FOOD SUPPLY CHAIN SYSTEM: CHARTING THE PATH TO SUSTAINABLE FOOD SYSTEMS

Abstract

Developing a food system capable of feeding the rapidly growing global population is an ongoing challenge because of continuous resource depletion. In past, the Green Revolution, along with Nutri-cultivation and eco-productive farming, emerged as potential solutions to address starvation and undernourishment. However, to push back the constraints associated with them, development of novel strategies in supplying food became crucial. Long food supply chain (LFSC), which is the current overly practiced reliable food system has proven inadequate in feeding the global population due to its non-eco-friendly and nutritional adversities. Short food supply chain (SFSC), has gained prominence for meeting demands of the environmental and consumer landscape. However, the sustainability of SFSC in all the aspects is still debatable. This review aims to explore sustainability of SFSC in terms of ecological, financial, health and societal dimensions.

Keywords: Food supply chain; Sustainable agriculture; Green revolution; Nutricultivation

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I. INTRODUCTION

The quest for sustainable food systems has a delicate balance between achieving the nutritional requirement of a burgeoning world populace and safeguarding the environment in the interest of future generations. This journey towards sustainability encompasses a rich historical narrative, from the transformative footprint of the Green Revolution to present-day challenges towards building resilient as well as efficient food supply chains.

The Green Revolution, heralded as a turning point in agricultural history, witnessed a significant increase in food production through the widespread adoption of high-yielding crop varieties, modern agricultural techniques, and increased use of fertilizers and pesticides [1]. By the 1960s and 1970s, the Green Revolution had played a crucial role in averting widespread famine and feeding millions in developing countries[2]. However, this intensive approach to agriculture also gave rise to unintended consequences, including environmental degradation, loss of biodiversity, and socio-economic disparities.

As we navigate the complexities of achieving sustainable food systems, we must reflect on the lessons learned from the Green Revolution era, to ensure that current and future solutions address its challenges more effectively. Today, the world faces an unprecedented convergence of environmental challenges, such as climate change, water scarcity, and soil degradation, which threaten food security and jeopardize the resilience of agricultural production systems[3]. Climate-related events, such as extreme weather events and shifting rainfall patterns, continue to disrupt agricultural productivity and exacerbate food crises in vulnerable regions [4].In this context, the urgent need to build resilience into food supply chains becomes apparent. Efficient and robust supply chains are vital to ensure food security, minimize food losses, and enhance the ability of communities to cope with shocks and stresses[5]. However, ensuring the resilience of food supply chains is a complex challenge that requires coordinated efforts from various stakeholders, including governments, private sectors, and non-governmental organizations (NGOs) [6].

To navigate these contemporary challenges, a multifaceted approach is indispensable. It involves embracing innovative technologies, sustainable farming practices, and inclusive policies that prioritize both environmental stewardship and social equity[7]. By harnessing the power of data-driven decision-making, emerging agricultural technologies, and precision farming, we can optimize resource usage and minimize waste [8]. Moreover, public-private partnerships can foster knowledge exchange, create enabling policy environments, and spur investment in sustainable agricultural practices and supply chain infrastructure[9].

This paper embarks on a comprehensive exploration of the pivotal elements that shape the trajectory towards sustainable food systems. Through critical analysis and evidence-based insights, we will uncover the potential solutions that address the challenges inherited from the Green Revolution while establishing resilient and equitable food supply chains for the future. By examining historical context and contemporary developments, we aim to contribute to the growing body of knowledge that paves the way for a more sustainable, secure, and prosperous global food system.

II. "EXPLORING GLOBAL NUTRITION THROUGH A HISTORICAL LENS"

Agricultural practices have undergone a significant shift since the early 20th century, transitioning from traditional systems reliant on natural resources and ecosystem services to modern approaches characterized by the use of advanced technologies, engineered methods for crop production, the application of fertilizers, and the artificial control of pests. These modern agricultural systems were expected to meet the nutritional needs of the growing global population, projected to reach 9.7 billion people by 2050 (United Nations, 2022). However, none of the existing food production systems, including both long and short food chains, are deemed capable of meeting the requirements for high throughput while providing healthy and environmentally sustainable products. Food systems must effectively respond to economic and sociocultural shocks, address stagnation in rural economies, prevent the depletion of natural resources, promote ecosystem restoration, and minimize actions that contribute to climate change[10].

