health-related issues have been confronted by the international agro-industrial food system in the past few years, which has prompted calls for a sustainable transformation using clean technology advancement. Important concerns that are now at the center of political agendas and reform initiatives include poor nutrition, rural poverty, and ecological degradation (Caron et al., 2018; Neven, 2015; Serhan & Yannou-Lebris, 2021). The agri-food industry's commitment to sustainable development calls for eco-innovation in business models (BM) and supply chains, which calls for the Sustainable Development Goals (SDGs) to be included in business practices and curricula in higher education (Bolton & Hannon, 2016; Lüdeke-Freund, 2014). The Idefi-EcoTrophelia program of the French government is an example of how engineers and designers are trained in eco-design and business model innovation. This program emphasizes the need for improved engineering skills and capabilities to create food items that are both environmentally and socially responsible (Lozano et al., 2015; Ramísio, Pinto, Gouveia, Costa, & Arezes, 2019; Sammalisto, Sundström, Von Haartman, Holm, & Yao, 2016). The curriculum shows how dynamic competencies are necessary to comprehend and carry out sustainable changes in the food business (Rahimifard & Trollman, 2018).

Food production must be balanced with resource and environmental conservation through sustainable food systems. They rely on resources like electricity, water, and fertile land (Morawicki & González, 2018). Nevertheless, these systems are under stress due to factors including global warming, rising food needs, fast population increase, and finite resources. By 2050, there will likely be 10 billion people on the planet, placing increased strain on resources and increasing the possibility of ecological harm, especially as the demand for dairy and meat products rises (Fasolin et al., 2019; Khan et al., 2021; McLeod, 2011; Searchinger et al., 2019). A crucial element of food sustainability is sustainable agriculture, which aims to strike a balance between environmental preservation, economical resource use, and food production (Morawicki & González, 2018). By 2050, it is expected that there will be 10 billion people on the planet, putting more strain on already scarce resources and perhaps inflicting ecological harm (Fasolin et al., 2019; Khan et al., 2021; Nations, 2017) (Fasolin et al., 2019; Khan et al., 2021; Nations, 2017). Modern technologies, including genome editing, artificial intelligence, and the Internet of Things, may improve agricultural sustainability and production by introducing new protein sources and improving resource utilization (Aiking & de Boer, 2020; Chardigny & Walrand, 2016; Henchion, Hayes, Mullen, Fenelon, & Tiwari, 2017). Even with these developments, attaining global food security is still a difficult task that calls for extensive planning and cutting-edge technology (Foley et al., 2011; Lindgren et al., 2018; Springmann et al., 2018).

2.Engineering Innovations in food systems

2.1 Food Processing and Preservation Technologies:

2.1.1 High-Pressure Preservation:

One method of preserving food that makes use of high pressure is called pascalization or high-pressure food preservation (Elamin, Endan, Yosuf, Shamsudin, & Ahmedov, 2015). Food may be processed by pressing it through a vessel that exerts at least 70,000 pounds per square inch to preserve its fresh look, taste, texture, and nutrients while killing off dangerous germs and delaying spoiling. Foods are processed using hydrostatic pressure technology (Knorr, 1996), a non-thermal technique, at room temperature or close to it. The pressure is typically between 100 and 600 MPa. At pressures of 400 to 600 MPa, high hydrostatic pressure (HHP) may render vegetative microbiological organisms inactive. Still, some spores can survive temperatures as high as 1000 MPa. Under HHP, the rates of microorganism inactivation differ. While some bacteria and yeast exhibit first-order kinetics, others show a two-phase inactivation pattern in which some cells are quickly inactivated at first, followed by a population of cells that is more resistant. Temperature, pressure, and media content are some of the variables that affect these inactivation patterns (Ariyamuthu, Albert, & Je, 2022).

2.1.2 Ultraviolet Radiation:

Most people are aware that bacteria in water may be killed by UV radiation. Compared with conventional chlorination, this kind of radiation is less costly to install and operate, safer, and more ecologically beneficial. It has no effect on water taste, in contrast to chlorine. Food surface germs may now be killed by high-intensity UV-C lamps, which are becoming more widely available. Commercial UV irradiation is used for a range of food applications, including pickle vats, bottling, food processing, and air purification. It is also used to tenderize meat, cure and wrap cheeses, and prevent surface mold growth on bakery products (Hauter & Worth, 2008; Zurer, 1986).

