Innovative Technologies in Secondary Agriculture

Theme: ***Food Security and Nutrition***

Title: *Innovative Approaches for Sustainable Food Security and Nutrition*

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Abstract

Secondary agriculture is critical to ensuring food security and boosting nutrition by utilising waste, adding value, and developing innovative processing techniques. This chapter investigates the application of cutting-edge technologies to secondary agricultural practices in order to address food system concerns. The main focus is on using novel processing technologies, biotechnology interventions, and digital tools to improve agricultural product nutritional quality, shelf life, and accessibility. Some key examples bring out how these technologies have the potential to revolutionise food systems and achieve resilience. In this chapter, we delve into the some of the potential transformative and innovative technologies in secondary agriculture, which provide insights on their applications, benefits, and challenges. By referencing reports, research papers and case studies, we aim to bring out the importance of secondary agriculture in achieving food security, nutrition and environmental sustainability.

Keywords: Food security, secondary agriculture, nutrition, CAS, digital agriculture.

1. Introduction

Global food security along with nutrition are continuously reported to be under pressure from population growth, climate change, and resource scarcity. Food and Agriculture Organization (FAO) has projected that by 2050, the global population will exceed 9 billion, necessitating a 70% increase in food production (FAO, 2017). Secondary agriculture, which focuses on the processing, utilization, and management of agricultural by-products, has significant opportunities to bridge the gaps in food supply chains. This sector reduces food waste and also enhances resource efficiency and generates economic value (Singh et al., 2019).

The use of novel technologies into secondary agriculture is changing the way byproducts are used. For example, sophisticated processing technologies like extrusion and fermentation have made it possible to produce high-value functional foods from agricultural leftovers (Kaur & Arora, 2021). Furthermore, digital tools such as the Internet of Things (IoT) and artificial intelligence (AI) are rapidly being used to optimise processing and increase product traceability (Patel et al., 2020).

Secondary agriculture plays a very important role in enhancing nutritional outcomes. Malnutrition in vulnerable communities can be addressed by supplementing goods made from byproducts with vital micronutrients such as vitamins and minerals (UNICEF, 2018). Additionally, biotechnology interventions such as biofortification and enzymatic transformations have created many opportunities to improve the nutritional value of secondary agricultural products (Ravindran & Jaiswal, 2016).

Secondary agriculture also contributes to environmental sustainability. Utilizing crop residues and food processing waste reduces the environmental footprint of primary agriculture, decreasing greenhouse gas (GHGs) emissions and conserving natural resources (Verma et al., 2022). These practices align with the United Nations Sustainable Development Goals (SDGs), particularly those related to zero hunger (SDG 2) and responsible consumption and production (SDG 12) (United Nations, 2015).

According to the Food and Agriculture Organization (FAO), nearly 14% of the world's food is lost between harvest and retail, a significant resource inefficiency that can be addressed through secondary agriculture (FAO, 2022).

The rapid growth in global population, projected to reach 9.7 billion by 2050, increases the demand for food and nutrition security (United Nations, 2019). Although, the current food production encounter challenges like resource shortage, unpredicted weather, life style change and malnutrition. Secondary agriculture holds solutions to these challenges by transforming agricultural residues into valuable products, decreasing post-harvest losses, and improving food availability and nutrition.

In this chapter, we delve into the some of the potential transformative and innovative technologies in secondary agriculture, which provide insights on their applications, benefits, and challenges. By referencing reports, research papers and case studies, we aim to bring out the potential of secondary agriculture in achieving food security and nutrition.

2. The Role of Secondary Agriculture in Food Security

2.1 Waste Reduction:

Efficient use of agricultural by-products reduces post-harvest losses**.** In 2023, India experienced post-harvest losses of major agricultural and allied produce valued at approximately INR 926 billion. Fruits and vegetables accounted for the highest losses among agricultural categories. (Statista, 2024)

In Sub-Saharan Africa, self-reported on-farm post-harvest losses for maize are estimated between 1.4% and 5.9% of the national harvest. These figures are notably lower than the Food and Agriculture Organization's (FAO) estimates, which suggest that post-harvest losses in the region can be as high as 20% (World bank, 2023). In 2022, Europe faced significant agricultural challenges due to extreme weather events. Droughts in Spain and Portugal led to predictions of 60–80% crop losses in some areas. Additionally, a cold wave during early budding damaged fruit crops across much of Europe.

