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Revolutionizing Food Processing: Innovative Sustainable Technologies and Future Opportunities

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Authors' contributions

This work was carried out in collaboration among all authors. All authors read and approved the final manuscript.

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ABSTRACT

Everyone having access to or not to a sufficient supply of processed, safe, fresh, nutritional and in pocket-friendly food is a significant worldwide issue. By 2050, it could pose a major challenge for feeding 9 billion people, for which increasing food production technologies need to be addressed. Long term enhancement in food processing by reducing losses at every stage of the supply chain, managing the supply chain from production to consumption, including preservation, nutrient content, safety and shelf life. Massive amounts of streaming data, known as big data come under the Internet of Things (IoT). A new technology based platform helps in food production and processing technology by maintaining the big data and its further analysis. This review approaches scope and food production, food processing and its related technologies. Emerging technologies

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are saving the food supply and making the food economy more sustainable. Furthermore, this review is based on an overview of artificial intelligence, big data and sensors used in the food production sector.

Keywords: Food production; emerging technology; artificial intelligence; supply chain; sensors.

1. INTRODUCTION

Sustainable diets have minimal negative effects on the ecosystem and support as they support food's health and nutritional value for current and future generations (Steffen et al., 2015). Preventing environmental or storage damage is as important as accomplishing the nutritional requirements of the anticipated population (Weitz et al., 2017). To extend food's shelf life, food processing technologies are necessary to maximize nutrient availability and quality (Nilsson et al., 2017). Sustainable diets have minimal negative effects on ecosystems and are proven sustainable for current and future generations. Sustainable, affordable diets are taken into account by adding ecosystems, cultural legacy, and practices to increase agricultural productivity, making it possible to feed the world's rapidly expanding population (Johnston et al., 2024). A sanitary environment and a nutritious diet are important to promote a healthy lifestyle. For an excellent nutrition-balanced diet, it's important to have nutritional security. Environmental quality and natural resources can be improved by integrated technologies of sustainable agriculture, which directly relates to food security (Knorr et al., 2018). Along with sustainability, effective and integrated, it are important to reach locations to provide food to maintain nutritious health globally (Iqbal et al., 2019). To decrease down graph for the persistent prevalence of food insecurity concerning present and future needs, it's important to come together with efforts and coordination from relevant fields such as nutrition, food, agriculture and sustainability (Khan et al., 2018).

This review focuses on how food processing and creative, sustainable primary production methods can help address issues with food and nutrition security.

Sustainable food processing technologies are approaching with improved population and minimal environmental effects for future generations. The food industry commonly uses a variety of preservation methods to sustain food quality (Morris et al., 2007).

Sustainable food processing techniques for successful scientific careers Food has major repercussions on our health in various dimensions of our lives, including the economy, health and society. Our environmental surroundings are changing at an alarming and alarming rate. As per the study, the global food system is facing major challenges, including an increasing population, a shift inedible preferences etc. One of the major concerns and challenges is to accomplish growing food demands for present and future generations without affecting the earth's resources beyond a certain limit. Over time, the population's rapid increase will lead to chronic hunger and malnutrition.

Without paying close attention to the role of food processing, it is difficult to be successful in addressing the growing issues of providing sustainable food for everyone. It is impossible to overestimate the significance of creating technology for food processing and preservation that can lower food waste and losses during surplus seasons. Thus, it is necessary to create sustainable food systems that offer wholesome meals without endangering the environment and its resources. The objective is to validate the importance of food processing for the future food supply by using a variety of viewpoints.

1.1 Potential Role of Tech Innovation in Transformation of Sustainable Food systems

Food sustainability and sustainable agriculture are closely related. Sustainable agriculture could improve environmental quality and natural resources while meeting human demands for food and fiber. Water, climate, and fertilizers are the most important components of successful, sustainable farming. Future demands will put unrivaled strain due to unexpected population rise and global growth on factors such as land, climate, energy, etc. As per the measured census, there are about 7.69 billion people on the planet, and the growth rate is 1.08% per year, which means steady growth is been observed and calculated annually. Future food

demands need to be addressed and sustained because population growth could hit up to 9.9 billion by 2050 approximately a 30% hike in population growth. Technology by itself does not always transfer things and relies on economic policies along with administrative approaches. Not too many research studies have been conducted on innovative technologies in the food sustainability sector. Currently, there are ongoing sustainable technology trends that can be applied to food systems to make them more sustainable.