2.1.3 Pulsed Electric Fields:

A shock wave produced by an electric arc deactivates microorganisms and leads to the development of highly reactive free radicals from a variety of chemical species in the meal. In general, scientists have found that bacteria become dormant when the electric field strength and pulse count are increased. The formation of holes in cell membranes may lead to the death of microorganisms (Knorr, 1996).

2.1.4 Bio preservation:

Bio preservation is the process of preserving food and extending its period of storage by adding natural or controlled bacteria or disinfectants (Ashagrie & Abate, 2012; Considine & Considine, 2013). Since the beginning of time, food has been bio preserved, mostly by using lactic acid bacteria that inhibit food degradation microorganisms. This practice was first done unintentionally but has steadily gained scientific support. By using beneficial bacteria or the fermentation products these bacteria make, bio preservation limits food deterioration and renders pathogens dormant. Some ways that microbes could stop others from developing include the creation of organic acid, which lowers pH and the antibacterial activity of the un-dissociated acid molecules, as well as a variety of other tiny inhibitory compounds, such as hydrogen peroxide. It's a typical ecological tactic that doesn't harm the environment (Ananou, Maqueda, Martínez-Bueno, & Valdivia, 2007).

2.1.5 Combined/Hybrid Methods:

Hurdle technology, defined by (Leistner, 2000), is a method that combines multiple preservation techniques to ensure the safety, stability, and quality of food products. It is helpful for foods that need to be kept fresh without refrigeration in underdeveloped nations and for goods that are lightly processed in wealthy nations. This technique combines elements including pH, redox potential, temperature, water activity, and water activity to stop microbiological development and preserve food quality, resulting in food items that are safer, more durable, and more affordable (Ariyamuthu et al., 2022).

2.2 Energy Efficiency and Waste Management

2.2.1 Waste Heat Recovery:

The food business uses a lot of energy, especially for heating, which often results in waste heat. Utilizing this extra heat through power production technology is known as waste heat recovery. For example, (Chowdhury, Hu, Haltas, Balta-Ozkan, & Varga, 2018) investigated a number of methods, such as the use of heat exchangers, which improved a milk processing plant's energy efficiency by 10% (Philipp et al., 2018). Other approaches include storing recovered heat or using it for other purposes, as shown by the use of solar energy for cold storage during periods of high power rates (Rosiek, Romero-Cano, Puertas, & Batlles, 2019). Moreover, low-temperature process waste heat may be recycled into high-temperature processes, increasing total energy efficiency. However, because of fuel-related, socio-technical, and governmental hurdles, putting these solutions into practice may be difficult. The use of business models is essential to addressing these obstacles. (White et al., 2018) investigated several thermodynamic fluids with an emphasis on power production and cost-effectiveness to improve the Organic Rankine Cycle for a range of heat source temperatures and process sizes.

2.2.2 Novel Thermodynamic Cycles

- **Heat Pumps:** Heat pumps are used to transport heat from sources of waste or renewable energy (RE) to enhance heating conditions. They are composed of heat exchangers, a compressor, and a valve (Jouhara et al.). Heat pumps may directly support food industry operations such as pasteurization or raise inadequate waste heat to temperatures as high as 150°C. According to (J. Wang, Brown, & Cleland, 2018) heat pumps and traditional air-to-air heat exchangers may recover up to 40% of waste heat and save energy expenses by 20% in a milk powder business. Additionally, research on the German meat and dairy sectors has shown that heat pumps may dramatically cut greenhouse gas emissions (Philipp et al., 2018).

- **Novel Refrigeration Cycles:**

○ **Absorption-Desorption Cycle:** Low-grade waste heat is used in this cycle, which also has a generator, absorber, and heat exchanger. (Yildirim & Genc, 2015) presented how to employ geothermal heat in the pasteurization process of milk.