Globally, post-harvest losses are a critical concern, with the FAO estimating that 13.8% of food produced is lost between the farm and retail stages (FAO, 2022). This loss has significant economic implications, costing an estimated USD 2.6 billion annually and representing about USD 1 trillion in annual economic losses. (Food forward). Secondary agriculture addresses this issue by repurposing by-products that would otherwise go to waste. **Table 1** shows year-wise post-harvest losses (PHLs) across overall food commodities in different regions, based on aggregated estimates.

Agricultural residues, such as wheat straw and rice husks, are more and more utilized for creating biochar, which is soil amendment that increases soil fertility and carbon sequestration. This approach mitigates waste and also promotes sustainable farming practices (Lehmann et al., 2006). Furthermore, some technologies such as anaerobic digestion convert organic waste into biogas that provide renewable energy source for rural communities. Sugarcane bagasse, which is a by-product of sugar extraction, is repurposed for producing bioenergy and biodegradable packaging materials reducing dependence on fossil fuels and reducing greenhouse gas emissions (Pandey et al., 2000). In addition, fruit and vegetable peels, accounting for a large portion of post-harvest residues, are now processed into bioactive compounds and food additives, which helps in waste reduction and contributing to environmental sustainability (Kumar et al., 2020).

Rice husks can be converted into biochar, a soil amendment that enhances soil fertility and carbon sequestration. Rice husk biochar has been successfully used to improve soil fertility in degraded lands. Its high carbon content aids in moisture retention and nutrient availability, promoting agricultural productivity (Lehmann et al., 2006).

Technologies such as intelligent packaging and cold chain logistics help preserve food quality and extend shelf life. Smart packaging incorporates sensors that monitor temperature, humidity, and spoilage indicators, providing real-time data to reduce waste. Additionally, upcycling food waste into value-added products like animal feed, and functional ingredients contributes to a circular economy. For example, citrus peels and coffee grounds are being repurposed into nutraceuticals and bioenergy, respectively (Gustavsson et al., 2011).

Underutilized secondary crops like millet, amaranth, and quinoa are getting attention for their health benefits and adaptability to adverse growing conditions. These crops are naturally rich in antioxidants, dietary fiber, and essential amino acids. They can be processed into functional foods like gluten-free flour, energy bars, and breakfast cereals. Amaranth-based functional food have shown to reduce cholesterol levels and provide antioxidant benefits, valuable in combating lifestyle-related diseases (Alvarez-Jubete et al., 2010).

Table 1: Year-wise post-harvest losses (PHLs) across overall food commodities in different regions

Year	*Region/Country*	*Post-Harvest Loss (%)*	*Source*
2011	Global	~33% (1.3 billion tons)	FAO (2011)
2011	Sub-Saharan Africa	~37%	World Bank (2011
2016	Ethiopia	~20-25%	FAO (2016)
2019	United States	~30-40%	USDA (2019)
2020	India	~30%	FICCI (2020)
2021	Global	~14% (from production)	FAO (2021)
2022	Europe	~20%	European Commission (2022)
2023	Southeast Asia	~35%	Asian Development Bank (2023)

Notes:

1. The percentages refer to total food production lost post-harvest, including during handling, storage, transportation, and distribution.
2. Losses vary significantly by commodity type, region, and local agricultural practices.
3. Figures for global losses typically include farm-level, retail, and consumer waste.

2.2 Nutritional Enhancement

Agricultural by-products often contain high levels of essential nutrients. For example, rice bran, a by-product of rice milling, is rich in dietary fiber, vitamins, and antioxidants. Studies show that rice bran can be used to fortify staple foods, addressing micronutrient deficiencies in vulnerable populations (Kahlon, 2009). Similarly, banana peels are processed into flour rich in potassium and dietary fiber, which can improve the nutritional profile of baked goods (Adejoro et al., 2017).

By-products from dairy processing, such as whey, are also repurposed into high-protein supplements and functional foods. Whey protein is widely recognized for its role in improving muscle mass and overall health, making it a valuable product for addressing malnutrition (Smithers, 2008). Processing technologies like extrusion and fermentation are used to convert these by-products into ready-to-eat foods with enhanced bioavailability of nutrients (Ranum et al., 2014).