1.2 Different Technologies Harnessing Sustainable Food Processing Systems

A) Digital agriculture

Big data analytics, drones, and inventive sensors such as technologies are been used in precision farming as digital agriculture. Artificial intelligence and data integration increase efficiency and productivity while optimizing operations (Ashton, 2018). Emerging technologies such as robotics technology in field enhance crop protection automation, and disease and pest warning systems (Lasi et al., 2014).

Digital agriculture has amore extended fieldin terms of nanotechnology, and livestock with pre-birth sex determination, with the use of smartphones (Lokers et al., 2016).

B) Gene technology

Agriculture biotechnology has significantly contributed to crop production, enhanced yields, along better output (Ahmed et al., 2019). Agriculture biotech involves techniques such as genome-wide selection, GM-assisted domestication and genome editing. Effective seed formation and RNAi gene silencing targets are achieved by apomixis to target particular genes for disease and insect resistance (Kaplan and Haenlein, 2019).To address situations like bio-fortified crops, plant phenomics and synthetic biology is been used as gene technology in crops for desired growth and traits.

C) Agriculture using cells

Cellular technology is known to produce artificial edible products such as artificial meat and fish by stimulating natural species (Nilsson,1980). These are bioengineered products that are made by sophisticated molecular printing (Goyacha et al., 2001). Such products replicate and copy the texture of conventional meat, nutritional value, important extracts, and content, providing substitutes and promoting sustainability without harming the environment, and meeting present-day and future generation needs also increases food security (Rajan and Saffiottti, 2017).

D) Technology of substitute food and nutrition

Alternatives are also important for sustainable crop production as they can replicate the original substance in terms of flavor, texture, color and nutrient value (Sole, 2007). Effective and ecological livestock production is facilitated by the development of sea-based alternatives and additives for nutrition for animals (Mohri, 2012). The development of alternative food sources is best addressed by animal-based product cellular technology such as microalgae, cyanobacteria, seaweed and insects. Molecular approaches have made it possible to improve nutritional profiles by culturing organisms e.g. production of omega-3 fatty acids for aquacultural (Hinton,2015).

E) Nutritional health and environment concerning food processing

Few would proclaim about availability of micronutrients with bioavailability of starch along with the availability of seasonal fruits year around providing a perfect nutrition diet globally through food processing techniques such as preservation, canning, and of course freezing technique, meanwhile improvement in the food processing sector including processing of grains into flour and making it to bread (Dilbal et al., 2021). Continuing to pasteurize milk, safety measures through canning, and freezing have not proven to increase nutritional security in society (Wang et al., 2021). Additionally, fat along with sugar, salt, and refined starch, also provides unfavorable food alternatives.However, consumers are also presented with unhealthy dietary options by processed meals that are heavy in fat, sugar, salt, and refined starch. It’s a prophecy that non-communicable diseases would be significantly reduced by methods of lowering processed food’s sugar and salt. Food categories have been significantly reported for the reduction of salt and sugar levels (Gao et al., 2021).

Table 1. Techniques for food preservation

S. No.	Method of preservation	Definition	Methodology
1	Freezing	The freezing method increases food's shelf life by slowing down the process ripening. Major cooling and freezing methods are frequently used in milk products, spices, and green vegetable	Freezing methods are of two types of which include common freezing methods and immersion methods
2	Pulse Electric field	This is a kind of more advanced technique Because it could be a substitute for thermal drying which can elevate the process and techniques of food drying. This method has been hyped in recent times as it requires a low electric field, a temperature below 40 degrees Celsius which improves the pre-drying of food.	This method is used by using 2 electrodes which involves compressing food items such as fruit, milk, vegetables, etc. This method uses electro- mobilization and electroporation.
3	Thermal treatment	A high-temperature treatment A high- temperature treatment of 75 to 90 degrees is been suited for about 25 to seconds. A variety of food industries claim various features of this technique. Majorly used in industries including dairy, baked goods, fruits, etc.	This method is endowed with the technology of 30 cooking, which involves cooking for about 25 to 30 seconds at 75 to90 degrees Celsius. A disadvantage can be seen as color and taste are significantly impacted. For example in the case of maize.
4	Ultrasound	This method is proven to be effective as used in various industries such as healthcare, medical along with food sector.	High-intensity and high frequency sound waves are used in ultrasound techniques. In this technique, particles are disrupted by ultrasonic radiation including high frequency sound waves.