○ **Adsorption System:** This technology generates a cooling effect by use of an adsorber rather than a compressor. For small-scale milk chilling, (Ndyabawe, Brush, Ssonko, & Kisaalita, 2019) discovered that a zeolite-based adsorption system using biogas performed effectively.

○ **Ejector Refrigeration System:** In this cycle, a fluid refrigerant is heated to a boil and then compressed within an ejector. (Shaozhi, Luo, Wang, & Chen, 2018) demonstrated how this method might cut heat use in comparison to traditional freeze dryers by 46.1%.

- **Heat Pipes:** This technique effectively transfers heat via a pipe that contains a working fluid. It has benefits including cheap operating and maintenance expenses. When its performance was simulated (Brahim & Jemni, 2015) discovered that it outperformed traditional tubular heat exchangers.

- **Hybrid Heating Systems:** These systems integrate several energy sources, including heat pumps, grid power, and renewable energy, to provide warmth for the food sector. For example, despite issues with grid pricing and the availability of renewable energy, a research (Schumm et al., 2018) showed that low-temperature hybrid heating systems could be implemented in the dairy sector without compromising operations.

2.3 Waste Management and Waste-to-Energy:

The depletion of natural resources and the creation of pollutants have made waste management more and more important. The waste-to-energy idea is a well-known remedy in this field; it converts waste materials into useful energy forms, including heat or electricity (Philipp et al., 2018). Because of environmental laws, rising processing expenses, and energy needs, the agroindustry is one area where this strategy is very pertinent. Using waste-to-energy techniques may help the agroindustry generate energy, dispose of trash less, or even produce extra that can be sold to other businesses. For example, municipal solid waste factories employ plasma gasification to turn garbage into energy-producing synthetic gas (Rojas-Pérez, Castillo-Benavides, Richmond-Navarro, & Zamora, 2018), a method also applicable to agricultural residues (Pourali, 2009). Furthermore, food industry waste may provide waste heat, single-cell protein, and plant nutrients in addition to power (Palanichamy, Babu, & Nadarajan, 2002).

2.3.1. Biodiesel

During the hydrolysis and esterification procedures, vegetable oil is transformed into biodiesel. Research conducted by (Hossain, Siddik Bhuyan, Alam, & Seo, 2018) and (Prussi et al., 2013) showed that biodiesel made from leftover edible oil functions similarly to regular diesel and may produce fewer pollutants. (Hossain et al., 2018) have shown how to enhance the re-esterification process by using several catalyst materials.

2.3.2 Biogas

Anaerobic digestion of an organic feedstock at 20 to 60 degrees Celsius produces biogas. The kind of feedstock and feeding ratio have a major effect on the generation of biogas (Lorenz, Fischer, Schumacher, & Adler, 2013; Muradin, Joachimiak-Lechman, & Foltynowicz, 2018; Zhu, Hsueh, & He, 2011). For instance, a factory that uses local leftovers lowers expenses and its effect on the environment (Muradin et al., 2018). The location of a biogas plant has a significant impact on feedstock transportation and heat usage. (Pantaleo, De Gennaro, & Shah, 2013) discovered that utilizing energy crops and cow dung might be profitable in Italy, highlighting the significance of manure recovery and cogeneration. Significant energy demands may be satisfied by the technology, including 72% of the requirements of the beer sector and 1% of the energy consumption in 27 EU member states (Lorenz et al., 2013).

2.3.3 Biomass

Biomass is mechanically pretreated to lower moisture content and increase calorific value before being used primarily for heating. Crop residue biomass has the potential to reduce greenhouse gas emissions in British Columbia, Canada, by 2% (H. Wang, Zhang, Bi, & Clift, 2020). Assessments that are both technical and economic, such as the examination of waste pellets from olive mills in Cyprus, show that biomass has the potential to be a competitive energy source (Christoforou, Kylili, & Fokaides, 2016). Anaerobic digestion digestate pellets have an energy potential similar to wood fuels, although they may release more nitrogen monoxide (Chen et al., 2019).