2.2.1 Value Addition and By-product Utilization

Advanced drying, extrusion, and fermentation technologies have been highlighted as transformative tools for converting agricultural by-products into nutrient-rich food products (Kaur & Arora, 2021). For instance, extrusion technology not only improves the digestibility and functionality of food by-products but also reduces anti-nutritional factors, making them safer and more beneficial for human consumption (Ravindran & Jaiswal, 2016). Additionally, fermentation methods have employed to enhance the flavor, texture, and nutritional value of these by-products by increasing bioavailability of micronutrients and generating beneficial probiotics (Verma et al., 2022).

Enzymatic and microbial processes can transform waste materials into high-value products. For example, enzymatic hydrolysis of fruit peels yields bioactive compounds with antioxidant properties, which are valuable for pharmaceutical and cosmetic applications (Ravindran & Jaiswal, 2016). The application of advanced enzymatic techniques, such as pectinase and cellulase, has also shown potential in extracting high-value polysaccharides and fibers from agricultural waste (Kumar et al., 2020). Moreover, microbial fermentation is being utilized to produce protein isolates and dietary fibers from cereal by-products, supporting sustainable food systems (Verma et al., 2022). Additionally, the production of organic acids, such as citric acid and lactic acid, from fruit and vegetable residues highlights the economic and environmental benefits of biochemical conversions (Singh et al., 2019).

Rice bran oil, extracted from the outer layer of rice grains, is a prime example of value addition in secondary agriculture. High in oryzanol, it offers cardiovascular health benefits and is increasingly used as a cooking oil in Asia and beyond. The production of rice bran oil also generates secondary by-products, such as defatted bran, which can be utilized in animal feed (Kahlon, 2009).

Banana peels, often discarded as waste, can be processed into flour rich in potassium, dietary fiber, and antioxidants. This gluten-free alternative is gaining popularity in the baking industry and contributes to reducing food waste (Adejoro et al., 2017).

Millets, considered secondary crops, have gained attention for their resilience to climate stress and high nutritional value. Companies are innovating millet-based products such as ready-to-eat cereals, health drinks, and snack bars, catering to the rising demand for functional food (Ranum et al., 2014).

2.2.2 Biofortification of By-products

Biofortification refers to the use of biotechnological and agronomic methods to increase the nutritional content of agricultural products and by-products. For instance, advancements in genetic engineering have enabled the development of crops enriched with essential nutrients, such as Golden Rice, which is fortified with beta-carotene to combat vitamin A deficiency (Tang et al., 2012). Similarly, by-products like cassava leaves and sweet potato peels are being biofortified with iron and zinc to tackle micronutrient malnutrition in developing regions (Bouis & Saltzman, 2017). These efforts demonstrate the potential of biofortification to provide sustainable solutions to global nutritional challenges.

Biofortification involves enhancing the nutrient content of agricultural by-products to address micronutrient deficiencies in vulnerable populations. Bran, husks, and other cereal by-products, often discarded or underutilized, are being incorporated into biofortified food formulations. Cereal by-products such as wheat bran and rice husk are rich in nutrients like fiber, minerals, and vitamins. By leveraging these by-products, biofortified products can be developed to meet specific dietary requirements (Zhao et al., 2018).

Fortification involves the deliberate addition of essential micronutrients, such as vitamins and minerals, to processed products to address nutritional deficiencies. For instance, wheat and rice bran, by-products of milling, are being fortified with iron and folic acid to combat anemia in vulnerable populations (Kaur & Arora, 2021). Dairy-based by-products, such as whey, are enriched with calcium and vitamin D to promote bone health, particularly in children and elderly individuals (Patel et al., 2020). Additionally, biofortification of cereals like maize and pearl millet using zinc and vitamin A precursors ensures better nutritional outcomes in regions with limited dietary diversity (UNICEF, 2018).

