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Perspectives on sustainable food production system: Characteristics and green technologies

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ABSTRACT

Sustainable food production covers a wide range of perspectives and embraces issues relating to environment, economy and society. Sustainability of food production systems faces challenges ranging from environmental degradation, resource competition to elevated food demands and integration of agriculture into the global economy. Considering its far-reaching socio-economic implications, this review first provides an overview of key characteristics that distinguish sustainable food production from conventional agricultural practices. In addition, emerging green technologies in promoting sustainable food production are summarized. Among those modern techniques, urban agriculture, next-generation plant-based foods and food nanotechnology are discussed in detail. Finally, futuristic solutions and research work are proposed to provide guidance for designing sustainable Agri-Food system.

1. Introduction

The Green Revolution, spanning from 1960 to 2000, is marked as an exceptional phase of increased worldwide food security [1]. The period was distinguished by a notable surge in global food production and distribution as a result of rural agriculture intensification. This intensification is promoted by a combination of crop research advancement, agricultural expansion, mechanization and massive use of synthetic fertilizers, pesticides and genetically improved high-yielding crop species [2]. Despite the advances in food production, certain negative impacts on environmental and human health could not be negligible. For instance, the transformation of forest into agricultural land or pasture has led to the air and water pollution along with elevated greenhouse gas emissions [3]. Excessive nitrogen and phosphorus usage has imposed negative impacts on the aquatic environment. Eutrophication of waterbodies arose due to agricultural watersheds runoff and nutrient enrichment [4]. The development of inexpensive, energy-dense, low-nutrient fast foods led to significant malnutrition in many parts of the world [5]. Given the continuing degradation of soil and water alongside the decline in biodiversity and ecosystem services within agricultural landscapes, it is pivotal to refresh the concept of the Agri-Food system and minimize their environmental footprint.

Agri-Food systems encompass the entire range of factors and interconnected projects from food production, processing, distribution, and consumption to disposal of food products [6]. Sustainable food production, which is considered as philosophy of food farming system, interacts with other key systems (i.e., energy system, trade system, health system, etc.) and has received growing attention since last century [7]. Fundamentally, it is rooted in values that reflect heightened levels of awareness and empowerment, where short-term viabilities should be in line with the long-term sustainability [8]. It is worthwhile to notice that every operation and performance should be balanced and co-optimized in terms of the environment, social and economic perspectives. Practically, the sustainable food production has the features of reducing environmental impacts through effective utilization of material, energy and manufacturing processes [9]. In terms of the social aspect, sustainable food production delivers food security and nutrition for future generations in such a way to link the local resources and the resilient Agri-Food networks [10]. Subsequently, the economic aspect is correlative with risk assessment and reduction, birth of enterprises, development of low-cost and high-profit food products.

This review paper is structured as follows: in Section 1, the characteristics and principles of sustainable food production are discussed to understand its profound significance. Section 2 introduces the technologies employed for the long-term sustainability of food production. Specifically, urban agriculture, next-generation plant-based foods, and

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food nanotechnology are discussed as three of the most emerging and exciting technologies in food production sector. Finally, conclusions and futuristic solutions are proposed to guide future work in this subject.

2. Characteristics of sustainable food production

Issues linked to conventional agricultural practices can be grouped into two categories: (1) loss of wildlife to expand the arable land and (2) intensive land use [11]. Therefore, sustainable food production has been introduced as a method to alleviate the reliance on conventional agriculture [11]. Sustainable food production should be examined holistically and designed to boost three dimensions simultaneously: economic, social and environmental. Therefore, to propose a new methodology (i.e. gene editing techniques) or to leverage a new opportunity (i.e. intelligent food packaging), decisions should be assessed against all three dimensions [12,13]. Fig. 1 depicts a structural framework for the design of a sustainable food production system [14]. Blockchain technology (BCT) based food supply chain is interwoven within three dimensions of sustainability: environment, society and economy. Six themes in the sustainable food system framework are classified as: (1) resilience and resource efficiency; (2) sustainable and healthy diets; (3) circular economy; (4) profitability and efficiency; (5) sustainable supply chains and fair trade; and (6) transparency, traceability and trust. Notably, circular economy, as one of the emergent topics, plays a significant role in resource consumption reduction, waste elimination, economic development continuity and ensuring recycle, reuse, remanufacturing, and reclamation within a closed system [15]. In addition, life cycle assessment can be employed to support decision-making and holistically investigate environmental impacts of emerging technologies from "cradle to grave" within the sustainable food production system [16]. Despite the continuous progress, the key characteristics of sustainable food production are worth more attention in view of the increasingly complex food production challenges.

