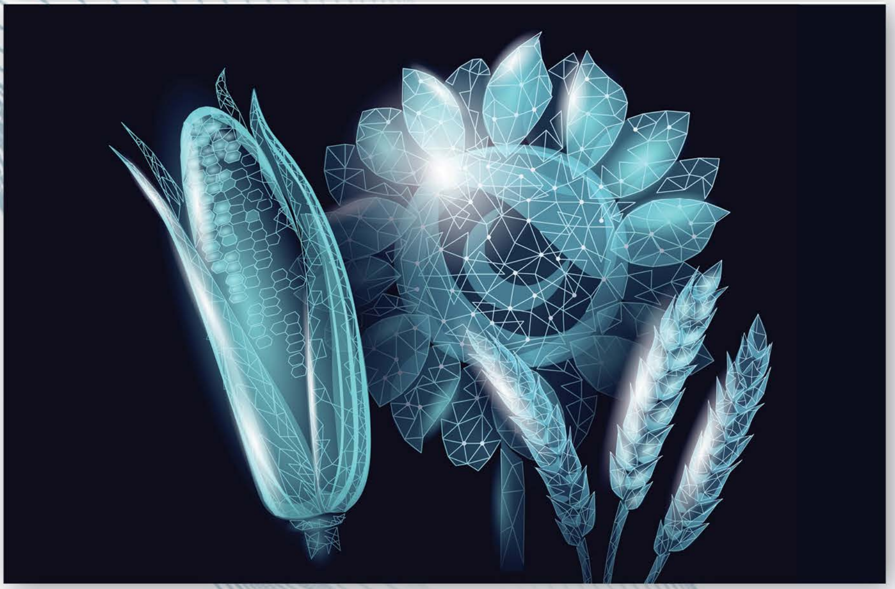
FUTURE CROPS AND PROCESSING TECHNOLOGIES FOR SUSTAINABILITY AND NUTRITIONAL SECURITY



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Future Crops and Processing Technologies for Sustainability and Nutritional Security

Our current food system faces challenges across the board – from ensuring food security and reducing environmental impact to managing costs and minimizing waste. Fortunately, cutting-edge food processing technologies play a critical role in paving the way for a more sustainable future. Taking a two-track approach, *Future Crops and Processing Technologies for Sustainability and Nutritional Security* presents sustainable technologies and emerging crops that are capable of ensuring nutritional security. There are various crops that are nutritious but under-utilized. Crops covered in the book are those that are climate resilient and exhibit less use of water and zero discharge to environment, such as millets and legumes like chickpea, groundnuts, and pigeon pea.

KEY FEATURES:

- Provides a comprehensive literature review on the opportunities and challenges in achieving sustainability and nutritional security.
- Presents compatible, relevant crops to address both sustainability and nutritional security.
- Discusses the emerging technologies/crops/food products to justify sustainability and potential to ensure nutritional security.

This book also provides information on all aspects related to the processing and use of sustainable technologies and crops. The use of technologies like 3D printing, novel drying method, high pressure processing, high-voltage treatments, and the proper combination of conventional methods are addressed.

Future Crops and Processing Technologies for Sustainability and Nutritional Security

Edited by
Soumya Ranjan Purohit, Vasudha Sharma,
Meena Kumari, Kasi Muthukumarappan and
Joanna Kane-Potaka

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Vasudha Sharma is Assistant Professor in the Department of Food Technology, Jamia Hamdard, New Delhi, India. Dr. Sharma obtained her PhD in Food Process Engineering from IIT Kharagpur and has more than ten years of teaching and applied research experience in food processing technologies. She has published widely in the areas of functional foods, nondairy probiotics, sustainable food technologies, process optimization, and nanobiosensors for food safety. Dr. Sharma has guided four PhD and more than 50 MTech students for their dissertations. She has over 32 research publications, 16 book chapters, two books, five popular articles, and two patents granted on her name. Dr. Sharma has completed two funded projects, and currently she is the principal investigator of DST-SHRI project on processing and value addition of millets. Dr. Sharma has received Centre for Quality and Food Safety (CQFS) Award for Food Safety; Mentor in 2022 & CQFS Food Safety Award 2021 on World Food Safety Day; and has served as Member of National Level Expert Committee for drafting academic curricula for food safety education in India.

Meena Kumari is working as Assistant Professor at Amity University, Noida, Uttar Pradesh, India. Her research area is focused on the bioavailability of nutrients from foods. She has done her PhD from CSIR – Central Food Technological Research Institute, Mysuru, Karnataka, India. She had published papers in peer-reviewed international SCI journals. She had also presented papers at various national and international conferences. She has been awarded for being the best oral presenter at 46th National Conference of Nutrition Society of India. Dr. Meena has also served as a reviewer for some international journals. She also had organized two international conferences and various events at university level. She is a life member of some prestigious professional bodies including, NSI, AFSTI, and Indian Society of Clinical Nutrition.

Kasi Muthukumarappan has established himself as a global leader in research and mentoring within the food processing sector. He has obtained 65 grants, totaling over $20 million, as a principal investigator (PI) and co-PI. His scholarly output includes over 250 peer-reviewed publications and more than 350 regional, national, and international presentations. His international recognition stems from his pioneering work in nonthermal processing, rheological properties, and the thermo-chemical conversion of biomass. Dr. Muthukumarappan's research encompasses fruit juices' rheological properties, coproducts' value addition, and efficient biomass conversion. His contributions to setting national and international standards in bioprocessing and bioenergy have been influential. Further, Dr. Muthukumarappan's leadership extends to developing commercial processes for the dairy industry, notably the ProFrac process, which efficiently separates high-value proteins from complex mixtures like cheese whey. This innovation has significantly enhanced profitability and energy efficiency in the US dairy sector.