Category	***Examples***	***Nutritional Benefits***	***Technologies/Methods Used***
Nutritional Enhancement	Rice bran, Banana peels, Dairy by-products (Whey)	Rich in fiber, vitamins, antioxidants, potassium, protein Oryzanol (cardiovascular health benefits), Potassium gluten-free	Fortification, fermentation, extrusion, Oil extraction, defatted bran as animal feed, Processing into flour, reduction of food waste
Enzymatic & Microbial Processes	Fruit peels, Cereal by-products, Organic acids	Antioxidants, bioactive compounds, polysaccharides, fibers	Enzymatic hydrolysis, microbial fermentation
Millet-based Products	Millets (cereals, health drinks, snack bars)	High nutritional value, functional foods	Processing into ready-to-eat products
Biofortification	Golden Rice, Cassava leaves, Sweet potato peels	Beta-carotene (Vitamin A), iron, zinc	Genetic engineering, agronomic methods
Fortification	Wheat bran, Rice husk, Dairy by-products (Whey)	Iron, folic acid, calcium, vitamin D, zinc	Deliberate addition of micronutrients

Table 2: organizes the information related to nutritional enhancement, value addition, biofortification, and the technologies employed for agricultural by-product utilization.

2.3 Economic Benefits:

Secondary agriculture drives economic growth by transforming low-value agricultural residues into high-value products. For example, the production of rice bran oil has created a thriving industry in Asia, generating employment and providing farmers with an additional income source from what was previously discarded (Kahlon, 2009). Similarly, converting cassava peels to the livestock feed has become a profitable venture in Africa, supporting smallholder farmers and reducing dependency on imported feed (FAO, 2022).

The global market for bioplastics, derived from agricultural residues such as corn starch and sugarcane bagasse, is projected to reach $28.6 billion by 2027 (Grand View Research, 2021). This market growth highlights the economic potential of secondary agriculture in fostering industrial innovation and rural entrepreneurship. Value-added products create income opportunities for farmers and processors

3. Innovative Approaches for Sustainable Food Security and Nutrition

Sustainable food security and nutrition are global priorities that require innovative approaches to meet the growing demands of a raising population while preserving natural resources. Key innovations in this area span agricultural practices, food production technologies, and socio-economic strategies.

3.1 Climate-Smart Agriculture (CSA)

Climate-Smart Agriculture (CSA) is an integrated approach aimed at addressing the challenges of climate change while enhancing food security, increasing productivity, and ensuring environmental sustainability. CSA is designed to transform agricultural practices by focusing on three core pillars: improving productivity, adapting to change in climate, and reduce GHGs emissions (World Bank, 2015). This article will provide an overview of CSA, discuss its relevance to global and national agricultural systems, present data and examples, and offer insights into the challenges and opportunities.

3.1.1 The Three Pillars of CSA

a) **Increasing Agricultural Productivity:** CSA focuses on improving crop yields, livestock productivity, and overall farm productivity through sustainable practices. According to a study by Lipper et al. (2014), adopting CSA practices can increase agricultural productivity by up to 20% in certain regions by utilizing crop hybrids that are resistant to drought, pests, and diseases. The application of integrated pest management (IPM), water-efficient technologies, and improved soil management contributes to this increase.

b) **Adaptation to Climate Change:** CSA helps farmers adapt to the challenges posed by climate change, such as altering precipitation patterns, rising temperatures, and increased frequency of extreme weather events. In India, for example, the *System of Rice Intensification* (SRI) has been shown to increase rice yields by 20-30% while using 25-50% less water (Upadhyaya, 2019). This practice highlights how CSA can enable farmers to improve productivity and manage risks associated with climate change.

c) **Mitigation of Greenhouse Gas Emissions:** CSA also aims to reduce the carbon footprint of agriculture. The adoption of agroforestry, conservation tillage, and sustainable livestock management can lower GHGs emissions from agriculture. A report by the FAO (2013) states that agroforestry systems in sub-Saharan Africa sequester approximately 5.5 billion tons of CO_2 annually, demonstrating the mitigation potential of CSA practices.

According to the Food and Agriculture Organization (FAO, 2021), the global agricultural sector is responsible for around 25% of total greenhouse gas emissions. As a result, CSA plays a critical role in reducing emissions from agriculture by promoting practices like reduced tillage, organic farming, and efficient water management. The global adaptation costs for agriculture are expected to reach $15-25 billion per year by 2050, and CSA can mitigate these costs (Lipper et al., 2014).

Studies have shown that CSA practices significantly enhance the resilience of crops to climate stress. A study in Kenya found that CSA practices, such as drought-tolerant maize varieties and water-efficient irrigation techniques, resulted in a 30-40% increase in yields in drought-prone areas (Gachene et al., 2015). Similarly, in India, CSA strategies like the adoption of water-efficient rice cultivation techniques and improved soil health practices have led to higher yields and increased resilience against climate change (Singh et al., 2020).