2.1. Innovation and adaptation

Compared with traditional food production, the sustainable food production embraces emerging technologies and practices to achieve continuous improvement [17,18]. The evolution of sustainable and ethical food production system is guided by this characteristic in order to fulfill the requirements of the current generation without compromising the capacity of future generations to satisfy their own needs. The characteristic of innovation and adaptation led to food production advance in numerous ways, such as soil loss minimization, fossil fuels usage reduction and genetic diversity maintenance [19,20].

2.2. Environmental stewardship

The second characteristic is environmental stewardship, where natural resources, such as water, land and energy, are utilized based on designed strategies to maintain and improve the long-term availability and stability [21,22]. It highlights the responsible and sustainable management of natural resources to maximize their long-term performance. It involves in minimizing environmental impact through greenhouse gas emissions reduction, soil erosion minimization and water conservation [23]. Strategies, such as renewable energy adoption, synthetic pesticides and fertilizers reduction and groundwater protection, can stimulate the establishment of sustainable food production [24].

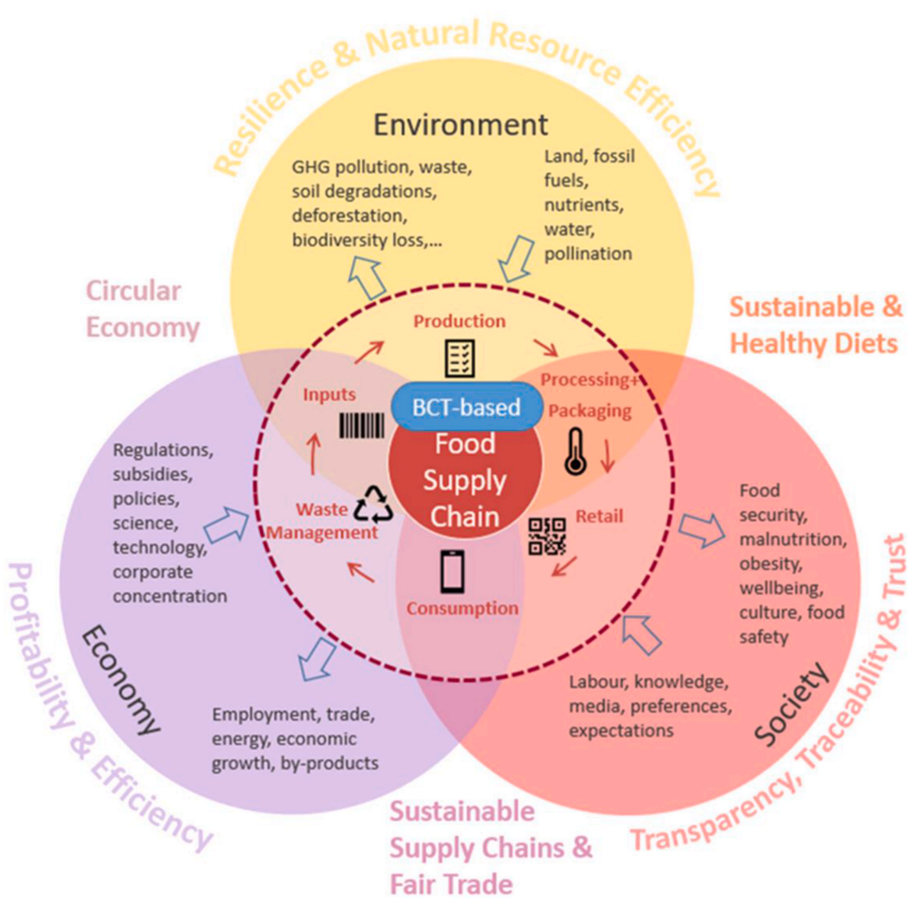

Fig. 1. Framework for the design of a sustainable food production system [14]. This figure was quoted and reused under the terms and conditions of the Creative Commons public use license.