Joanna Kane-Potaka is a marketing expert with global leadership in public, private sectors, and with nonprofit organizations including four CGIAR centers – WorldFish, Bioversity, International Water Management Institute (IWMI), and most recently at International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) as Assistant Director General of External Relations. She began her career as an agricultural economist and later moved into market research in agribusiness and spent most of her career in international development. Bringing her professional experience in Asia, Africa, Australia, and Europe with specific expertise in strategic marketing, communications, business development, knowledge management, and uptake of scientific research, Joanna works toward having a big impact on the health of the people and the planet. She founded the Smart Food Global Movement, recognized by the United States and Australian governments in the top ten global food innovations in 2017.

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SECTION A

Sustainable Food Processing Technologies

Sustainable Food Processing Technologies

1

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Sushil Kumar Singh and Poonam Singha

Abbreviations

FAO	Food and Agriculture Organization
UN	United Nations
IFAD	International Fund for Agricultural Development
UNICEF	The United Nations Children's Fund
WFP	World Food Program
WHO	World Health Organization
LCA	Life Cycle Assessment
ISO	International Organization for Standardization
SFIMT	Sustainable Food Intelligent Manufacturing Technology
IoT	Internet of Things
GHG	Green House Gas
GWP	Global Warming Potential
FSFs	Future Smart Foods
PEF	Pulsed Electric Field
HTST	High Temperature Short Time
USFDA	United State Food Drug and Administration

1.1 INTRODUCTION

An increase in the world's population and changing dietary habits pose a great challenge to global food system. The big question of the hour is how to feed all the world without impairing the natural resources and ecological balance of the planet which, if occurs, would endanger the survival of human and animal race (Steffen et al., 2015). According to United Nation, the population of the globe is predicted to hike by 8.5 billion by 2030 and 9.8 billion in 2050. The respective drops in the percentage of undernourished people were 23.3% in 1990–1992 and 12.4% in 2014–2016 by Millennium Development Goals.

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However, a significant figure of 800 million people is still remaining undernourished, and the number is increasing (FAO, 2017b). The Sustainable Development Goals aim at achieving hunger-free population with zero malnutrition by 2030, which can be possible by ensuring full access to safe and nutritional food to all the population at all the time that could fulfill their dietary habits and health-forming activities (UN, 2015).

Malnutrition that occurs due to a lack of proper nutrition and micronutrient deficiency, and irregular growth and obesity, which occur due to over consumption of high-energy food, are the biggest problems for a major part of global population. Diabetes and cardiovascular diseases are the possible risks due to prolonged malnutrition and obesity. About 13% adults of the global population are suffering from obesity, and this percentage is increasing rapidly day by day (FAO, 2017a). Negative environmental impact caused by land degradation; diminishing of natural resources; biodiversity loss; and pollution of air, soil, and water are somehow associated with the harsh food processing and agricultural practices (Whitmee et al., 2015). According to FAO, nearly one-third of the greenhouse gases are emitted from food systems, and about 70% of the global fresh water is consumed for agricultural production alone (FAO, 2017a). Moreover, chemical-based agricultural practices like use of pesticides and synthetic fertilizers and the application of synthetic hormones in animal husbandry are responsible for food contamination and toxicity which can lead to adverse health consequences among humans (Landrigan et al., 2018). These practices can have serious hostile repercussions for future sustainable food systems as well. Sustainability in food production and supply is a bigger challenge in the world of exhausting natural resources, changing climatic conditions, faster urbanization, rapidly growing human population, and shifting conventional energy sources to emerging energy sources. The above factors could be the major restraints in the process of achieving sustainability in food processing and agricultural systems.

Sustainability in food system requires an integrated approach that encompasses the use of advanced technology, capital management, and social and ecological balance together (Lindgren et al., 2018). Advanced sustainable technology in food processing enables the reduction of energy and water consumption, increasing the production of safe and nutritious food which keeps an eye on environmental, social, and economic sustainability also.

1.2 SUSTAINABILITY IN FOOD PRODUCTION

Sustainability in food production along with a proper food supply chain to feed the fast-growing population is one of the major challenges faced by food industries. Sustainable food production refers to

> the systems and processes that are non-polluting, safe for worker, communities, and consumers, economically feasible, conserve natural resources and non-renewable energy and does not compromise future generation needs.
>
> *Senker, 2011*

Alongside food production issues, food security, consumption, and nutrition are also concerns of food production sustainability, which require immediate action. By 2050, it is estimated that the world population is predicted to reach 9.1 million, i.e., 34% higher than the current population. To feed this population, a prerequisite of 70% increase in food production is essential (Alexandratos, 2009). Thus, more food must be produced with limited resources of water, energy, and land to maintain sustainability. This requires proper planning and usage of sustainable technologies in food production henceforth. Thus, the food production system must be reformed globally to minimize environmental impact and sustain future food production.

1.3 CHALLENGES IN SUSTAINABLE FOOD PRODUCTION

Most food industries utilize natural resources as an integral part of sustainable food production and rely upon proper resource management and waste reduction (Castro-Muñoz et al., 2020). One-fourth of global water resources are consumed by food processing sectors and are being discarded into the ecosystem as contaminant (Pereira & Vicente, 2010). For sustainable usage of water, either food processing techniques that utilize less water or reuse contaminated water after proper treatment can be developed. Additionally, food wastage during processing, storage, and transportation can further contribute to environmental issues (Arshad et al., 2020). Fruits, vegetables, and grains are primary sources of food waste, which negatively impact the ecosystem (Barbhuiya et al., 2022 a,b; Singha 2017). Some of the reasons for food wastage are depicted in Figure 1.1.