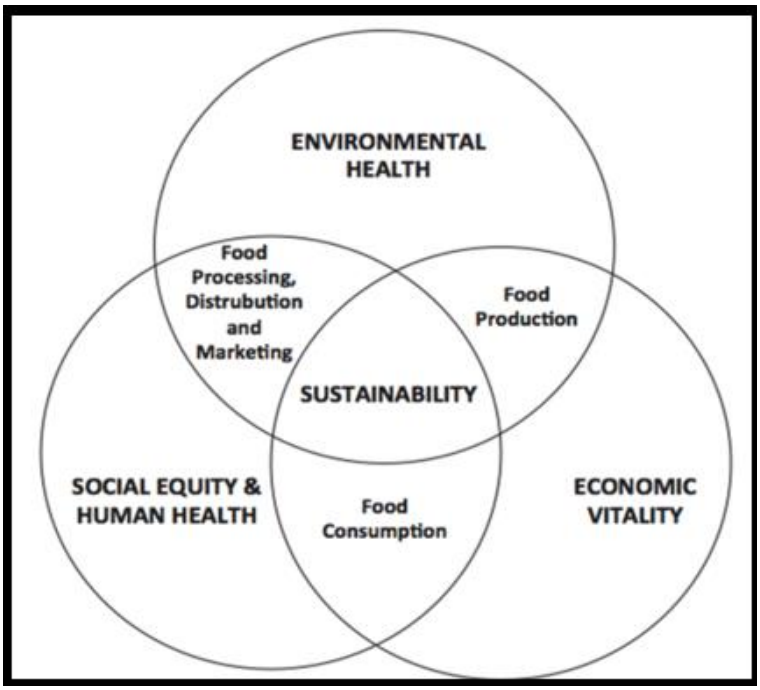

Fig. 1. Sustainable food system

1.3 Consumption of Processed Foods

American data on food consumption revealed that minimally processed foods and processed foods contribute significantly to total energy and health factors. (Stella, F., and Hughes,2023). Cleaned and packaged fruit which are typically stated as minimally processed foods. Vegetables, fruits, and minimally processed fruits contain higher amounts of vitamin B12, vitamin D, calcium, potassium and dietary fiber (Huang, 2023). About 13 to 15 % of total energy is made up of minimally processed foods. Getting to the edge of increasing the percentage of processed foods, which is about 56 – 58% of the energy intake from added sugars, iron and folate (Gonzalez-Vazquez et al., 2023).Taking into account that food and restaurants have a higher portion of added sodium and sugars. According to recent analyses and studies, minimally processed food contains less amount of saturated fat, sugar, and sodium as compared to highly processed foods (Morris et al.,2023). Choosing healthier options in terms of food would be a more nutritious option as processed food may be a constant component for the population's need, but it may contain much higher levels of saturated fat, sugar, and sodium. According to research, there is a significant increase in the use of processed foods within medium to high-income countries, as, from 1938 to 1939, processed foods intake was 29-30% as compared to2011, which was 62-63.7% in Canada. (Huang et al., 2023).

1.4 Convenience of Food with Respect to Fortified and Processed Foods

Taking into account commercially produced iodized salt, due to such food processing in salt has resulted in a significant decrease in problems such as goiter, endemic brain disease, and cretinism (Heiden et al., 2022). As achieved by correcting the amount of iodine by improving, processing and fortification of food. Such disorders arise through deficiency of iodine, which food processing techniques could prevent (Tan, 2022). In the middle of the 20 thcentury, a significant decrease in iodine deficiency was achieved. Vitamin D is an important requirement for the human body, as a nutritionally balanced diet is a growing pathway for vitamin D’s function beyond bone health (Hogueras-Ruiz et al.,2021).Low levels of folic acid are been found in major food types, which in turn affect the diet of pregnant women, including malformations that impact the poorly developed fetus’s organs, such as the spinal cord and brain (Won et al.,2021).Fortified foods would rather recover from the deficiency of folate, which is already used in a few countries, and there are reports about lower rates of foetal development issues. Countries like the USA, Iran and Canada have reported lower rates of neural tube defects (Li et al., 2022).