2.3. Economic viability

The third characteristic is correlated with economic viability [24]. It emphasizes the economic sustainability of farming and food production, ensuring that producers can make a living while practicing sustainable methods. Farming practice implementation, such as diverse crops and practices, integrated pest management and conservation tillage etc., can help reduce risks associated with crop failure and market fluctuations [25]. In addition, processing raw agricultural products into value-added products can boost their market value while minimizing resource wastage. This can involve activities such as canning, packaging, and creating specialty foods [26].

2.4. Social responsibility

The last characteristic is associated with social responsibility. Sustainable food production emphasizes a fair and ethical labor practice, including fair wages, safe working conditions and equal labor rights [27]. In addition, biodiversity conservation and cultural preservation should be included to protect natural resources and cultural varieties. Furthermore, sustainable food production also calls for community engagement to support small-scale family farming, which directly benefits the local economy and reduces carbon footprint associated with transportation [20,28]. It was reported that transportation of fruits and vegetables could contribute up to half of the overall carbon emissions [29]. Local food production facilitates the cultivation of food within or near cities and shortens the food supply chain distance.

3. Green technologies for sustainable food production

Employment of green technologies in food production is significant for creating a long-term sustainable and environmentally friendly system via limiting resource consumption, enhancing productivity, and minimizing environmental side impact [19,30]. A list of green technologies ensuring the long-term sustainability of food production are illustrated in Table 1. Theoretically, it can be categorized into seven primary groups. Many of the ideas have been proposed and employed at the industrial level. However, it should be noted that most of the green technologies require profound and long-term worldwide collaboration [21,30]. The current review mainly investigates the role of urban agriculture, next-generation plant-based foods and food nanotechnology since these are the three most emerging and exciting applications.

Table 1
List of green technologies ensuring the long-term sustainability of food production.

Green technologies categories	Contents	Reference
Digital agriculture	Data integration Disease/pest early warning Robotics for precision farming Climate forecasts 3D printing Battery technologies Traceability technologies	[102–104]
Urban agriculture	Indoor agriculture Remote sensing Vertical agriculture Precision agriculture Hydroponic, aeroponic, aquaponic and soilless agriculture	[1,40,43]
Alternative food sources	Plant-based alternatives Cultured meat Alternative protein sources	[105,106]
Food nanotechnology	Nano-enabled sensors and probes Targeted delivery of agrochemicals Nano-enabled smart and/or active food packaging Water treatment or resource recovery	[107–110]
Gene technology	Whole-genome sequencing Genome editing Plant phenomics Synthetic biology Genome-wide selection Re-engineering photosynthesis Disease/pest resistance Novel nitrogen-fixing crops Genome selection	[111–113]
Intensification	Irrigation expansion Microalgae and cyanobacteria Seaweed	[52,114, 115]
Resource use efficiency	Resurrection plants Nitrogen use efficiency Next generation bioenergy solutions By-product utilization	[108,116, 117]

3.1. Urban agriculture

Urban agriculture is defined as a set of agricultural practices including indoor agriculture, remote sensing, vertical agriculture, hydroponic, aeroponic, aquaponic and soilless agriculture, precision agriculture etc. within the urban and peripheral area [31,32]. It is primarily classified into two segments: commercial (for profit) and gardening (non-profit), which includes various forms, productions, activities, actors, motivations, experiences and objectives [33].

3.1.1. Features of urban agriculture

Urban agriculture touches on the three pillars of sustainable food production: economics, society, and the environment [31]. From the economics perspective, it contributes to a household's income, offset food expenditures and create jobs. Urban agriculture was found to decrease the economic costs of waste stream by providing alternative means for compostable waste processing [34]. From the society perspective, urban agriculture has the feature of narrowing down nutrient and water cycles in urban areas and moderating agricultural production on less fertile soils [35]. Therefore, it has shown its capacity to synergistically enhance urban food resilience and counteract urban challenges and vulnerabilities in relation to food production, fostering community networks and food supply chains in the agri-food business. In addition, it can help to reduce the unequal distribution of environmental burdens through global teleconnections of urban food demands [34]. Finally, in terms of environmental benefits, urban agriculture can play an important role in urban microclimate regulation, urban stormwater regulation as well as reducing the energy embodied in food transportation [36]. Moreover, it can fulfill environmental functions to maximize urban biodiversity and degraded areas recovery, thereby enhancing the performance of environmental services. It has been reported that in highly urbanized developed nations, the interest in urban agriculture as a sustainable alternative to traditional agriculture was further emphasized due to its contribution as food sources in cities where food supply had been cut during COVID-19 pandemic in 2019 [37,38].