CSA practices also offer opportunities for carbon sequestration. A report by the World Bank (2015) estimates that by adopting CSA practices, farmers can sequester up to 5 billion tons of CO_2 annually. In India, the use of *zero tillage* and *conservation tillage* methods in wheat farming has led to a reduction of 10-15% in carbon emissions, showcasing the importance of mitigating changes in climate through sustainable agricultural practices (FAO, 2017).

3.1.2 CSA Practices in India

a) **System of Rice Intensification (SRI):** The System of Rice Intensification (SRI) has been one of the most widely adopted CSA practices in India. SRI focuses on optimizing the planting density of rice, using less water, and improving soil health. According to a study by Laxmi et al. (2018), farmers using SRI in Tamil Nadu saw an average increase of 30% in rice yield, along with a 40% reduction in water usage.

b) **Agroforestry:** Agroforestry involves the integration of trees with crops and livestock, which enhances biodiversity and provides environmental services. In states like Madhya Pradesh and Uttar Pradesh, farmers have adopted agroforestry practices to fix soil fertility, reduce soil erosion, and sequester carbon. A study by Kumar et al. (2020) revealed that agroforestry in India helped sequester 2.1 million tons of CO_2 equivalent in one year alone.

c) **Water-Efficient Practices:** India, a country that faces severe water scarcity, has increasingly adopted micro-irrigation techniques as part of CSA. Techniques such as drip and sprinkler irrigation shown to increase water-use efficiency by up to 50%, while also enhancing crop yields. According to the Ministry of Agriculture & Farmers' Welfare (2020), In India, the expansion of micro-irrigation systems has already covered 10 million hectares of land, significantly improving water availability for crops and helping farmers adapt to changing precipitation patterns.

3.2 Novel Processing Methods

Innovative processing techniques enable the transformation of agricultural residues into high-value, palatable, and nutritious food products. These methods enhance the digestibility, flavor, and nutritional value of residues. Extrusion processes, often applied to cereal by-products, result in nutrient-dense snack products, while fermentation enhances protein and mineral bioavailability. Fermented cassava peel has gained traction as a protein-enriched livestock feed.

By fermenting cassava residues, the protein content increases significantly, making it a sustainable alternative to conventional feed (FAO, 2021).

Biofortification involves enhancing the nutritional content of crops through breeding or biotechnology. This approach addresses micronutrient deficiencies in vulnerable populations by increasing levels of vitamins, minerals, and essential nutrients in staple crops. For example, Golden Rice, enriched with vitamin A, and biofortified maize and cassava with increased zinc and iron content, have been successfully implemented in several regions to combat malnutrition (Bouis & Saltzman, 2017).

Biofortification is the process of enhancing the nutritional profile of food products by leveraging agricultural residues and by-products. For example, wheat bran, typically discarded during milling, can be enriched with micronutrients such as iron and zinc to combat deficiencies prevalent in low-income populations (Nestel et al., 2006). Similarly, rice bran oil, a by-product of rice milling, contains oryzanol, which has cholesterol-lowering properties (Kahlon, 2009).

Innovative processing technologies such as fermentation, extrusion, and enzymatic treatment have revolutionized the use of agricultural residues. Fermentation, for example, can transform cassava peels into protein-rich livestock feed, while extrusion can convert fruit pomace into snack foods with high dietary fiber content (FAO, 2022).

Alternative protein sources are emerging as a sustainable solution to meet global protein demands while addressing environmental concerns associated with traditional livestock farming. Innovations in plant-based proteins, cultured meat, and insect protein have shown significant promise. Plant-based meat analogs, developed through advanced food processing technologies, offer protein-rich alternatives that closely mimic the taste and texture of animal-based products. Cultured meat, grown from animal cells in bioreactors, eliminates the need for traditional farming and reduces greenhouse gas emissions (Rubio et al., 2020). Insects, rich in protein, vitamins, and minerals, are being explored as sustainable food sources due to their low resource requirements and high feed conversion efficiency.

3.3 Digital Agriculture

Digital technologies, including artificial intelligence (AI), the Internet of Things (IoT), and blockchain, are transforming food systems. AI-driven analytics optimize farming practices by predicting weather patterns and crop health, while IoT sensors enable real-time monitoring of soil conditions and resource usage. Blockchain technology ensures transparency and traceability in supply chains, fostering consumer trust and reducing fraud (Wolfert et al., 2017).