Present-day food processing technologies utilized by industries largely depend on non renewable fossil fuels and contribute to 37% of global greenhouse gas emissions (Rahimifard et al., 2017). The food industries, such as meat and dairy industries, are big producers of greenhouse gases accounting for 57% emissions, while only 29% emission occurs from plant-based foods among which beef and rice are the highest contributing sources (Dash et al., 2024a; Xu et al., 2021). All these concerns of environmental challenges, along with other problems like food security, accessibility, quality, and safety, pressurize food industrialists to adopt production systems that are sustainable, cheaper, efficient, and environment-friendly.

1.4 FOOD INDUSTRY ACTIONS ON SUSTAINABLE FOOD PRODUCTION

Sustainable food production has been proposed among scientists, producers, and government agencies for possible actions, which can be adopted to help address food loss, wastage, and other environmental

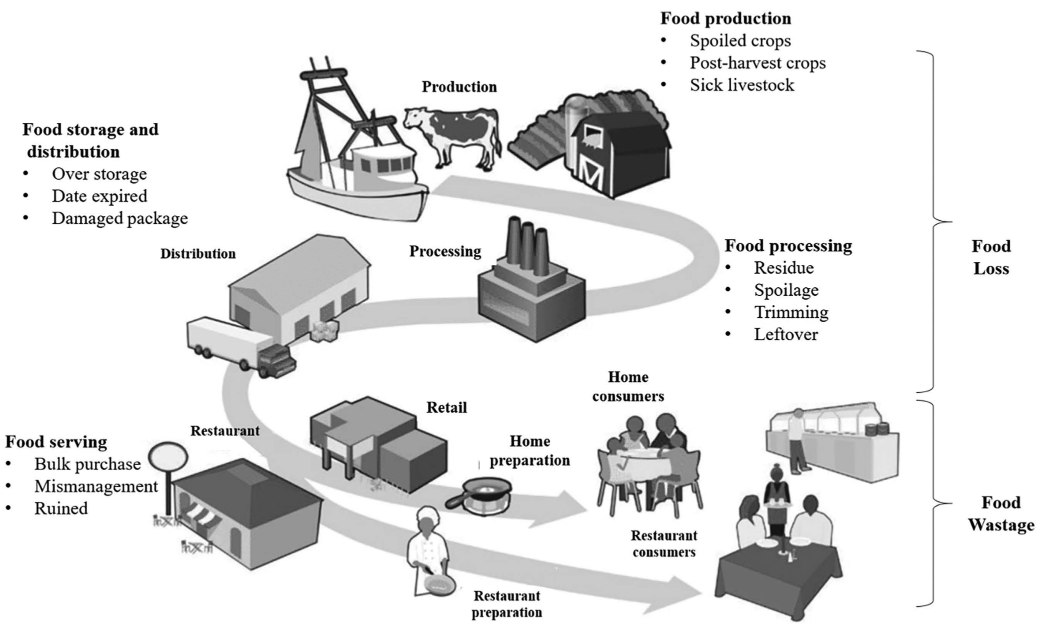

FIGURE 1.1 Reasons for food loss and wastage at different stages of food processing (modified from Arshad et al., 2020; Centers for Disease Control and Prevention (CDC), 2015).

impacts. The European Commission, over the last few years, has put in much efforts to improve sustainability through policies such as Code of Conduct, Common Agriculture Policy, and Sustainable Development Goals with the context of international commitment as the threats to environmental viability have become even more apparent (Nori & Gemini, 2011; Rayner et al., 2008). The actions that were suggested to make food production more sustainable using current technologies, implemented in food industry sustainable plan, include (Europeia, 2012):

- Efficient use of natural resources
- Reducing food waste
- Procuring food supplies like ingredients from sustainable sources
- Use of environment-friendly packaging systems
- Protection of marine resources

The European Commission continues to work toward achieving its goal of having more resource-efficient and sustainable food systems, with more policies to be expected in the future.

1.4.1 Life Cycle Assessment (LCA)

To estimate the food product environmental impact, LCA tool was found to be helpful. LCA is a multidimensional tool implemented in food supply chain at every stage, i.e., from farm to fork for assessing the environmental impact of food products (Pérez et al., 1999). From the beginning of raw material procurement to product disposal, LCA evaluates the inputs, outputs, and potential environmental impact throughout its life cycle (ISO, 1997, 2006). According to ISO (International Organization for Standardization, 2006), LCA includes a set of scientific methods such as setting scope and boundaries, data collection, mapping, calculation, evaluation, and interpretation of results that could eventually improve the environment. The five main constituents for LCA processing method according to Food and Agricultural Organization (FAO) are: a) primary production, b) transport and storage, c) food processing, d) distribution, and e) consumption (Clairand et al., 2020).

The LCA method, in recent years, has been proven to be one of the most effective tools to compare products and services, especially in identifying the stages that require improvements in food product life cycle. In general, LCA methodology components can be categorized into scope and goal characterization, impact assessment, and inventory analysis (Pardo & Zufía, 2012). Meanwhile, various LCA stages included describing the system limitation, functional unit, raw material and energy utilization, inventory, assessment of ecological stress, and possible enhancements required (Lillford et al., 1997). In this way, LCA estimates the food production and consumption chain and environmental sustainability profile.