2.3.4 Pyrolysis

Pyrolysis entails heating organic materials without oxygen, resulting in the production of energy fuels such as pyrolytic oil, charcoal, and light gases. Research on sugarcane bagasse, like that conducted by (Kanwal, Chaudhry, Munir, & Sana, 2019) shows that pyrolysis may boost the material's carbon content and heating value. Additional improvements, such as the use of CO2, may reduce the creation of H2 and boost the formation of CO (Lee et al., 2019). (Amer et al., 2019) showed that heating values comparable to bituminous coal may be obtained by microwave pretreatment of agricultural wastes such as rice straw and sugarcane bagasse. Pyrolysis has noteworthy potential for reducing carbon emissions as well. In China, agricultural wastes may yield up to 1.41×10^6 t CO2e of biochar (Dai, Zheng, Jiang, & Xing, 2020).

3.Technology Developments for Sustainable Food Systems

3.1 Artificial intelligence (AI):

Artificial Intelligence is the processing of data by computers to gain information and make judgments. It includes a range of technologies built on computers, robotics, and electronic devices that increase and improve the user's activity's acuity, speed, accuracy, and efficiency (Ben Ayed & Hanana, 2021). AI's main objective is to create intelligent devices, robots, or computers that are comparable to human cognitive processes. In the world of technology, artificial intelligence (AI) need to be able to quickly identify items, recognize objects, evaluate profiles, discover answers, make judgments, provide commands, anticipate abnormalities, and memorize and learn the subsequent stages in the supply chain (Ayed, 2022; Hassoun et al., 2022).

Artificial intelligence (AI) may be utilized in agri-food processing to automate processes including crop yield predictions, product sorting, grading, packing, and risk assessment for the security of food. In addition, it may be used to lower risk factors, enhance food security, and attain self-sufficiency while limiting hunger, poverty, and the depletion of natural resources. Artificial intelligence-based emerging technologies have the potential to improve agriculture and conserve biodiversity while also increasing the production and efficiency of the food supply chain (Ayed, 2022; Lezoche, Hernandez, Díaz, Panetto, & Kacprzyk, 2020).

3.2 Internet of Things (IoT):

The term "Internet of Things" (IoT) describes how sensors and actuators are integrated into physical items to enable communication between them across wired and wireless networks, often using the same Internet Protocol as the Internet itself. The IoT industry was valued at $385 billion in 2021 and is expected to grow to nearly $2.4 trillion by 2029 (Insights, 2021). The idea is to use the Internet to link devices and sensors in order to gather data and automate procedures (Ayed, 2022; Colizzi et al., 2020).

"Precision agriculture" or "smart agriculture," which refers to the combination of IoT platforms in agriculture, offers more data sources that describe agricultural aspects including water, soil, people, and animals (Colizzi et al., 2020). But a new study highlights the spread of IoT platforms with an increased emphasis on IoT. Different demand models, heterogeneous components, sensor networks with various monitoring designs, temporal processing patterns, and uneven energy consumption are all brought about by this expansion, which also results in new implementation frameworks. One of the main research issues associated with integrating IoT platforms into agricultural operations is the interoperability of cloud-based data storage and use (protocols, security, etc.), performance monitoring, etc (Lezoche et al., 2020). In addition, training sessions are necessary for the end user to comprehend how to utilize and use the technology (Ayed, 2022).

In the agri-food sector, the majority of Internet of Things (IoT) applications use digital technology to monitor climate, traceability, moisture, color, and enhance sustainability performance (Endres, Pelisser, Finco, Silveira, & Piana, 2022). These kinds of applications are quite important in the vegetable supply chain, especially in the agricultural stage. To increase crop yield at this time, careful indicator monitoring is required. The optimization of operational factors, such as pesticide and water consumption, has been made possible by IoT devices (Hassoun et al., 2022; Moysiadis et al., 2021). IoT may also be used to monitor other characteristics, including crop physiology, temperature, humidity, and composition of the soil, which can provide data for more precise crop monitoring (Hassoun et al., 2022; Karmakar, Sengupta, & Banerjee, 2022; Maraveas & Bartzanas, 2021).

3.3 Blockchain:

Blockchain is an open digital ledger system that securely and decentrally stores data and records transactions. There are three varieties of it: open blockchain, private blockchain, and hybrid blockchain. It was invented in 2009. Because of the technology's advantages in guaranteeing food traceability, transparency, safety, and security, its use in the agri-food supply chain has progressively expanded (Ayed, 2022). It offers a creative response for these problems facing the industry.