1.5 Sustainable Development Agriculture Concerning Food Processing Technologies

a) Food processing technologies to supply chain management

Looking back 10,000 years ago, in the early era of hunter-gatherers, when food was a need for survival and not just a commodity (Spiess et al., 2003). As urbanization gradually increased, workers grew more urbanization and separation grew between industrialists and urbanization. As there was increased demand for food and supply chain management, there was a growth and development of retailers and middlemen (Lzaridesa, 2011). As processed food was in demand and was easier to get, instant-ready mix meals and semi-cooked foods were developed to meet consumer demands and a sustainable food supply chain (Manzini and Accoaari, 2013). Taking the supply chain system into account, it's a system from farm to fork in including retailers, marketers, and consumers. As the population increases, demand increases for wealthier food choices (Irani, 2016). Both foreign as well as domestic markets pressurize marketers, retailers and food processors to expand market operations while keeping expenses low and consumers contented. Quality control systems has been incorporated into quality control systems mainly by large companies (Lan and Zhong, 2018).Along with product safety and quality control measures, it also involves processing technologies, also take transportation, sustainable agriculture, greenhouse gases and increasing waste and water management (McCarthy et al.,2016).

b) Use of green technology in the processing of food production

Production of green food has often been elicited by organic methods for decades. Farming or fodder crops have been grown on a small piece of land and another allotted space is being used for goat, beef, and sheep grazing (Ananta et al.,2004). For sustainability, the organic farming method is used with green technology. Undoubtedly use of no fertilizers or herbicides was enough for farm areas, still opted for green technology to build a sustainable environment for the food processing domain (Berry et al.,2015). Few production systems don't own animals, so manure is not readily available. Management of nutrients like phosphorus, nitrogen, etc, should be done for the fast release of mineral nutrients for the under growth of chemical transformations according to the type of soil, crop and climate (Holdaway, 2015). Fertilizers should be used mindfully, for the sustainability of the land and processing of food processing industry (Smetna et al., 2015). For growth-limited crops, fertilizers can be applied in slight excess. Excess manure helps to prevent problems like the volatilization of nitrogen and phosphorus run off. Such problems mainly occur during the rainy season. Soil fertility and sustainability can be achieved through the management of phosphorus and nitrogen as excess manure is been washed away and nutrients are seeping into the soil.(Metcalfe R 2019).For example, around 29-30% of nitrogen is been expelled and lost worldwide in the form of gases such as NH3 and N2O.Out of 30%, only 16% is been used and to control such losses production value chain and the sustainability of the food production sector (Velenurf et al.,2019).

c) Green technology in food processing

To improve shelf life, nutritional qualities and safety, food must be processed under optimum conditions and to make food more expedient (Warangham, 2009). Primary, secondary and tertiary processing methods are used to convert raw produce into foods. Primary methods of processing, like sorting, grading, milling and dehulling need to be assessed first. Primary processing doesn't stop here, it includes blanching, pasteurization, scaling, packing, storing, freezing, acidification and separation through homogenization (Knorr, 1999). Further processing techniques to add more value-added products along with refined food, secondary, and tertiary methods are been aligned (Spiess et al.,2003). Secondary and tertiary processing techniques are further applied to transform these foods into other value-added food products. Secondary and tertiary processing techniques are further applied to transform these foods into other value-added food products (Ferrando and Spiess, 2000). Enzymes could prove to be one of the most promising and advancing technologies for lessening the environmental impact of food processing (Petrotos and Lazarides, 2001). Enzymes act as excellent biological catalysts by accelerating reaction rates, providing time savings, energy, and cost. Ease of inactivation, non-toxicity, sensitivity, specificity and major activity at low concentration are the potential of food enzymes for food processing. (Hite,1899). Even been proven to be more environmentally friendly as compared to traditional methods. Goods with a longer shelf

life, yield, good textures, and flavours can be drawn out by enzymatic activity in food. Taking case into points, enzymes like amylase, pectinase, galactosidases, lipases, isomerases, transferases etc can be used as enzymes in food processing (Knorr and Heinz, 1996).

d) Artificial intelligence in food processing

Artificial intelligence has been a tremendous aspect to be used in the food industry. Food and agriculture processes have been monitored by big data made by the Internet of Things (Ben-Daya et al.,2017).Use of artificial intelligence in food processing also includes social media and supply chain monetization. Artificial intelligence in the food industry often includes the following steps:

- Taking technology into the world of food processing domain, the Internet of Things, a technology that connects the agricultural world to the digital world (Lézocjhe et al., 2020) Not only agriculture, but also the related domains.