Despite LCA being a standardized tool, current LCA practices often fail to address certain food supply chain aspects (Notarnicola et al., 2017). For example, the issue of wastage and loss of food and its connection to packaging for food products besides consumer perception have been frequently neglected. Moreover, household actions, i.e., movement of food from retail to consumers, food preparation, waste disposal, storage time, and conditions are considered only in few LCA food studies (Østergaard & Hanssen, 2018; Wohner et al., 2020). LCA assessment was done for some of the food products including chicken meat, cheese cake, milk waste, and in juice industry (Chakka et al., 2021; Cooreman-Algoed et al., 2022; Gutierrez et al., 2017). It was observed, among all the environmental issues, that the greatest challenge faced by the industries and research community was solving the issues of food loss and waste. Moreover, most of the studies concluded that packaging systems contributed to a major part of the environmental and economic impact on the food sector. Sustainable food packaging and shelf-life extension were proposed as possible actions that were suggested by producers and scientists to address these issues (Dash et al., 2024c; Pavani et al., 2024).

1.4.2 Sustainable Food Smart Manufacturing Technology

Current development and research based on the technological aspect of food processing are largely influenced by large manufacturing drivers that can augment economic scale efficiently. However, increased demand, limited ingredient availability, and consumer awareness have led to the development of novel processing technology that enables greater sustainability in food production and supply. People require an effective sustainable technology, and one among the latest elements of this in the food industry is the Sustainable Food Intelligent Manufacturing Technology (SFIMT). Recently, Wu et al. (2022) elaborated the latest technical advancements needed for preparing modern framework in sustainable food processing to guide potential assessment. The study emphasized on smart management and smart production based on sustainable aspects by utilizing equipment and technologies that are digitally monitored tools, industrial robots, and internet machineries to monitor the production. The application of automation and intelligent manufacturing was recommended on three areas including smart fabrication, networking, and manufacturing. The sustainable production technologies included cloud computing, artificial intelligence, Internet of Things (IoT), and cyber-physical systems. The contribution of smart, digital, and intelligent production can make food processing sector more sustainable, and effective.

1.4.3 Sustainable Indicators

In spite of its success from the day one of its advent (1980s), the concept of sustainable development remains indistinct on the incorporation of scientific discipline into field progression (Bettencourt & Kaur, 2011). It was observed that there was a lack of international standards for measuring sustainability especially in terms of where, when, and what indicators to be employed for better understanding. Most of the existing indicators for sustainability measurements cover social, environmental and economic aspects. This included labor standards, pollution, ethics in waste issue, and food supplier relations. However, there was a need to apply integrated sustainable solution, and this led to the seven indicators of sustainability introduced by Gustafson et al. (2016). The seven domains of indicators includes nutrition, food safety, food affordability and availability, environment, waste, resilience, and sociocultural well-being. These indicators and methodologies can provide different priorities and conclusions for sustainable actions to be taken in the industries.

1.4.4 Sustainable Food Sources

Sustainability has influenced food industries in product development as well. Recently, a sourcing strategy based on sustainable and nutritional aspect, has led to an ingredient branding concept along the food chain. For instance, there is a widespread acceptance of organically grown products as they are harmless to the environment. Moreover, the awareness on greenhouse emissions from livestock sectors has urged a new interest toward alternative protein sources such as plants, insects, microorganisms, aquatic photosynthetic organisms, and in exploring meat-free diets (Dash et al., 2024a; Ravindran et al., 2024). Williams et al. (2010) conducted a study on Green House Gas (GHG) emissions in the UK food system estimated to determine the potential hotspots for GHG emissions. Table 1.1 outlines the suggested measures that must be implemented soon to reduce GHG emissions. Based on the market and product type to which it is transported, the sum total of environmental impact output per unit is termed as the "global warming potential" (GWP). To improve consumers awareness, eco-labelling is one of the emerging tools taken as a sustainable initiative that marks safe and green products. According to ISO, eco-labelling "is a voluntary method practiced all around world for labelling and certification of environmental performance" (Miranda-Ackerman & Azzaro-Pantel, 2017).

TABLE 1.1 Measures to Reduce Greenhouse Gas (GHG) Emissions in the Food System.

COMPONENT	*DESCRIPTION*
Non-mobile energy	The use of renewable energy for electricity production instead of fossil fuels contributes to reducing global warming potential (GWP).
Mobile energy	Substituting hydrogen or electric engines for fossil fuels to run tractors, ships, and similar equipment can reduce GWP.
Direct greenhouse gas emissions	Direct emission of GHGs like refrigerants, methane, and nitrous oxide especially from soil and refrigerant sources should be reduced.
Production efficiency	Proper waste management at every stage of processing can reduce GWP.
Consumption	The consumption of animal-based products like milk, eggs, and meat and plant-based sources like rice, which contribute to a large GWP can be reduced.
Conservation	Avoiding and decreasing wasteful use and efficient usage of 3R (Reduce, Reuse, and Recycle) can inhibit global warming.

Source: Modified from Chakka et al. (2021).

