**Food Supply Chain System: Charting the Path to Sustainable Food Systems**

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**ABSTRACT**

Developing a food system capable of feeding the rapidly growing global population is an ongoing challenge, especially considering the depletion of natural resources. In the past, the Green Revolution, along with Nutri-cultivation and eco-productive farming, emerged as potential solutions to address hunger and malnutrition in the latter half of the 20th century. However, to overcome the limitations associated with them, the development of food supply chains became crucial. The 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. The short food supply chain (SFSC), has gained prominence recently for its ability to meet the demands of the present environmental and consumer landscape. However, the sustainability of SFSC in terms of environmental, economic, and social aspects is yet to be fully determined. This review aims to explore the sustainability of SFSC in terms of ecological, financial, health and societal dimensions.

**Keywords**—Food supply chain; Sustainable agriculture; Green revolution; Nutricultivation

1. **INTRODUCTION**

The quest for sustainable food systems has emerged as one of the most critical challenges of our time, requiring a delicate balance between meeting the nutritional needs of a burgeoning global population and safeguarding the environment for future generations. This journey towards sustainability encompasses a rich historical narrative, from the transformative impact of the Green Revolution to the present-day challenges of building resilient and 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 countries2. 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 systems3. 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 stresses5. 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 equity7. 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 infrastructure9.

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.

1. **"EXPLORING GLOBAL NUTRITION THROUGH A HISTORICAL LENS"**

In the early 20th century, agricultural practices underwent a significant transformation from traditional systems reliant on natural resources and ecosystem services to modern methods characterized by advanced technologies, engineered methods of crop production, fertilizer application, and pest control by artificial means. A growing global population, estimated at 9.7 billion by 2050 (United Nations, 2022), will require these modern agricultural systems to meet their nutritional needs. Both long and short food chains do not meet the requirements for high throughput while providing healthy and environmentally sustainable foods. As a result of economic and sociocultural shocks, stagnation in rural economies, preservation of natural resources, and restoring ecosystems, it is essential that food systems are able to respond effectively10.

We must develop and implement new methods for closing yield gaps between countries, improving food production, improving economic access to food resources, and maintaining environmental integrity in order to reach these goals11,12,13. 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.

**A. 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 crops2. 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 availability14. 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 success2. 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 areas18,8. 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 impacts19.

**B. 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 grains20. Nutricultivation has become a promising remedy for this problem. Through traditional breeding methods or genetic engineering, nutricultivation tries to increase the quantity of micronutrients in the edible sections of plants, improving the nutritional value of crops. It was created as a low-cost strategy to address micronutrient deficiencies, especially in rural populations in developing nations where the issue is common21. Nutricultivation has a number of benefits, including increased production of staple crops, improved accessibility to rural and underserved areas, a favorable environmental impact through the promotion of environmentally friendly products, and cost-effective maintenance22.

Although the theoretical foundations of Nutricultivation are well-known, there are still few real-world applications in the agri-food industry. Examples include the addition of zinc to rice and wheat in Asia and the addition of provitamin A to sweet potatoes and maize in Africa. Among the first examples are transgenic golden rice that has been supplemented with provitamin A and multivitamin corn that is resistant to Bacillus thuringiensis and biosynthesizes greater quantities of carotenoids, ascorbic acid, and folate. Even though there aren't many instances, nutriculturization has the potential to be a sustainable method for enhancing the nutritional status of developing nations, so long as the newly added nutrients have equivalent bioaccessibility and availability to those naturally found in plants23. However, there are some restrictions to nutriculturization, mostly because of crop genetic engineering. Cross-contamination risk and biodiversity loss are issues that could lead to the extinction of existing ecosystems in order to increase cultivated areas24.

**C. Eco-Productive Farming: Striking a Harmony between Yield and Environmental Stewardship**

Globally widespread industrialization and urbanization processes have increased soil deterioration and significantly reduced the amount of land that can be used for agricultural production25. In consequent action, eco-productive farming has become a viable and efficient strategy for raising agricultural yields without negatively affecting the environment or necessitating the conversion of more non-agricultural land. This strategy attempts to support the availability of products made from crops in the countryside and resource-constrained groups26.

In order to improve the efficiency of the entire food chain, environmentally friendly intensification is a holistic approach to managing natural resources that incorporates a variety of scientifically supported ecological, institutional, and social concepts16. Eco-productive farming's ultimate objective is to completely support every link in the food chain by using good management techniques that maximize the use of natural resources and reduce the adverse effects of agricultural activity27,28. Eco-productive farming uses a variety of agricultural practices to accomplish this7.

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

Genetic techniques: the improvement of agricultural practices' performance, particularly with regard to their resilience to climate change, and the appropriateness of genetic approaches to sustain the integrity of different agroecosystems.

Irrigation efficiency: Utilizing water-saving irrigation technologies to maximize farmed areas while reducing water waste and consumption.

Integrated pest management: Putting integrated pest management methods in place to reduce possible threats to food safety and the health of the agroecosystem.

By adopting these measures, eco-productive farming aims to enhance agricultural productivity while minimizing environmental impacts, promoting long-term sustainability in food production19.

1. **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 creation of SFSC is primarily a result of the drawbacks of LFSC, which include growing consumer concern for environmental sustainability and welfare of animals, a global movement toward choosing healthier choices, as well as an increased interest in details about the place of origin and evaluation of food products' quality29. The long food supply chain (LFSC) is a production chain that is international and involves numerous intermediaries between manufacturers and customers. The following are the LFSC's four main tenets: manufacturing, alterations, distribution via logistics, and consumer delivery30,31. Nevertheless, the rapid expansion in the world's inhabitants and the ensuing pressure on the environment to meet consumer demands have led to a number of repercussions of various kinds that are ascribed to LFSC32, 33. As a whole, LFSC poses a significant number of natural, social, logistical, and dietary challenges, and as a result, a variety of remedies have been put forth to mitigate the detrimental effects of this worldwide chain 19.