Therefore, the objectives that must be achieved include developing and implementing new methods to close the yield gaps between countries, enhancing food production, improving the economic accessibility to food resources, and maintaining environmental integrity and preservation[11,12,13]. In pursuit of these goals, three major approaches have been established for agricultural-mediated improvements in global food supply and production:

- **Technological Advancements:** Recent studies emphasize the crucial role of technology in boosting agricultural productivity and food supply. Innovations such as precision agriculture, drone technology, IoT devices, and advanced machinery enable farmers to optimize resource use, increase crop yields, and reduce production costs.

- **Genetic Improvement and Biotechnology:** Advances in genetics and biotechnology have led to the development of genetically modified organisms (GMOs) and gene editing techniques. These approaches offer opportunities to enhance crop resilience, nutrient content, and pest resistance, contributing to increased food production and quality.

- **Sustainable Farming Practices:** Research highlights the significance of sustainable farming methods like agroecology, organic farming, and permaculture. By promoting biodiversity, reducing chemical inputs, and focusing on ecological balance, these practices contribute to long-term food security while minimizing environmental impacts.

- **Climate-Resilient Crops:** As climate change poses challenges to food production, studies emphasize the importance of developing and adopting climate-resilient crop varieties. Breeding crops that can withstand drought, heat stress, and other extreme weather conditions is crucial for ensuring food security in the face of a changing climate.

- **Improved Water Management:** Efficient water management practices, such as drip irrigation and rainwater harvesting, have been identified as essential for optimizing water usage in agriculture. These approaches help conserve water resources and increase agricultural productivity, especially in water-scarce regions.

- **Enhanced Supply Chain Infrastructure:** Strengthening supply chain infrastructure is critical for reducing food losses and ensuring timely delivery of produce to consumers. Investments in transportation, storage facilities, and cold chains can improve food supply chain efficiency and minimize post-harvest losses.

- **Data-Driven Decision Making:** The use of data analytics and remote sensing technologies enables evidence-based decision-making in agriculture. Access to real-time data on weather patterns, soil conditions, and market trends empowers farmers to make informed choices and improve their overall productivity.

- **Knowledge Transfer and Capacity Building:** Studies highlight the importance of knowledge transfer and capacity building among farmers, especially in developing regions. Training programs, extension services, and farmer-to-farmer knowledge sharing can enhance agricultural practices and productivity.

- **Public-Private Partnerships:** Collaboration between governments, research institutions, and private sector entities plays a pivotal role in driving agricultural-mediated improvements in food supply and production. Public-private partnerships can foster innovation, facilitate technology transfer, and promote sustainable agricultural practices on a larger scale.

1. **Green Revolution's Enduring Impact: Tracing the Agrarian Transformation:** The Green Revolution of the mid-20th century significantly increased global food production, but it also led to some unintended consequences such as environmental degradation, loss of biodiversity, and overreliance on chemical inputs. Understanding and addressing these historical challenges is crucial for shaping future food systems. The Green Revolution refers to the significant increase in agricultural productivity that took place in the United States and Europe during the 1960s. It was seen as a potential solution to combat hunger by rapidly increasing the production of specific crops[2]. To achieve this, new farming techniques were adopted, including the installation of irrigation systems, large-scale mechanization, and the use of fertilizers and agrochemicals. The widespread implementation of these methods, along with advancements in crop genetics, brought about a substantial transformation in the food supply chain. It resulted in a decrease in food prices and a subsequent increase in global food availability[14]. These strategies had a positive impact on consumers worldwide, particularly in underdeveloped countries, by initially reducing malnutrition rates, especially in Asia and Latin America [2]. Cereal crops, such as corn, wheat, and rice, experienced significant improvements in production during the Green Revolution, playing a crucial role in alleviating hunger-related malnutrition due to their caloric nature [15].