Sustainable food should not have nutritional benefits only, it must take care of sustainability at global level as well (Meybeck & Gitz, 2017). As per Food and Agriculture Organization, United Nations, sustainable food enables food and nutritional security with low environmental stress that ensures good public health for the present and future generations. Sustainable diet must have positive effects on biodiversity and ecosystem; it should be safe, nutritionally rich, economically affordable, accessible to every section of the society while maintaining natural and human resources (FAO, 2010). Animal-based food has high fat content and puts more burden on the environment as compared to plant-based diet. Shifting from animal-source food to plant-based diet will put less environmental pressure, produce less greenhouse gases, and provide more health benefits (Tilman et al., 2011). The increasing trend of consuming plant proteins replacing protein from animal sources (fish, meat, poultry) has several health and environmental benefits (Dash et al., 2024b; Singh, 2016; Singh & Muthukumarappan, 2016). Protein from fungal biomass and other microorganisms can fulfill the nutritional requirement that comes from animal-based sources. Cellular agriculture industry is one of the novel sectors where *in vitro* production of eggs, meat, and milk occurs by utilizing animals, plant cells, and microorganisms. Cultured meat requires less land and emits less greenhouse gases, as compared to the conventional red meat production (Lindgren et al., 2018). Food crops' diversification can be possible through the consumption of local, underutilized, and indigenous crops rather than relying on the three major crops namely, paddy, wheat, and corn. Apart from pulses, tubers and roots, and fruits and vegetables, various cereal crops are considered as future smart foods (FSFs) – for example, millets, sorghum, quinoa, amaranth, and buckwheat (FAO, 2019a). These FSFs contain micronutrients, carbohydrate, fat, protein, dietary fiber, etc. According to FAO (2019b), 90% diet is fulfilled by using 103 crops out of 30,000 edible plant species. The major three crops contributing over 50% of plant-based diet are wheat, rice, and maize (Mustafa et al., 2021). A sustainable food production and consumption system must have positive nutritional and environmental impact, and that should focus on the loss of biodiversity, greenhouse gas emission, and land utilization.

In addition to new sustainable sources, the solution for sustainable food system must also include food loss and waste reduction. An emerging new source of ingredient from food waste can be introduced as an edible portion to the food supply (Singha & Muthukumarappan, 2017; Singha et al., 2019). The edible biomass that is currently wasted in the food industry can be reused and recovered (Hertel, 2015). In order to prioritize beneficial interventions, it is necessary to assess both environmental as well as economic costs of accomplishing initiatives that can reduce the wastage of food (Muth et al., 2019).

1.4.5 Sustainable Emerging Technologies

Industrial processing of food involves several stages including raw material receipt, storage, heating, washing, cooling, drying, emulsification, and many more. All these processes are capable of releasing waste stream that can negatively impact the environment. Moreover, most of the conventional technologies are thermal processes and utilize fossil fuels for energy production (Chakka et al., 2021). To find an alternative for traditional thermal and chemical preservatives, a more energy-efficient and environment-friendly food processing technique such as the nonthermal technology was introduced. These technologies have the potential to minimize water and energy consumption, improve product quality, and minimize the environmental impact (Pereira & Vicente, 2010). The current emerging technologies utilized for sustainable production include high-pressure processing, ultrasound, pulsed electric field, ohmic heating, pulsed light, ozone technology, cold atmospheric plasma, and microwave (Barbhuiya et al., 2021; Dash et al., 2024a).

In addition to this, some of the nondestructive techniques such as hyperspectral imaging and other spectrophotometric techniques (Goyal et al., 2024) in raw material reception and active/smart packaging for food packaging systems are other emerging sustainable technologies for both food production and supply chain management (Gorde et al., 2024). A summary of traditional and emerging technologies is represented in Figure 1.2. However, it should not be overlooked that all these emerging technologies have unavoidable drawbacks such as requirements of large capital, costly equipment, and skilled labor for handling sophisticated system, which hinders the widespread application of these technologies in food industries (Priyadarshini et al., 2018).

1.5 NOVEL THERMAL AND NONTHERMAL TECHNOLOGY

In the last decade, various novel technologies have been developed that enhance the physicochemical properties and reduce the quality loss of food product due to thermal degradation. The primary target of these innovated novel technologies is to reduce the food quality changes, food waste, and energy consumption and prolong shelf life with maximum production and process efficiency. Various novel nonthermal and thermal technologies are trending in food processing, compared to conventional methods due to the contribution of these technologies in producing more fresh foods with longer shelf life and higher nutraceutical properties with native structure and texture of the natural food products (Table 1.2). Sustainable development goal by UN encouraged the application of sustainable novel technologies such as nonthermal with the combination of advanced thermal technologies for achieving maximum log reduction of food microorganisms and pathogens ensuring food safety. The focus of implementing the novel technologies is to reduce environmental impact, consumption of energy, and time requirement by the processes and meet consumer perceptions. Therefore, the purpose of adopting these technologies as compared to the conventional technologies is a prioritization not only for enhanced food preservation but also for food quality and sustainability without taking food safety risks.

The advantages of novel nonthermal and thermal technologies over the conventional processes are:

- Controlled Maillard reaction
- Enhanced product quality
- Reduce negative impact on environment
- Enzyme deactivation
- Improvement in the functionality of the product
- Speed up the process of heat and mass transfer
- Increase in product quality
- Reduce process and product exposure time
- Enhanced preservation
- Longer shelf life