3.1.2. New technologies for urban agriculture

Due to the limited farming area, cities were deemed as incompatibility with traditional agriculture [39]. Advancement in new technologies significantly promotes the expansion of urban agriculture with contemporary vertical farming techniques, which paves a way for better management of space. Vertical farming is one of the urban agriculture techniques applied in indoor crop cultivation, where precise controls can be achieved over factors such as lighting, temperature, and nutrients [40]. Apart from the land and soil conservation, it essentially reduces freshwater consumption in a cultivation setting and eliminates the need for further sprawl of the conventional rural farms. An additional advantage of vertical farming is the absence of harmful pesticides and herbicides in the produced food. In a controlled indoor farming system, the potential for pest infestation is minimized, leading to enhanced overall sustainability [41,42].

In addition, biotechnological progress has evolved and contributed to the development of diverse crop varieties that thrive in specific conditions or urban settings [43]. Limited space and high operational costs are two major challenges in terms of urban agriculture. Developing plants with compact architecture and accelerated life cycle can be used to address these challenges. Kwon et al. identified the regulator in tomato stem length and employed one-step CRISPR–Cas9 genome editing technique to create a smaller plant size that can produce fruits within a reduced time frame [43]. Similarly, genome editing has been applied for the stress resistance, fruit yield and quality improvement and tomato cultivars customization for urban agriculture applications [44,45]. Kumar et al. demonstrated that the enhanced stem thickness with declined tiller number would be the key for the crop mainstreaming in the urban agriculture setting. Dynamic genetic elements such as microRNAs, transposable elements, *cis*-regulatory elements and epigenetic changes can be applied to reshape the urban agriculture evolvement [46].

3.2. Next-generation plant-based foods

Throughout the past few years, there is a growing trend in plant-based foods in replacing the traditional animal-sourced food products, such as meat, seafood, egg, and dairy products [47–49]. Different from the conventional plant-based foods (i.e. fruits, vegetables, cereals, and tofu), next-generation plant-based foods are the food products formulated using plant-based ingredients. At present, the next-generation plant-based foods are designed to mimic the desirable physicochemical properties, sensory, quality and functional attributes of the animal-sourced products [50]. The trend of plant-based diet was mainly driven by the consumer concerns on the animal welfare, sustainability and climate change since the production of traditional animal-sourced foods are associated with serious environmental footprints, such as deforestation, greenhouse gas emissions and water usage, etc. [51]. One potential solution for creating a more sustainable and efficient agricultural system involves employing compounds derived from biological sources. Among these products, microalgal and cyanobacterial biomass (or their extracts) have attracted increasing attention due to their potential sustainability and nutritional value [52]. Compared to traditional agriculture, microalgae and cyanobacterials can be cultivated in a controlled environment, requiring minimal land or freshwater, and can be used as a source of various bioactive compounds, such as proteins, polysaccharides, free fatty acids, phenolic compounds, etc.

3.2.1. Plant-based ingredients

The ingredients are considered to play a pivotal role in determining the physicochemical, sensory and gastrointestinal characteristics of plant-based foods [53]. Theoretically, they can be classified into three major categories: proteins, carbohydrates and lipids. The most widely-used proteins, carbohydrates and lipids found in plant-based foods are illustrated in Fig. 2 [54]. Among them, protein ingredients are typically recognized as the most significant due to their desirable functions in emulsifying, structuring, gelling and nutritional values [55]. Apart from the direct extraction from plants, it was reported that plant protein ingredients can also be generated through microbial fermentation, which is considered as an innovative and emerging field in cellular agriculture [56]. Undergoing reshaping processes (i.e., stretching, kneading, trimming, pressing, folding, extrusion, etc.), plant proteins can be used to mimic the texture of meat products [51,55]. However, when selecting a suitable plant-based protein to replace properties of animal protein, factors such as off-flavor, solubility, stability, purity and cost are of great importance. It should also be noted that the selected proteins are digestible and supply the entire range of essential amino acids [57].