   However, the Green Revolution also brought about unintended consequences in various areas, including environmental, geographical, and nutritional concerns, which limited its effectiveness as a sustainable food system. From an environmental standpoint, the intensive use of Green Revolution practices contributed to water resource depletion, soil degradation in cultivated areas, and chemical runoff [16,17]. These factors hindered further yield growth and posed long-term threats to the sustainability and replicability of the Green Revolution's success[2]. Additionally, the geographical impact was uneven, as the revolution mainly focused on areas with favourable conditions for intensification, neglecting marginal lands and exacerbating regional disparities. This approach overlooked environmental and geographical constraints, failing to address climate-related challenges and poverty in marginal cultivation areas[18,8]. Furthermore, the initial goal of countering hunger was overshadowed by various malnutrition issues. The emphasis on grain crops with low nutritional value displaced traditional crops with higher nutritional content, leading to a decline in the cultivation of legumes, vegetables, and fruits, which are important sources of critical micronutrients like iron, vitamin A, and zinc. As a result, despite the introduction of novel technologies, the Green Revolution ultimately fell short of its long-term objectives. It not only failed to effectively address hunger, poverty, and food security but also had significant negative environmental impacts[19].

2. **NutriCultivation- Augmenting Crop Nutrition for Enhanced Human Health:** The Green Revolution, while successful in increasing grain yields, also led to a loss of dietary diversity and a decline in the mineral concentrations of grains[20]. To address this issue, Nutricultivation emerged as a potential solution. Nutricultivation is a process that aims to enhance the nutritional value of crops by increasing the content of micronutrients in the edible parts of plants through conventional breeding techniques or genetic engineering. It was designed as a cost-effective approach to alleviate micronutrient deficiencies, particularly in rural populations of developing countries where the problem is prevalent[21]. The implementation of Nutricultivation offers several advantages, including increased production of staple crops, positive environmental impact through the promotion of environmentally resistant products, cost-effectiveness in terms of maintenance, and improved accessibility to rural and underserved areas[22].

   While the theoretical principles of Nutricultivation are well established, practical examples in the agri-food market remain limited. Notable examples include zinc fortification of rice and wheat in Asia, and provitamin A fortification of sweet potatoes and maize in Africa. Transgenic golden rice, fortified with provitamin A, and multivitamin corn, engineered to biosynthesize higher levels of carotenoids, ascorbic acid, and folate, while also being resistant to Bacillus thuringiensis, are among the pioneering examples. Although these examples are few, Nutricultivation holds promise as a sustainable approach to improve the nutritional status of developing countries, provided that the newly incorporated nutrients exhibit comparable bio accessibility and bioavailability to those naturally present in plants[23]. However, Nutricultivation faces certain limitations, primarily associated with the genetic modification of crops. Concerns include the potential for cross-contamination and loss of biodiversity, which could result in the destruction of existing ecosystems to maximize cultivation areas[24].

3. **Eco-Productive Farming: Striking a Harmony between Yield and Environmental Stewardship:** The process of industrialization and urbanization in extensive regions worldwide has led to accelerated soil degradation and a significant reduction in available land for agricultural cultivation [25]. In response, eco-productive farming has emerged as an effective and sustainable approach to increase agricultural yields without causing harmful environmental impacts or requiring the conversion of additional non-agricultural land. This approach aims to support the accessibility of crop-derived products in rural areas and communities with limited resources [26].

Sustainable intensification is a comprehensive approach to natural resource management that encompasses a range of scientifically based environmental, institutional, and social principles, which can be implemented throughout the entire food chain to enhance its efficiency[16].The ultimate goal of eco-productive farming is to transform the entire food chain into a fully sustainable process by implementing sound management practices that optimize natural resource utilization and minimize the negative impacts associated with agricultural activities[27,28]. To achieve this, eco-productive farming involves the application of various agricultural measures[7].

Soil management: Recognizing soil as a living organism and utilizing natural sources of nutrients while practicing rational and responsible soil exploitation.

Genetic techniques: Enhancing the suitability of genetic techniques to support the integrity of diverse agroecosystems and improve the performance of agricultural practices, particularly in terms of climate change resilience.

Irrigation efficiency: Utilizing efficient irrigation technologies to minimize water waste and consumption while maximizing cultivated areas.

Integrated pest management: Implementing integrated pest management systems to mitigate potential risks to food safety and agroecosystem health.

By adopting these measures, eco-productive farming aims to enhance agricultural productivity while minimizing environmental impacts, promoting long-term sustainability in food production[19].