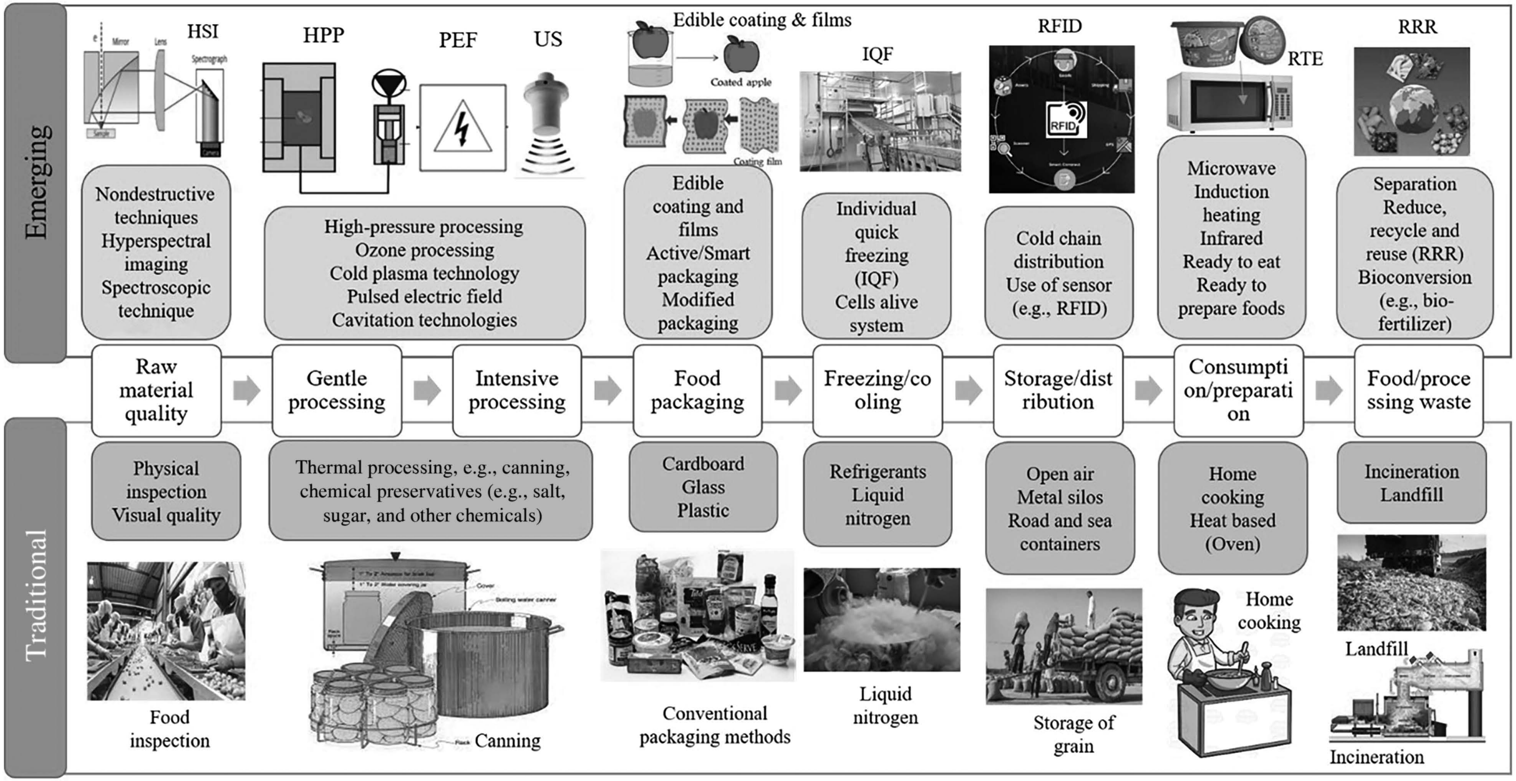

FIGURE 1.2 Emerging and traditional technologies and approaches throughout the food chain modified from Knorr et al., 2020.

TABLE 1.2 The application of Novel Thermal and Nonthermal Technology in Food Processing

TECHNOLOGY	*APPLICATION*	*REFERENCES*
Ultrasound	Extraction of oil from oil seeds and bioactive compounds from fruits and vegetable Ultrasonic-assisted filtration in dairy and beverages industry, aids in the process of freezing, drying, and thawing	Chow et al. (2005); Juliano et al. (2017); Qin et al. (2021); Saxena et al. (2009); Wu et al. (2020); Dash et al. (2021)
Cold plasma	Microbial inactivation food product, antimicrobial washing and in-package cold plasma treatment, functionality modification of proteins and carbohydrates	Bang et al. (2020); Devi et al. (2017); Jahromi et al. (2020); Lin et al. (2020); Sharma and Singh (2020)
Supercritical technology	Supercritical carbon dioxide technology used for the extraction of temperature-sensitive bioactive compounds	Lefebvre et al. (2021); Santos et al. (2021)
Pulsed electric field	Used for shelf life increase by decreasing microbial load, inactivation of enzyme from fruit juices, extraction of functional ingredient from microalgae, assists in the process of dehydration and freezing-like operation	Gateau et al. (2021); Käferböck et al. (2020); Liang et al. (2017); Liu et al. (2020); Mannozzi et al. (2019); Preetha et al. (2021); Timmermans et al. (2019)
High hydrostatic pressure processing	Used for the inactivation of microbes of fruits, vegetables, meat and dairy products; extraction of antioxidant, anthocyanin-like nutraceutical compounds from fruits; improvement in physical and chemical properties of fermented fruit juice; technological and functional modification of protein	Bulut and Karatzas (2021); Cap et al. (2020); Carullo et al. (2021); Cascaes Teles et al. (2021); Ninčević Grassino et al. (2020); Rios-Corripio et al. (2020); Suwal et al. (2019)
Ultraviolet light	Used for the inactivation of pathogenic microbes in fruit juices, milk products, etc., for longer shelf life, improvement in physical and chemical properties of plant and animal-source proteins, surface decontamination of freshly harvested fruits and vegetables	Delorme et al. (2020); Dyshlyuk et al. (2020); Fenoglio et al. (2020); Ferreira et al. (2020); Kumar et al. (2020); Xiang et al. (2020)
Ozone	Used for the inactivation of spoilage microbes, toxins present in meat, fruit juices, etc., surface sterilization of freshly harvested fruits and vegetables, enhancement in physical and chemical properties of food products	Choi et al. (2012); Giménez et al. (2021); Mohammad et al. (2020); Taiye Mustapha et al. (2020); Tiwari et al. (2010)
Microwave technology	Used for cooking, blanching, tempering, thawing, pasteurization, sterilization, drying, baking, packaging of food products, extraction of bioactive compound from fruits and vegetables, and the extraction of oil from oil seeds, etc.	Başkaya Sezer and Demirdöven (2015); Chizoba Ekezie et al. (2017); Orsat et al. (2017); Si et al. (2016); Turabi et al. (2007); Vinatoru et al. (2017)
Infrared heating	Used for pasteurization, disinfection, blanching, drying, dehydration, roasting, and heating of food products	Guiamba et al. (2015); Lao et al. (2019); Özdemir et al. (2017)
Radio frequency heating	Heating, blanching, thawing, drying, the inactivation of microorganisms from milk and meat products	Altemimi et al. (2019); Li et al. (2017); Siefarth et al. (2014); Zheng et al. (2017)
Ohmic heating	Used for dairy processing for food safety and quality, pathogenic microbes, and enzyme inactivation of food products in extraction and thawing processes	Aamir and Jittanit (2017); Knirsch et al. (2010); Liu et al. (2017); Ribeiro et al. (2022); Termrittikul et al. (2018)