Carbohydrate components utilized in plant-based formulation encompass diverse simple carbohydrates (such as sucrose and glucose)

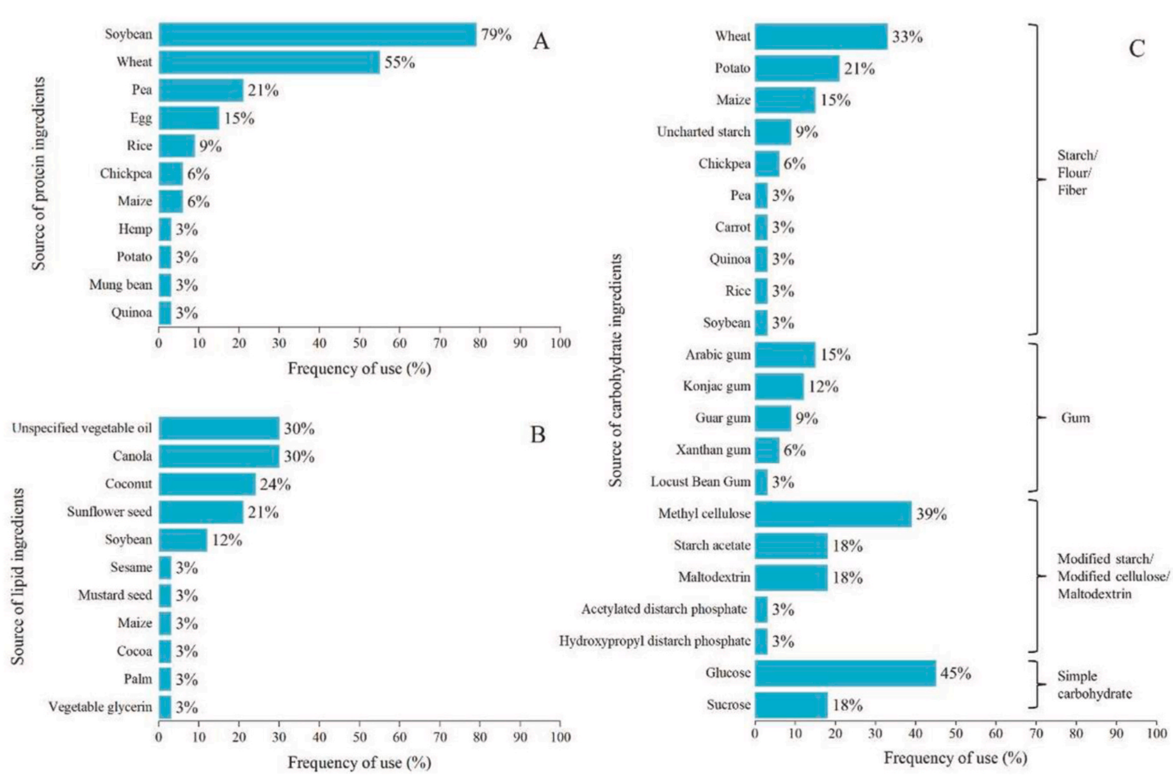

Fig. 2. The most commonly used sources of protein (A), lipid (B) and carbohydrate (C) ingredients in plant-based foods [54]. This figure was quoted and reused with copyright permission from Elsevier.

and polysaccharides (such as starch, fiber, gum and modified cellulose). They can provide fundamental properties (such as reducing power, hydration, gelation, dehydration and degradation) and functional behaviors (such as rheological behaviors, phase behaviors, thermos-responsive behaviors, flavoring and coloring behaviors) in the plant-based food matrices [54]. Therefore, carbohydrates have been reported as promising texture modifier, fat replacer, animal skin and tissue simulator in previous plan-based food studies [58–60]. Specifically, algal, seaweeds, apples, corns and various seeds are deemed as the common sources for plant-based carbohydrates (agar, alginate, carrageenan, pectin, xanthan and guar gum) [54]. Since the taste, texture and mouthfeel of meat are closely related to the physicochemical properties of its structural ingredients, it's essential to deliberately combine selected carbohydrates with other plant-based ingredients to enhance the overall sensory values of the final product. For instance, previous studies uncovered the possibilities of using β-cyclodextrin to mask the off flavor of soybean proteins [61,62].