3.4 Big data (BD) technologies:

Large, complicated, and moving data that cannot be handled or analyzed using standard methods is referred to as big data (BD) (Hassoun et al., 2022). It pertains to data that is exceedingly large, diverse, and swiftly evolving, making it difficult for traditional technologies, tools, and systems to manage efficiently. This technology is defined by its five "Vs" (volume, velocity, variety, veracity, and value), which contribute to its expansive nature (Belaud, Prioux, Vialle, & Sablayrolles, 2019). These five "Vs" refer to the vast amounts of low-density unstructured data, the high speed at which data is received and utilized, the diversity of data types available, the level of reliability and quality of the data, and ultimately, the extraction of useful insights from the database to aid in decision-making (Ayed, 2022; Belaud et al., 2019).

There are three key areas where agri-food projects must incorporate Big Data (BD) technologies: i) extending and customizing BD models related to ICT and Factories of the Future (FoF) for agriculture; ii) creating novel services and procedures by software developers and IT providers; and iii) growing farmers' data to yield fresh insights. Many Big Data Repositories are currently accessible to guarantee the use and accessibility of data related to agriculture and food. For example, data from the "National Climatic Data Center" is available every day at about 2.9 GB; Google and NASA Earth Exchange offer satellite imagery and meteorological information; the National Resources Conservation Service (USA) offers soil, water, and geospatial data; and Open Corporates provides data, among others (Ayed, 2022; Lezoche et al., 2020).

3.5 Automation and robotization:

Robots and machines may now carry out duties that were previously completed by humans thanks to digital technologies. The food industry's shift to smart factories and the emergence of smart farming are being propelled by automation and robotization (Hassoun et al., 2022). Robotics can automate processes including picking, handling, harvesting, weeding, seeding, planting, slicing, and packaging in agri-food processing, increasing productivity and lowering labor costs (Botta et al., 2022). **Figure 1** summarizes the sectors in which technologies are used in the food industry.

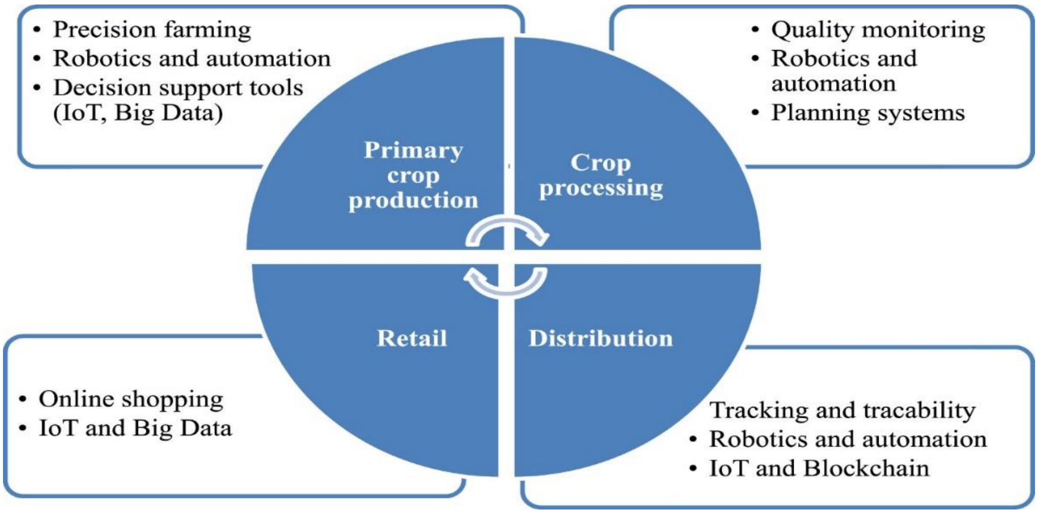

Figure 1: Concept of digitalization in the agri-food supply chain. From the paper of (Konfo et al., 2023)

3.6 Blue River technology:

Blue River Technology has created a weed-removal device that recognizes and eliminates weeds from crops using visual recognition and machine learning. By identifying certain plants and applying herbicides selectively, the technique lowers the quantity of chemicals needed and may even boost agricultural yields (Fennimore & Cutulle, 2019). Herbicide use has been shown to be effectively reduced using this method, as evidenced by a research that showed a 90% decrease in herbicide use in cotton fields (Malkani et al., 2019; Toscano-Miranda et al., 2022). Additionally, the See & Spray technology may lower labor costs and increase crop management efficiency (Abbas et al., 2020).