IOT or Internet of Things is also referred to as the Internet of Industry. To comprehend the state of the agri-food system, pre-processing of data for yield is been required (Verdouw et al., 2016). Techniques such as data collection, data curation, and storage in order to extract critical insights and essential information (Accorsi et al., 2017). Agri-field industry uses various sensing and IOT devices to collect a larger amount of data to provide insights for better, optimum results. For such big database systems and an optimum output data-driven decision system, programming models, agriculture data science models, etc, are required (Ulrich, 2021).

- Adding artificial intelligence to precision agriculture is expected to improve agricultural operations efficiency by concept of applying material in the right amount of time and place (Rushton et al., 2014). Precision agriculture is set to elevate profit for the agriculture sector, concurrently reducing environmental effects and increasing variability of soil environment by applying doze at the right time and place by using material mindfully and accurately (Mahalik and Nambar, 2010).

Current technologies related to agriculture in artificial intelligence: AI-powered agricultural equipment, e.g. harvesters and tractors, makes precision farming plausible by standardizing planting, watering and harvesting procedures. Decision-making with analyzed data and well-informed information is possible withAI-powered tractors, which minimize manual work and optimize outputs for better results (Caldwell, 2012).

a) Drones for crop monitoring

Drones with high-resolution pictures are used to scan and identify nutrient deficiencies, pest infestations, and crop diseases by monitoring crop and yield. Such technologies are used to amplify output (Christopher, 2016).

b) AI-Powered precision irrigation systems

Artificial intelligence in irrigation channels has been expected as well as proven to be an excellent source of sensing data to optimize irrigation timings. Irrigation is an important aspect for crop maturity, by AI-driven tools make water supply more cost-effective (March, 2015).

c) Monitoring for regenerative agriculture

Monitoring, reporting, and sensing are been improved by artificial intelligence.

Sustainable farming methods are supported by such technologies, including agriculture's soil carbon sequestration, such as AI-driven soil analyzers, and automated soil core extraction vehicles, which in turn more effectively analyze soil carbon (Allen, 2016).

Table 2. Emerging technologies for microbial control in food processing

Technologies	Examples
Preservation through bio-preservation	Uses organic acids and probiotics
Technologies that don't use magnetic fields	Uses moderate heating by induction and electric
Magnetic and electric fields	Uses high-intensity electric fields along with high- intensity ultraviolet rays.

1.6 Potentials for Sustainable Food Processing Technologies

a) Sustainable protein source by food processing technologies

As compared to conventional plant breeding techniques along with animal husbandry, the development of plant-based sources such as biotechnology-grown meat and plant-based proteins are better sustainable option because they use fewer resources and emit less greenhouse gases (Olsen and Christensen, 2015).

b) Minimizing food waste

Innovative processing methods include turning leftover food into usable products, which makes efficient and whole use of food. Modern preservation techniques increase shelf life by reducing negative effects such as spoiling and elevating cost-effectiveness in the production of food. Processes of converting waste food products into valuable products contribute to the reduction of waste by methods such as up cycling and recycling (Chesbrough, 2016).

c) Advancement on food resilience

Blockchain technologies and Internet of Things (IOT) are such amazing technologies which made real-time tracking across the food chain possible, which advances operational success and functional efficiency, and decreases the risk of contamination (Sarkar and Costa, 2008). Effectively securing food builds consumer trust. By guaranteeing product authenticity, these technologies increase consumers' trust, decreasing health-related risks and improving food security (Saguy and Taoukis, 2017).

d) Operational efficiency and increased productivity

Food processing techniques have been simplified by using automation and robotics techniques, by minimize human error and give the best error-free results (Saguy and Sirotinskaya.,2014) Also, modifications in packing techniques under suitable atmospheric conditions by edible coatings, which help protracted shelf life and lower waste and spoilage

e) Supply chain management

Farming of food products from farm to fork is possible by better supply management with plausible technologies such as block chain, which increases supply chain management. Risk of contamination is reduced and food safety is been increased (Bigliardi and Galati, 2013). By introducing food sustainable technologies into supply chain management, the food supply chains became more traceable and tracking (Tobey and Manore, 2014). Quality and food security are been ensured, making it through well-informed decisions by assisting producers and merchants (Klassen et al., 2018).