Lipids can originate from an array of plant-derived sources, such as avocado, canola, coconut, corn, soybean and sunflower [63]. Compared with animal lipids, in addition to the environmental sustainability, the most favorable feature of plant-based lipids is lower saturated fat and cholesterol-free [50,64]. Nevertheless, a major difficulty in stimulating the physicochemical feature of animal lipids is that most plant-based lipids are composed of high level unsaturated fatty acids with relatively low melting points. Thereby, they are liquid-like under ambient temperature and fail to mimic the sensory attributes of animal lipids with high levels of saturated fatty acid [50]. It has been reported that melting point of unsaturated fats could be increased through hydrogenation, where hydrogen atoms can link and thus decrease the number of double bonds in the fatty acids [65,66]. However, more rigorous research and studies are needed to optimize crystallization/melting properties of plant-based lipids to supply the necessary mechanical characteristics, especially for the plant-based cheese formulation.

3.2.2. Plant-based food products

A wide range of characteristics, spanning from low viscosity fluids (milk analogs), high viscosity fluids (heavy cream or mayonnaise analogs) to viscoelastic solids (meat, fish, egg, or cheese analogs) could be found in the plant-based food sector [67]. It is critical to study the primary elements influencing the physical and chemical characteristics of plant-based food formulation since a wide spectrum of ingredients interacting with each other at molecular levels. McClements et al., summarized the physicochemical principles underlying the appearance, texture, stability, retention/release, oral processing and sensory attributes of plant-based foods [50]. They pointed out that biopolymers (i.e., proteins and polysaccharides) and colloids (i.e., protein aggregates, fat droplets, fat or ice crystals, starch granules and air bubbles) are the most important functional constituents in the plant-based foods. The nature of biopolymers and colloidal particles, i.e. size, composition, interfacial property, structure-functional property etc., ultimately established the physicochemical attributes of plant-based foods [68]. For example, the optical characteristics of plant-based milk can be improved by altering the concentration and size of the fat droplets in the colloidal system [69]. Polysaccharides within the plant-based milk system can play a role in thickening the aqueous phase to provide the desirable mouthfeel and textural attributes as a result of the extended conformations in water [70]. Quality attributes (such as long shelf-life and limited phase separation) can also be modulated by the addition of polysaccharides in the plant-based milk system.

In terms of the viscoelastic solid food products, such as plant-based cheese, rather than proteins, starches are the main functional ingredients due to their thickening, gelling and water-holding properties [71,72]. Upon heating in water, a gel may be formed as a result of swelling starch granules and increased viscosity. During cooling, water and additional ingredients can be confined within the three-dimensional structure established by the hydrogen bonded starch molecules. To further mimic the molecular interactions in dairy-based cheeses, multivalent cations can be introduced into heat-treated plant-based milks to fulfill a similar function to calcium in traditional milk [73]. Likewise, enzyme crosslinking is another strategy to solidify plant-based milks, leading to their transformation into a curd-like consistency [74,75].

3.3. Food nanotechnology

Nanotechnology encompasses the creation, design and utilization of materials featured by critical dimensions scales ranging from 1 to 100 nm but extended up to around 1000 nm occasionally [76]. It is considered that characteristics of nanomaterials diverge from those of standard materials owing to the reduced dimensions, increased specific surface areas and altered surface reactivities [77,78]. Hence, nanotechnology enables the development of novel materials endowed with new or enhanced functional properties, which can be leveraged to enhance the sustainable food production system.

3.3.1. Novel applications

Food nanotechnology provides opportunities to promote sustainable food production by developing nano-enabled sensors [79], enhancing pesticide and fertilizer performance [80] and remediation of contaminated soils [81]. Fig. 3 summarizes an overview of nanotechnology applications in sustainable food production.

Biosensors refer to a combined mechanism of receptor and transducer. They are utilized for detecting the physical and chemical characteristics of a target substance by utilizing biological or organic elements that identifies and detects specific biological analytes within the medium. Nano-enabled sensors are next generation of biosensors, which have been designed for the non-invasive detection of contaminants, glucose, small organic molecules, pigment additives and adulterants in Agri-Food system [79,82]. Other advantages are associated with low requirements on sample volumes and facile sample preparation steps when compared with traditional techniques. Advances in this area are expected to proceed since a wide spectrum of detection techniques (i.e. electronic, colorimetric, fluorometric or mass changes) can be provided via the nano-enabled sensor [78]. In addition, it has been reported that combination with microfluidic devices and cantilever arrays, multianalyte array sensors can be achieved to further amplify sensitivity and selectivity, empower the detection of target analytes (i.e. an antigen, target DNA, urea, glucose or a pesticide) at femtomolar level [83].