III. FOOD SUPPLY CHAIN SYSTEMS

Food supply chains can be categorized into two main types: short food supply chains (SFSCs) and long food supply chains (LFSCs).

SFSCs refer to localized or regionalized food systems where the distance between producers and consumers is relatively short. LFSCs involve complex networks and extended distances between producers and consumers, often crossing national or international boundaries. Each type has its unique characteristics, advantages, and challenges. In the below table the following are narrated.

The establishment of SFSC primarily stems from the limitations associated with LFSC, including increasing consumer awareness of sustainability and animal welfare, the global trend towards adopting healthier lifestyles, and a heightened interest in information regarding the origin and quality assessment of food products [33].

Long food supply chain (LFSC) is a globalized production chain, where multiple intermediates are involved between producers and consumers. The four major principles of LFSC are as follows: production, transformation, logistic distribution, and retail delivery[31,36]. However, the dramatic growth of the world population and the subsequent increased pressure on the natural environment to meet the consumption demands have caused several implications of different nature attributed to LFSC [37], whose responsibility relies on all the actors of the chain, including farmers, food suppliers, distributors, retailers, and consumers[38].

Overall, LFSC presents a high number of problems associated with its ecological, environmental, logistical, and nutritional implications and, consequently, several solutions have been proposed to counter the negative impact of this globalized chain [19].

Both food supply chains, LFSC and SFSC are strongly relevant, but none of them represent an ideal approach which could meet the current and upcoming requirements of food systems.

Table 1: Characteristics, Advantages and Disadvantages of LFCs and SFCs

Parameters	Short Food Supply Chains (SFSCs)	Long Food Supply Chains (LFSCs)
Characteristics	i. Direct Producer-Consumer Link: SFSCs often involve direct relationships between farmers, producers, and consumers. This direct link enables transparency and accountability in the food production process. ii. Reduced Carbon Footprint: Since the transportation distances are short, SFSCs generally have a lower carbon footprint, leading to reduced greenhouse gas emissions. iii. Emphasis on Local Produce: SFSCs prioritize locally grown or sourced food items, supporting local economies and fostering community connections.	i. Globalized Trade: LFSCs facilitate the global exchange of agricultural commodities and processed food products. ii. Economies of Scale: Large-scale production and distribution in LFSCs can lead to cost efficiencies and lower prices for consumers. iii. Diverse Food Choices: LFSCs offer consumers access to a wide variety of food items from different regions and seasons.
Advantages	i. Fresher and More Nutritious: With shorter supply chains, fresh produce can reach consumers faster, retaining more nutrients and flavor. ii. Increased Resilience: SFSCs are more resilient to disruptions in global supply chains, such as pandemics or natural disasters, as they rely less on international trade. iii. Strengthened Food Security: Localized food systems can enhance food security by reducing dependency on external markets and imports.	i. Market Access: LFSCs enable producers to reach a broader consumer base, expanding their market opportunities. ii. Seasonal Availability: Consumers can access out-of-season produce from regions with different climates through LFSCs. iii. Technological Advancements: LFSCs often benefit from advanced logistics and preservation technologies, reducing food waste.

Challenges	i. Limited Variety: SFSCs might have a narrower selection of food items compared to the extensive range available in global markets. ii. Scale and Efficiency: Scaling up SFSCs to meet the demands of larger populations can be challenging, as it requires overcoming logistical and organizational barriers.	i. Food Waste: Complex supply chains increase the likelihood of food losses due to spoilage and inefficiencies. ii. Environmental Impact: Long transportation distances in LFSCs contribute to higher carbon emissions and environmental degradation. iii. Vulnerability to Disruptions: LFSCs can be more susceptible to disruptions caused by trade conflicts, political issues, or global events.

IV. IMPACTS ON NATURE AND ECOSYSTEM

Agroecology focuses on producing food through regenerative and sustainable systems, utilizing resources more efficiently to enhance the productivity of biotic and abiotic components[41]. Agroecological practices involve the reduction of pesticides and fertilizers, the reliance on compost, the implementation of renewable resources and energy, the adoption of crop rotation, and the control of soil erosion. As a result, agroecology offers economic and social benefits, including stable profits and increased employment rates[42]. Additionally, the depletion of resources extends to marine ecosystems, with overfishing being a growing concern associated with intensive livestock practices within LFSC. To address this issue, sustainable solutions such as the implementation of catch shares and the promotion of aquaculture have been proposed [43].