The autonomous technology of Blue River Technology has additionally been employed for other agricultural management chores, like planting and crop thinning, and it has shown promise in cutting down on the time and manpower needed for these operations. Furthermore, this technology can lessen its negative effects on the environment by carefully targeting weeds and preventing the needless application of herbicides, which can pollute soil and water systems (Fennimore & Cutulle, 2019).

4. Future Pathways for Digital Innovations in Agri-Food Processing

As the agri-food processing sector deals with issues such as rising demand, limited resources, and sustainability concerns, the application of digital technologies is becoming more and more crucial. Digital technology adoption can enhance the quality and safety of food while also increasing productivity, efficiency, and sustainability (Bahn, Yehya, & Zurayk, 2021)

For instance, real-time data on crop growth, soil conditions, and environmental elements can be gathered using inexpensive and easily accessible Internet of Things (IoT) sensors (Muangprathub et al., 2019). The Growing adoption of IoT sensors will enable farmers and food processors to make better-informed decisions on planting, harvesting, and processing, leading to higher productivity and lower waste (Alladi, Chamola, Sikdar, & Choo, 2020). Additionally, by optimizing processing parameters, detecting problems with food security more rapidly, and making more accurate projections regarding crop yields, producers and food processors can benefit from AI and machine learning (Kler et al., 2022). As these technologies advance, they will be able to recognize developments and patterns that the human eye cannot, which will increase production and efficiency (Baduge et al., 2022). Additionally, as customers' concerns about food supply chain transparency and traceability grow, blockchain technology can aid in enhancing these aspects. More businesses are probably going to use blockchain technology as it becomes more affordable to use in order to improve supply chain management (Centobelli, Cerchione, Del Vecchio, Oropallo, & Secundo, 2022; Madumidha, Ranjani, Varsinee, & Sundari, 2019). Furthermore, as new robots technologies advance, the demand for human labor in agricultural and food processing may be lessened, leading to higher productivity and lower expenses. The agri-food sector will become increasingly automated as robots technology advances and becomes more reasonably priced (Marinoudi, Sørensen, Pearson, & Bochtis, 2019). Moreover, 3D printing has the power to completely transform the food production process by enabling highly customized goods and cutting waste (Baiano, 2022; Pereira, Barroso, & Gil, 2021). Although we are currently in the early stages of this technology, it could eventually become more widely used. In conclusion, agricultural processes might be replicated using augmented and virtual technologies, which could assist producers and food processors in pinpointing areas that require enhancement. In addition to its potential applications in training, this technology offers employees a regulated and secure environment in which to acquire experience (Ronaghi & Ronaghi, 2021). The obstacles pertaining to expense, technological accessibility, technical know-how, and change aversion must be addressed in order to realize these advantages (Abioye et al., 2021; Vern, Miftah, & Panghal, 2022). Overall, the possibility for future improvements in digital technology for agri-food processing is immense, and there are many intriguing areas where progress might be made. As these technological advances continue to progress, they will probably have an increasingly essential role in guaranteeing the long-term viability and effectiveness of the agri-food business.

5.Conclusion

The development of sustainable food systems must be multidimensional, marrying advanced technologies with holistic strategies. High-pressure preservation, ultraviolet radiation, and biopreservation make a difference in food safety and durability. Artificial intelligence, Internet of Things, blockchain, and big data optimize supply chains and make them sustainable. But above and beyond technological progress, sustainability in practices must direct its focus toward the conservation of the environment and efficient use of resources, besides social inclusion. This will be the correct balance if the world is to rise and satisfy other global challenges of food security, environmental degradation, and social justice. The following review discusses the evidence that it is only through collaborative efforts of various sectors contributing toward an ecological transition in the agri-food sector that sustainable development can be attained globally.

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