In terms of nanotechnologies for food pathogen control, the elevated surface to volume ratio of nanomaterials (such as silver, zinc oxide, and titanium dioxide nanoparticles) can improve the antimicrobial efficiency through enhanced reactive oxygen species production [84,85]. In addition, selective targeting to specific pathogens can be obtained through surfaces modification with antibodies [86]. Various antimicrobial nanocomposites have been developed to offer extended preservation during transportation and considerably prolong the shelf life of perishable food products [87]. Moreover, there is a burgeoning area of research focused on crafting nano-enhanced formulations for agrochemicals delivery [88]. The developed nano formulations improve the stability of active ingredients and facilitate precise and controlled release at the ideal operational concentration. Delivery of bio-fertilizer is one of the most significant applications in the agrochemical delivery sector [89–91]. They are fabricated as controllable and customizable fertilizers with developed functionality and efficiency. Nano-enhanced formulations are employed to optimize soil nutrient management, improve nutrient absorption efficiency, alleviates nutrient resource depletion, and thus promote a sustainable Agri-Food system cycle. In addition, progress have also been found in nano-enabled formulation for pheromones [92], plant growth regulators [93] and nucleic acid pesticides [94] delivery using natural and biodegradable fabricated nanocarrier.

Due to the features of the enormous specific surface area,

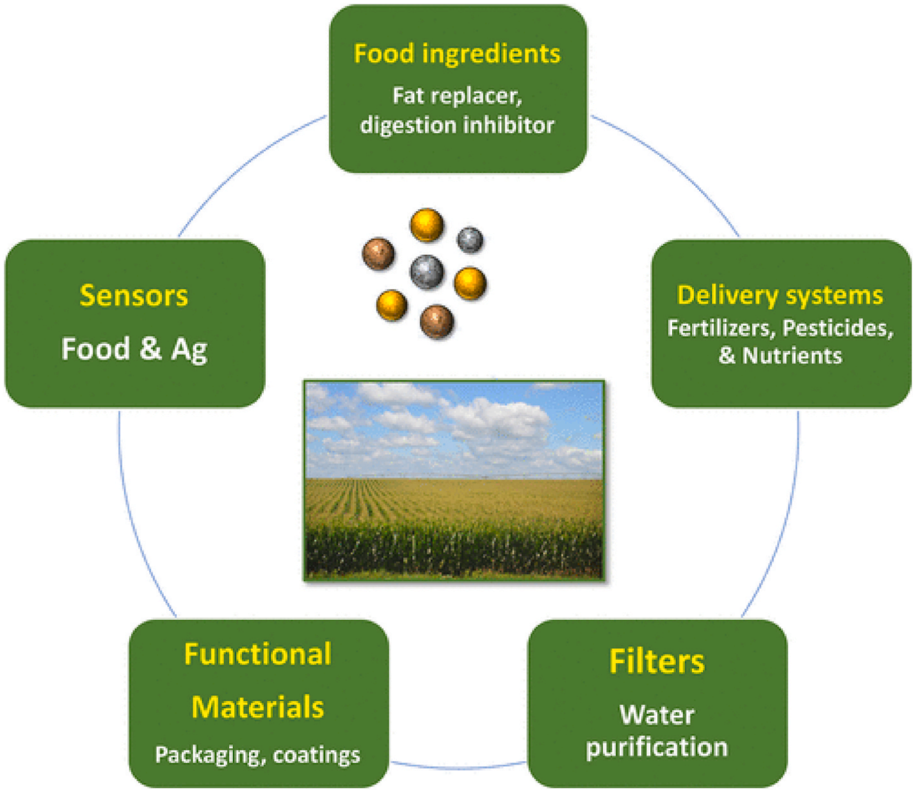

Fig. 3. Overview of nanotechnology applications in sustainable food production [77]. This figure was quoted and reused under the terms and conditions of the Creative Commons public use license.

nanotechnology-based materials have been employed in the area for contaminants elimination in polluted soils. The mechanisms are mainly involved in adsorption, redox reaction, precipitation and co-precipitation [81,95]. In addition, nano-remediation technologies have been proposed and discussed in recent studies [95,96]. It is considered that with the aid of nanoparticles, biodegradation could be amplified by hyperaccumulators and indigenous soil microbes, which ultimately augment the potential of nano-remediation technologies. The primary benefits include cost savings, accelerated cleanup timelines and full decomposition of certain pollutants [96]. However, it is worth noting that application of nanoparticles may alter the soil pH levels, which is correlated with the soil health, plant nutrient accessibility and microbial activity. A few recent review articles are available concerning the application of nanomaterials for soil remediation and point out that future work should take various factors (i.e., cost, treatment depth, soil characteristics and subsequent toxicological effects) into account to select the best method for soil decontamination and remediation [97–99].