f) 3D food printing technology

This technology is especially crafted for space exploration and is used by astronauts to have meals that have a guaranteed 30 + years of shelf, guaranteeing nutritional needs and providing satisfaction during long space travels (Abbas et al.,2016) Advanced preservation methods are being adopted in space for the survival of long durations of time, in which durable, nutritional, and lightweight qualities are been accomplished, enabling astronauts to survive and complete their nutritional requirements by food technology techniques (Freeman et al.,2014).

1.7 Pitfalls of Food Processing Techniques

a) Fortification with preservatives

Artificial colors, flavors, additives, etc are added beyond the limit to increase shelf life and appearance. Negative health outcomes are such as reactions, high blood pressure, and even cancer (Alexandratos and Bruinsma, 2012).

b) Forming of toxic agents cum harmful substances

Food processing techniques often involve methods such as high temperature frying produces harmful substances like acrylamide, trans fats, etc., and are linked to major diseases such as cancer and heart disease (Gomez et al., 2006).

c) Proliferation due to microbial contamination

Poor handling, cross-contamination, and insufficient sterilization lead to the risk of microbial contamination. Though goal is to lower the risk of bacteria such as Salmonella, E. coli and Listeria. Such pathogens may risk food security by resulting in food borne pathogens,

which in turn may cause food borne illness (Gowen et al., 2007)

d) Dependency on mechanized systems and displacement of traditional practices

Conventional food preparation methods such as fermentation, artisanal techniques, etc are somehow lost due to high technological advancement and the use of industrial-based high-processing techniques. In such a process, traditional knowledge and conventional practices may be lost (Dixit et al., 2016).

e) Environmental impact

Food processing industries notably harm the environment due to high energy, water, and greenhouse gas emissions. Ecological balance is displaced due to chemical byproducts (Nicloi et al., 2007).

f) Nutrient degradation and loss of dietary fibre

The nutrient loss declines the nutritional content of food due to high cooking, blanching, and refining, which in turn cause degradation of nutrients such as vitamin B, vitamin C and vitamin A, E. (Salguero et al.,2013).

2. UPCOMING MAJOR CHALLENGES

There are various challenges related to food processing technologies. Initially for ecological food and long-term urbanization, schemes should be applied to lower waste and carbon emissions (Berry et al., 2015). Sustainability should be incorporated into food security for long-term sustainable usage. To create a sustainable food chain, it is significant to contribute food value chain, which would furthermore require multidisciplinary approaches. Majorly more focus is required on an integrated well well-planned structure, including the making of business models, broader aspects of consensus, and strategies to create a better, sustainable economy (Solodar et al., 2018). All such challenges could be faced in the future, and they need to be overcome today by maintaining a sustainable approach towards food security. Also, to maintain consumers' trust in the long term, it's one of the challenging situations (Linder, 2019).

3. CONCLUSION AND FUTURE TRENDS

Diligence of experts in food science and technology for strengthening the field of food science and technology is a key component of evolution by enhancing the latest food technologies techniques. Such techniques have guaranteed the safety and security of food and made the global diet much better (Khoo and Knorr, 2014; Knorr and Khoo, 2015).Current food processing technologies are such sustainable that they are securing present as well as future needs. Such techniques may disrupt consumers' trust, for which proper labelling on packages must be done to avoid any serious disease related to diet, obesity, or any kind of allergic reactions due to the processing of food. Evaluation of the food supply chain is important for feeding the world's population and maintaining the diet. Lack of integrated plans or insufficiency of budget for sustainable food systems would make such technologies difficult in fewer countries. For long-term health and sustainable food development goals, researchers and scholars are looking further to improve food management systems for long-term health and ensuring nutritional value for generations. Taking into consideration biodiversity and the environment, people are continuously testing and researching sustainable refined food techniques to guarantee equal nutritional value for all. There is a need to add more innovative ideas, technologies, and research pooling them together would lead to advanced, sustainable development of the food system.

DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Authors hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT etc) and text-to-image generators have been used during writing or editing of this manuscript.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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