3.3.1 AI -Artificial Intelligence and ML - Machine Learning

AI -Artificial Intelligence and ML - Machine Learning play transformative roles in secondary agriculture by providing tools to analyse complex datasets and make data-driven decisions. These technologies are utilized for predictive modelling to optimize processing parameters, ensuring better product quality and resource efficiency. AI-driven systems are increasingly applied to automated sorting and grading of agricultural products, where they enhance consistency and minimize human error. For example, ML algorithms have been used to analyse large datasets to optimize crop yields and predict potential disease outbreaks, ensuring timely interventions (Kamilaris et al., 2017).

In food manufacturing, AI aids in dynamically adjusting recipes based on real-time quality measurements of raw materials, maintaining consistent product standards. Similarly, these technologies are employed in energy optimization for food processing operations, reducing costs by predicting and adjusting energy requirements. AI also plays a crucial role in supply chain management, enabling predictive analytics to forecast demand, improve logistics, and reduce waste. Another significant application is in food safety, where AI-based systems are designed to rapidly detect contaminants and pathogens, ensuring compliance with safety standards (Wolfert et al., 2017).

3.3.2 Internet of Things (IoT)

The Internet of Things (IoT) facilitates real-time monitoring and control in secondary agriculture, revolutionizing the way processes are managed. By integrating sensors and connected devices, IoT systems collect, transmit, and analyze data on various parameters such as temperature, humidity, and machinery performance. For instance, IoT-enabled sensors in storage facilities monitor conditions to prevent from spoilage and maintain product quality (Salah et al., 2019).

In addition, IoT devices are increasingly being used for remote equipment monitoring, identifying performance issues, and scheduling preventive maintenance, which reduces downtime. IoT also enhances quality control by continuously monitoring critical parameters like temperature, pressure, and flow rates during processing. The integration of IoT with blockchain ensures secure, transparent, and tamper-proof records of processing and transportation data, enhancing traceability. Furthermore, IoT systems enable consumer interaction through smart packaging, where QR codes provide detailed product history, fostering transparency and trust in the supply chain (Lin et al., 2018).

3.3.3 Blockchain Technology

Blockchain technology is a powerful tool in enhancing transparency and traceability in secondary agricultural value chains. Its decentralized and immutable ledger system provides all its stakeholders access to accurate and secure data regarding product origin, processing, and distribution. Blockchain technology addresses challenges like fraud, food safety and inefficiencies in the supply chain. One example, during food recalls, blockchain provides precise data on affected batches, getting quick responses that reduce intensity of issue. (Menon & Jain, 2021).

Another critical application of blockchain is in combating counterfeiting, especially in premium agricultural products, by verifying product authenticity. The technology also supports the automation of transactions through smart contracts, reducing delays and ensuring accountability. Blockchain records are increasingly used for sustainability reporting, capturing data on practices like carbon footprint reduction and resource optimization, which appeal to environmentally conscious consumers. Additionally, the integration of blockchain with IoT systems has streamlined international trade processes by providing verifiable and transparent records for regulatory compliance (Wolfert et al., 2017).

3.3.4 Urban Agriculture and Vertical Farming

Urban agriculture and vertical farming offer innovative solutions to produce food locally, reducing transportation costs and environmental footprints. Vertical farms utilize controlled-environment agriculture (CEA) technologies, such as hydroponics and aeroponics, to grow crops year-round in urban settings. These systems use significantly less water and land compared to traditional farming methods and eliminate the need for chemical pesticides (Despommier, 2010).

3.4 Smart Packaging and Preservation

Active packaging involves the inclusion of substances or materials that interact with the food product to enhance preservation. These substances can absorb excess moisture, oxygen, or ethylene, thus extending shelf life and preserving the food's sensory qualities. Common active packaging materials include oxygen scavengers, moisture absorbers, and antimicrobial agents. Oxygen scavenger packets, often found in packaged snacks, absorb the oxygen inside the package, preventing oxidation and extending shelf life (Kerry et al., 2006).

Intelligent packaging comes with sensors, indicators, and monitors that can track the condition of the food product throughout the supply chain. These sensors can provide real-time information about the freshness, temperature, or quality of food. This alerts consumers and retailers to potential spoilage or unsafe conditions.