3.3.2. Barriers and overlapping challenges

Nanotechnology-enabled food production system is at the preliminary phase of growth, however, it is promising in improving the efficiency of Agri-Food system and reducing the environment pollution [77]. As discussed above, one of the main reasons of utilizing nanoparticles in the food industry is correlated with small particle size, allowing them to breach biological barriers more efficiently compared to larger ones. These traits are advantageous for acquiring new or enhanced qualities in food products, however, unforeseen adverse effects demand further research and investigation. Likewise, some other scientific challenges in engineering and technoeconomic aspects include: (1) competition with traditional formulations in terms of performance, cost, scalable manufacturing technology and potential commercialization prospects [78]; (2) safety and public perception considerations regarding nanomaterials utilization in water systems [100]; (3) life-cycle issues such as biodegradability and recyclability of original materials, manufacturing of nano-enabled structures at large scales as well as the potential hazards of engineered nano-sized materials in the ecosystem [101]; (4) application in complex matrices/systems and unleash its potential as selective, sensitive, robust and durable nanomaterial for use in highly complex soil, water, food or waste matrices; (5) the long-term efficiency of nanotechnology-infused solutions must be evaluated systematically [93]; (6) implementation of clear policies and public awareness of new technologies to facilitate its continued advancement.

4. Conclusions

The relationships among economy, social and environment have become increasingly vital. Sustainable food production offers state-of-the-art techniques to guarantees the long-term prosperity in the Agri-Food sector. Characteristics, such as innovation, adaptation, environmental stewardship, economic viability and social responsibility, are the essences of the modern sustainable food production. Meanwhile, it is noteworthy to acknowledge that elevating productivity in a sustainable manner demands greater emphasis on innovative research, product development and concerning education. In order to achieve continuous success, collaborative efforts at regional, national and international levels are needed to unleash the potential of Agri-Food system.

A variety of technologies as outlined above can be employed to facilitate sustainable food production while securing sufficient food supplies to satisfy the ever-growing global population. Commercial urban agriculture, establishing itself as a crucial activity for the local production of nutritionally adequate foods, reduces the costs in the food supply and distribution as well as improves the access to food by the local market. Nonetheless, the hidden complexity underneath the urban food supplies and the teleconnections of environmental externalities should be considered in urban land-use planning. Importantly, the nature of agriculture in one specific city should be highlighted by the distinctive traits of that city due to its significant contributions to the sustainable city discourse. Next-generation plant-based foods are compositionally and structurally complex food matrixes and formulated to mimic certain physicochemical and functional properties. Thus, it is crucial to develop a more comprehensive study of how the composition and structure of these foods interrelate with their cookability, appearance, stability, texture, mouthfeel, flavor and gastrointestinal fate. In addition, holistic research is required to develop food products with enhanced nutritional values and commercial viabilities. In particular, it is of great significance to develop plant-based foods fortified with bioavailable forms of nutrients that might be deficient in a plant-based diet, such as iron, vitamin B12, vitamin D, omega-3 fatty acids, calcium and zinc. Inspired by nanotechnology, the sustainable food production achieved notable breakthroughs in the development of nano-enabled sensors and probes, food pathogen control and agrochemical delivery etc. Key concerns for the upcoming decades involve the potential adverse impacts of nano-enabled particles on both ecological systems and human health. For example, increased absorption of specific compounds may result in bioaccumulation and trigger detrimental effects. Therefore, deeper understanding of nano-enabled materials as well as their circulation and accumulation throughout the whole ecological system are demanded to ensure a safe design of sustainable Agri-Food system.

CRediT authorship contribution statement

Bai Qu: Writing – review & editing, Writing – original draft, Conceptualization. **Zhenlei Xiao:** Writing – review & editing, Writing – original draft, Conceptualization. **Abhinav Upadhyay:** Writing – review & editing, Writing – original draft. **Yangchao Luo:** Writing – review & editing, Writing – original draft, Supervision, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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