1.5.1 Nonthermal Technology

The nonthermal technologies can be categorized into electro-based (pulsed electric field, pulsed light, electron beam technology, cold plasma), pressure-based technology (high-pressure process, high-pressure homogenization, supercritical fluid extraction, subcritical water extraction), mechanical-based (ultrasound, hydrodynamic cavitation), and others including CO_2 processing and membrane processing that are largely used in drying, extraction, separation, fractionation, food functionalization, and microbes and enzyme inactivation to bring sustainability in food processing operation. These technologies are considered as sustainable over their conventional alternatives as they reduce the water and energy consumption during processing and limit the energy impact during storage due to their direct effect. However, waste utilization and biomass valorization are the important indirect effects of the nonthermal technologies, since waste generation, inadequate recovery of the food residues, and undesirable quality spoilage throughout the supply chain are the major problems in food sectors.

1.5.2 Novel Thermal Technology

Food preservation and preparation are usually performed by thermal processes such as drying, pasteurization, sterilization, and extraction. Thermal technology causes technological and functional changes in food including the modification of starch and protein, generation of aroma and flavor compounds, alteration in textural and structural changes, etc. (Asaithambi et al., 2023; Barbhuiya et al., 2021). However, there can be possible loss of nutrients (vitamins and minerals), texture, freshness, flavor, and aroma of the food product. The conventional method of avoiding adverse quality degradation through thermal technology is the HTST (high temperature short time) process. It involves the application of high temperature for short duration, where microorganisms and enzymes can be destroyed to achieve pasteurization (Asaithambi et al., 2021). The utilization of high temperature may degrade the nutritional aspects of the food products. The disadvantage of HTST is when it is applied to solid and high viscous products, it can overheat the food contact surface before the heat reaches the coldest spot.

To overcome these problems, novel thermal technologies are used, such as ohmic heating, radio frequency heating, infrared heating, microwave heating, and electric heating methods where electromagnetic waves are passed through the food sample to increase the temperature of the interior part of the food product. These processes are also known as minimal processing, where the quality degradation of the product is minimized. Due to the benefits like cost-effectiveness, environmental friendliness, and technological advancement of novel thermal technologies over conventional heating methods, they are largely used for dehydration, cooking, roasting, drying, pasteurization, blanching, and baking of agricultural and food products (Ramaswamy et al., 2012; Rastogi, 2012).

The combined use of novel technologies (novel thermal and nonthermal) in food processing would be a great development in terms of sustainable processing, food safety, food quality, and process efficiency. There should be an extensive future study for the applicability and feasibility of this technology in food industry. These technologies can reduce the carbon and water footprint of food processing by decreasing the energy and water consumption which ensures food security and environmental sustainability. However, apart from the technological drawback of these novel technologies, there are other disadvantages for adopting these technologies fully in food industry. Spectacular development would be noticeable after their potential is revealed by applying in food industry (Sun, 2014). The size of the industry, its market shares, and technological capabilities are some of the factors for adopting these technologies. Technological understanding, cost involved for its development and commercialization, amount of complexity, and compatibility are major influential factors for switching to the usage of novel technologies in industrial food processing.

There should be an extensive investigation on the impact of novel technologies on drying, extraction, overall quality, nutraceutical value, sensory characteristics, and microbial and enzyme inactivation along with the characterization of technological and functional properties of food products. A proper shelf-life study should be performed to know the preservative effect of the novel technologies in terms of microbial inactivation. The risks like "sub-lethal injury" where the microbes can revitalize and "stress" effect where the microbes are under stress, rather than being completely killed, need to be assessed (Režek Jambrak et al., 2019). The revitalized microbes may form biofilm which is very hard to remove later. There is still a gap in detailed knowledge about the negative impacts of novel nonthermal and thermal technologies on sensory properties of food products, stability of food in storage, radical formation by certain novel technologies, positive impact on energy saving, use of green solvents, green extraction processes, and their life cycle assessment. Hence, the process should be optimized in terms of application time, rate of application of each technology, and free radical formation to remove the negative effects of the novel technology on food products.

1.6 NANOTECHNOLOGY

The development of nanotechnology has wide and diverse applications in food industry such as food safety, food additives, and nano-delivery system. Food processing is the only sector where nanotechnology will play a major role. It could be broadly applied in two types of nano-food utilization: food packaging (nanomaterial outside) and food additives (nanomaterial inside) (Gorde et al., 2024). Food additives in nanoscale affect the food texture, structure, quality, flavor, and nutrient properties and detect foodborne pathogen helping in food quality determination (Barbhuiya et al., 2022c). Nanoparticle-based food packaging increases the product shelf life by reducing the water vapor and gas flow into the packaging space and provides extra strength to the packaging. Nanotechnology application in food processing is done by developing the nanostructure from the biomacromolecules present in the food materials. For example, cellulose nanocrystals and nanofibrils are incorporated in food packaging material to improve the strength and antimicrobial properties of the packaging film. Also, nanomaterial-based biosensor can detect the spoilage of food sample and work as a tracking device for foreign body detection (Gorde et al., 2024). Nanotechnology can be used for the design and development of food elements like flavor and antioxidants, where the concentration of these components can be reduced with the improvement of food product functionality. It can also be used to develop encapsules of bioactive compounds to protect them from unfavorable conditions of the environment (Pavani et al., 2022 a,b).