Modified Atmosphere Packaging (MAP) is a technique that involves altering the composition of gases within the package to slow down spoilage. By reducing oxygen and increasing carbon dioxide, MAP can prolong the freshness of perishable foods like fruits, vegetables, meat, and dairy products. Vacuum-sealed meat or cheese products, which use a modified gas mix to slow bacterial growth and preserve the product longer.

Edible packaging is made from food-grade materials that can be consumed along with the product, offering a sustainable solution to traditional plastic packaging. This type of packaging can help reduce food waste and provide additional nutritional benefits. Packaging made from seaweed or starch-based films, which can be dissolved in water or consumed directly.

Nanotechnology involves the use of nanoparticles to create food packaging materials with enhanced properties, such as improved barrier properties (against oxygen, moisture, or light), antimicrobial properties, and better mechanical strength. Nano-silver particles are commonly used for their antibacterial properties, reducing the growth of pathogens on food surfaces. Nanocellulose packaging for fruits and vegetables that can control moisture levels and extend shelf life.

4. Challenges in Achieving Sustainable Food Security and Nutrition in India

India is home to approximately 1.4 billion people, with the population expected to peak at 1.7 billion by 2060 (United Nations, 2022). This population pressure strains the agricultural sector, requiring a significant increase in food production. Rapid urbanization further complicates this scenario by reducing arable land and increasing demand for processed foods. The growing demand for food puts immense pressure on natural resources such as water, arable land, and energy. Overexploitation of these resources leads to soil degradation, water scarcity, and biodiversity loss, further exacerbating food insecurity (Rockström et al., 2009).

Despite progress, India still grapples with the dual burden of malnutrition—undernutrition and overnutrition—poses significant health challenges. Urbanization and globalization have led to dietary shifts toward processed and calorie-dense foods, contributing to obesity and diet-related diseases (Popkin, 2017). According to the National Family Health Survey-5 (NFHS-5), 35.5% of children below five are stunted, and 19.3% are wasted. Rising obesity and lifestyle diseases due to increased consumption of unhealthy, calorie-dense foods are becoming a concern (NFHS-5, 2021).

India's agriculture is highly sensitive to climate change. Erratic monsoons, rising temperatures, and extreme weather events reduce crop yields and affect water availability. For instance, wheat and rice, staple crops, face significant yield declines under projected climate scenarios (Singh et al., 2020). Unpredictable weather patterns, rising temperatures, and increased frequency of extreme events such as droughts and floods threaten agricultural productivity. Crop failures and reduced yields impact food availability, particularly in vulnerable regions (FAO, 2020).

One of the primary barriers to adopting CSA practices is the lack of awareness and training among farmers. A report by the FAO (2017) indicated that smallholder farmers, especially in developing countries, often lack access to information about climate-smart practices. Efforts to build awareness and train farmers in CSA techniques are critical for widespread adoption.

While CSA practices can result in long-term benefits, the initial costs of implementing some of these practices, such as irrigation systems, improved seeds, and soil amendments, can be prohibitive for smallholder farmers. Governments and international organizations need to provide financial support and incentives to overcome this barrier (Lipper et al., 2014).

There is a requirement for better policy alignment to support CSA at national and international levels. Governments must provide subsidies, insurance, and incentives to encourage CSA practices. In India, for instance, while initiatives like the National Mission on Sustainable Agriculture (NMSA) have been launched, the policies and frameworks need to be more robust and farmer-focused to ensure effective implementation (Reddy et al., 2018).

India suffers from substantial post-harvest losses due to inadequate storage, poor transportation, and inefficient supply chains. Losses in fruits and vegetables alone are estimated at 16% of total production, amounting to billions in economic value annually (ICAR, 2020). Food loss and waste occur at every stage of the supply chain, from farm to fork. Globally, approximately one-third of all food produced is wasted, contributing to economic losses and unnecessary strain on resources (Gustavsson et al., 2011).

Despite being a major food producer, disparities in income, education, and geographic location result in unequal access to nutritious food. Marginalized communities in rural and tribal areas often face severe food insecurity. Inequitable access to resources, infrastructure, and markets limits the ability of smallholder farmers to compete and sustain livelihoods. Additionally, food insecurity unequally affects marginalized communities, including women and children.