The depletion and mismanagement of natural resources, combined with the significant greenhouse gas (GHG) emissions associated with LFSC, have resulted in climate change-related challenges that undermine its sustainability. Moreover, the livestock sector, particularly ruminants like cattle, significantly contributes to LFSC's environmental impact through enteric fermentation, which produces methane—a potent greenhouse gas [44]. Furthermore, the transportation of products within LFSC also contributes to harmful emissions, primarily carbon dioxide[40]. To ensure the long-term viability of LFSC, two major approaches are crucial: the development of resilient crop varieties and the reduction of GHG emissions. Resilient crops can be achieved through molecular modifications, such as genetic engineering to enhance resistance against pathogens and adaptability to abiotic stresses associated with climate change, such as droughts, floods, and high salinity[45]. To mitigate GHG emissions from LFSC, reducing enteric fermentation in ruminants is a valuable option, primarily through dietary variation and supplementation for cattle. Additionally, biological control methods and the development of anti-methanogenesis vaccines are being explored [44]. Furthermore, reducing meat consumption is an effective strategy to address the environmental implications of LFSC. Plant-based diets, including vegetarian and vegan options, offer protein-rich alternatives with lower environmental impacts [46]. Alongside plant-based diets, innovative food formulations and products, such as algae, insect, and synthetic proteins, are being explored as means to reduce the excessive consumption of animal protein [46].

Globalization has had considerable impact on the food supply systems. In the LFSC model, it caused the separation between producers and consumers which affected the traceability. Besides, it increased the dependence on exportations and, consequently, transport trade got also increased[47]. In contrast, the short geographical distance between producers and consumers offered by SFSC may be essential for reducing the negative externalities connected to transport, such as GHG emissions. Several authors confirmed that the shorter the food mile, the lower GHG emissions and fewer distribution stages along the chain[48,49]. Some authors have reported that despite the significantly higher food distance for LFSC, food mile values were similar for both food chains[47]. Indeed, higher food mile values were reported for SFSC because SFSC products are transported in small quantities and require the participation of different individual transports[50,51].

V. EFFECTS ON HUMAN NUTRITION AND HEALTH

Developed countries have witnessed an increase in the consumption of processed and fast foods that are high in calories but low in nutritional value, leading to a rise in chronic diseases such as obesity, dyslipidaemia, and cardiovascular disorders[53,54]. Moreover, the production demands associated with fast food-based diets exert negative pressures on terrestrial, aerial, and aquatic ecosystems. Thus, there is a pressing need for global changes in dietary patterns and nutritional education to improve human health and safeguard the environment, aiming to reduce inequalities between countries with different income levels[53]. In line with this objective, the World Health Organization has proposed a dietary profile that emphasizes high consumption of fruits, vegetables, legumes, nuts, and whole grains while minimizing the intake of animal proteins and refined products. This shift would enhance the nutritional value of diets and alleviate environmental pressures associated with food production [55].

By understanding the impact of culture and culinary traditions, socioeconomic status, and family influences, educational programs, and sustainable awareness, dietary education can be tailored to different age groups to reshape people's preferences and promote healthier eating habits[56]. Socioeconomic status plays a significant role, as individuals with lower socioeconomic status often face barriers to adopting healthier diets, such as the high cost of nutritious foods and limited nutritional knowledge. As a result, they tend to consume diets rich in fat, sugar, and salt, with inadequate intake of fruits and vegetables[57].Conversely, individuals with higher socioeconomic status tend to have higher daily fruit and vegetable consumption. The food industry has shifted its focus towards the design and development of functional foods that offer not only good nutritional properties but also positive effects on health by improving cellular functions and reducing the risk of noncommunicable diseases[58]

VI. CONCLUSION

Green Revolution, in combination with Nutricultivation and eco-productive farming, emerged as promising solutions to increase food production but ended up causing a negative environmental impact. The shortening of food chain, known as SFSC, may constitute a hopeful strategy to overcome the limitations associated with LFSC. SFSC is based on the elimination of intermediaries between producer and consumer, geographic proximity, and traceability.

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