Nanotechnology applications in food sector include (Figure 1.3) the following:

- Usage as antimicrobial agent to protect food against biological degradation and shelf-life improvement.
- Nanomaterials are used in delivery systems for increasing the bioavailability of food bioactive compounds
- Protection of antioxidants, vitamin, and flavor compounds against chemical substance, processing, and environmental conditions
- Nanomaterials are used as color additives and anticaking agents to increase the physical properties of food
- Nanotechnology is used in biosensor development to enhance the quality and safety control of food
- For the detection of spoilage microbes in food and beverages
- Nanoparticles are used in the formulation of packaging materials of active and smart food packaging

Despite all these benefits, there are various factors that need to be researched to enhance the adoption of nanotechnology in food processing, which include types of nanoparticles, concentration, morphology, and surface chemistry. Due to the larger surface and vulnerable surface chemistry, nanoparticles

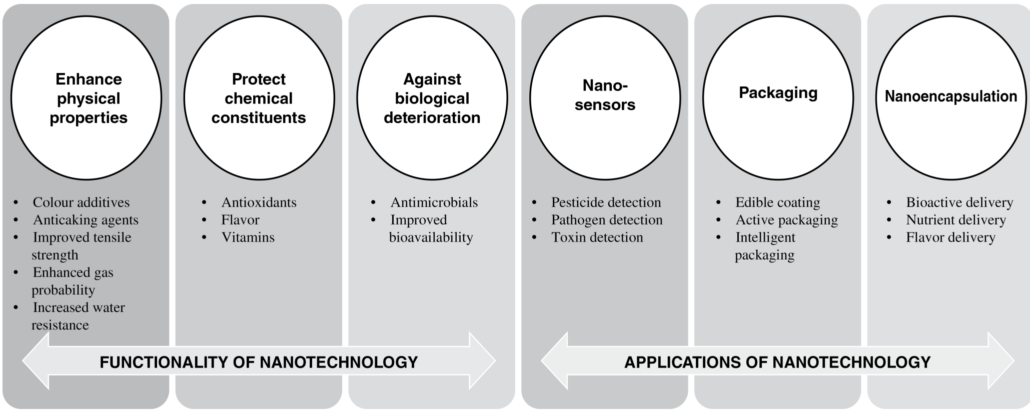

FIGURE 1.3 Application and functionality of nanotechnology in food processing (He & Hwang, 2016).

can participate in various unwanted chemical reactions which attributes to their higher bio-reactivity (Bradley et al., 2011). For the application of nanotechnology in food system, United State Food Drug and Administration (USFDA) has issued guidelines in August 2015 (He & Hwang, 2016). The European Commission issued a directive for the contamination of nanoparticles from the packaging material to the food stuffs that it should not be exceeded by 10 mg/dm^2 (Hannon et al., 2015). Possible leaching of nanoparticles from food packages and its limit and toxicological study need to be conducted. The legislative framework along with the safety risk associated when exposed to environment and human health should be of major concern in the implementation of nanotechnology in food manufacturing. The color additives and anticaking and whitening agents added as nanoparticles may go directly into our body on reaction with food and may accumulate in our body causing harmful effects. Hence, the negative effect of nano-food on human and animal health should be studied extensively. The shifting of consumer perspective to chemical-free, greener, and environment-friendly food products has put a big challenge for food industries to adopt this technology (Rossi et al., 2014). However, there are various barriers in the process of technological advancements in nanotechnology, which hinders its wider application in food sectors. Though the risk assessment of nanomaterial is still under process, a few safety assessments of it in food have been published (Cockburn et al., 2012; Hwang et al., 2012). If the application and implementation of nanotechnology can be governed and regulated properly, then its sustainable utilization will be possible in food processing in terms of product quality, food safety, human and environmental protection, and cost-effectiveness.

1.7 CONCLUSIONS

For a sustainable food system at the level of food production and supply in food industry, advanced and sustainable food processing technology is indispensable that can take care of food and nutritional security, environmental stress, cost-effectiveness, greenhouse gas emission, energy consumption, and food waste. Two technological strategies should be applied to bring sustainable technology in food processing. First is the substitution of traditional technology by a new and advanced one. Second is the detailed research and application of the existing technology for food treatment. Advancement in technology in food industry helps in putting less environmental impact by reducing waste and toxicity as compared to the conventional technologies. Recently, sustainable technologies like nanotechnology and novel thermal and nonthermal technology are being used to attain sustainable development in terms of energy efficiency and water consumption ensuring zero discharge and climate resilience. For a future sustainable with food and nutritional security, consumers and industries should work together. Shifting to plant-based food can help industries to emit less greenhouse gases putting less pressure on the environment, while consuming more local and underutilized food crops such as millets, sorghum, and quinoa can reduce the malnutrition and micronutrient deficiency among consumers. Moreover, it can also ensure food and nutrition security by reducing the overburden on three major crops such as wheat, maize, and rice worldwide. Consumers should be more aware to have a positive response and demand for products developed by using new technologies to support these novel techniques in food processing sectors. Further extensive investigation is required to properly check the potentialities and limits of these novel and advanced technologies to enhance the sustainability in food processing and optimize them to make more sustainable.

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