5. Opportunities in Sustainable Food Security and Nutrition in India

Emerging technologies such as AI, IoT, blockchain, and genetic engineering provide transformative tools to address food security challenges. For instance, precision agriculture improves resource use efficiency, while blockchain enhances traceability and transparency in food supply chains (Kamilaris *et al.,* 2017). Technologies like remote sensing(RS), GIS, and IoT can improve crop management and resource use efficiency. Some crops like zinc-rich wheat and iron-enriched pearl millet developed in India are critical in combating micronutrient deficiencies (HarvestPlus, 2021).

Implementing circular economy principles in food systems, such as recycling waste into bioenergy or compost, reduces resource consumption and environmental impact. Partnerships between government agencies, private corporations, and NGOs can help scale CSA by facilitating access to technology, financial resources, and market linkages for farmers. PPPs can also help build resilience against climate risks by enabling farmers to access climate data, weather forecasting, and crop insurance.

Providing financial incentives, subsidies, and low-interest loans for CSA adoption can encourage farmers to invest in climate-resilient agricultural practices. International climate funds and carbon markets can also provide financial support for implementing CSA practices that contribute to climate change mitigation (World Bank, 2015). National Food Security Act (NFSA), 2013, Provides subsidized food grains to over 800 million people, ensuring a safety net for the vulnerable. POSHAN Abhiyaan Focuses on improving nutritional outcomes among children, pregnant women, and lactating mothers through integrated measures. India is a global leader in organic farming with the largest number of organic farmers (APEDA, 2022).

Promoting organic and natural farming reduces reliance on chemical inputs, improving soil health. Zero-Budget Natural Farming (ZBNF) adopted in states like Andhra Pradesh and Karnataka, ZBNF uses traditional methods to minimize costs and improve sustainability.

The digitization of PDS has reduced leakages and improved access to subsidized food. Expanding its coverage to include more diverse and nutritious foods can further enhance its impact. Investing in local food systems through urban agriculture, farmers' markets, and community-supported agriculture (CSA) enhances resilience and reduces dependency on global supply chains. These systems also open opportunities in income generation and community engagement. Raising awareness about sustainable diets and food waste reduction among consumers can influence demand patterns and healthier, more sustainable food practices. Educational initiatives targeted at farmers encourage the adoption of best practices.

International cooperation through platforms like the United Nations' Sustainable Development Goals (SDGs) facilitates knowledge sharing, funding, and capacity building. Collaborative efforts can address transboundary issues like climate change and global food trade (FAO, 2020).

6. Way Forward

Encouraging mixed farming practices that combine crops, livestock, and aquaculture can diversify incomes and improve resilience. Nutrition education campaigns can shift dietary habits toward healthier options, emphasizing traditional and locally available foods. Expanding cold storage facilities, efficient transportation, and food processing units can reduce post-harvest losses and increase farmers' incomes. Policies should focus on incentivizing sustainable practices, enhancing women's participation in agriculture, and expanding social safety nets to cover nutrition-rich foods. Collaborations between government, private players, and civil society can drive innovation and resource mobilization.

7. Conclusion

In conclusion, achieving sustainable food security and nutrition requires a comprehensive and multi-dimensional approach that integrates innovative technologies, climate-smart agricultural practices, and systemic policy reforms. India, with its rich Agro-biodiversity, technological capabilities, and community-driven initiatives, has the capacity to lead the way in changing the sustainable food systems that can meet the demands of a growing population while safeguarding environmental resources.

Climate-Smart Agriculture (CSA) offers a promising solution by enhancing agricultural productivity, building resilience to climate change, and mitigating environmental impacts. For CSA to reach to its full potential, however, it is crucial to focus on raising awareness, providing financial support, and aligning policies to foster widespread adoption.

Secondary agriculture, with its emphasis on value addition, waste reduction, and efficient resource utilization, stands as a transformative strategy to address food security challenges. By incorporating innovative processing technologies and digital tools, secondary agriculture can maximize the potential of agricultural outputs, creating a more sustainable and nutritious food system.

To successfully achieve food security and nutrition, it is essential for stakeholders across various sectors—governments, industries, researchers, and communities—to collaborate and drive the integration of these solutions into global food systems. Through this concerted effort, we can ensure that future generations inherit a resilient, equitable, and resource-efficient food system capable of meeting global nutritional needs.

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