Although both LFSC and SFSC are very important, neither one is an optimal strategy that could satisfy both the present and future needs of food systems.

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

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|  | Short Food Supply Chains (SFSCs) | Long Food Supply Chains (LFSCs) |
| Characteristics | 1. 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. 2. Reduced Carbon Footprint: Since the transportation distances are short, SFSCs generally have a lower carbon footprint, leading to reduced greenhouse gas emissions. 3. Emphasis on Local Produce: SFSCs prioritize locally grown or sourced food items, supporting local economies and fostering community connections. | 1. Globalized Trade: LFSCs facilitate the global exchange of agricultural commodities and processed food products. 2. Economies of Scale: Large-scale production and distribution in LFSCs can lead to cost efficiencies and lower prices for consumers. 3. Diverse Food Choices: LFSCs offer consumers access to a wide variety of food items from different regions and seasons. |
| Advantages | 1. Fresher and More Nutritious: With shorter supply chains, fresh produce can reach consumers faster, retaining more nutrients and flavor. 2. 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. 3. Strengthened Food Security: Localized food systems can enhance food security by reducing dependency on external markets and imports. | 1. Market Access: LFSCs enable producers to reach a broader consumer base, expanding their market opportunities. 2. Seasonal Availability: Consumers can access out-of-season produce from regions with different climates through LFSCs. 3. Technological Advancements: LFSCs often benefit from advanced logistics and preservation technologies, reducing food waste. |
| Challenges | 1. Limited Variety: SFSCs might have a narrower selection of food items compared to the extensive range available in global markets. 2. Scale and Efficiency: Scaling up SFSCs to meet the demands of larger populations can be challenging, as it requires overcoming logistical and organizational barriers. | 1. Food Waste: Complex supply chains increase the likelihood of food losses due to spoilage and inefficiencies. 2. Environmental Impact: Long transportation distances in LFSCs contribute to higher carbon emissions and environmental degradation. 3. Vulnerability to Disruptions: LFSCs can be more susceptible to disruptions caused by trade conflicts, political issues, or global events. |

1. **IMPACTS ON NATURE AND ECOSYSTEM**

The goal of agroecology is to produce food using sustainable and regenerative systems while using resources more wisely to increase the efficiency of both both abiotic and biotic components 34. Reduced use of synthetic fertilizers and pesticides, an emphasis on composting, the use of renewable energy sources, crop rotation, and soil erosion control are all aspects of agroecological practices. As an outcome, agroecology provides financial and social advantages, such as steady revenue growth and higher employment rates35. The destruction of resources also affects marine habitats, as overfishing is a major issue brought on by the intensive livestock techniques used in the LFSC. Sustainable alternatives have been offered for tackling this problem, including the establishment of collect sharing and the advancement of aquaculture36.

Natural resource depletion and improper management, along with the substantial emission of greenhouse gases (GHG) connected to LFSC, have led to climate change-related issues that jeopardize its sustainability. Furthermore, enteric fermentation, which results in the production of methane—a potent greenhouse gas—significantly contributes to the environmental effect of the livestock industry, especially ruminants like cattle37. Additionally, the movement of goods within LFSC adds to the harmful emissions, particularly carbon dioxide38. Two key strategies are essential for ensuring the LFSC's long-term viability: the creation of resilient crop types and the decrease in GHG emissions. Molecular alterations, including genetic engineering to improve disease resistance and adaptation to abiotic hazards brought on by global warming, such as extreme weather events and excessive salinity, can be used to create resilient crops39. Lowering enteric fermentation in grazing animals is a significant strategy for reducing GHG emissions from LFSC, particularly for cattle by dietary supplementation and change. Additionally, efforts are being made to produce vaccinations against methanogenesis and biological control strategies37. Additionally, cutting back on meat intake is a successful way to mitigate the effects LFSC has on the ecosystem. Plant-based diets provide protein-rich substitutes with less negative effects on the environment, such as vegetarian and vegan options40. Innovative food items like algae, insect, and synthetic proteins are being researched as a way to cut back on the excessive use of animal protein in alongside plant-based diets 40.

The mechanisms that supply food have been significantly impacted by globalization. It resulted in the division of producers and consumers in the LFSC model, which had an impact on traceability. Additionally, it increased the reliance on exports, which led to an increase in transport commerce41. On the other hand, the close proximity of producers and consumers provided by SFSC may be crucial for minimizing the unfavorable externalities associated with transportation, such as GHG emissions. There is evidence from several writers that the fewer distribution stages and lower GHG emissions that result from a shorter food mile42,43. Despite the LFSC's substantially longer food distance, some authors claim that both food chains' food distance ratios were comparable41. Because SFSC goods are carried in tiny amounts and need the involvement of various individual transporters, greater food mile values are being observed for SFSC44,45.

1. **EFFECTS ON HUMAN NUTRITION AND HEALTH**

Developed countries have witnessed an increase in the consumption of high caloric refined junk food items arising a higher risk of nutritional deficiency and lifestyle related disorders46,47. Moreover, the production demands associated with fast food-based diets exert negative pressures on our ecosystems. Thus, to equalise the imbalance in the socio economical conditions around the globe there is a pressing need to improve human health by providing accurate education on nutrition and diet and safeguard the environment46.For the further fulfilment of this objective the World Health Organization have reconstituted the dietary guidelines focussing mostly on plant based whole foods that have minimum processing or animal products. Such guidelines will be improving nutritional status of the global population making food production much more sustainable in the future48.

To change people's preferences and encourage healthy eating habits, nutritional education can be adapted for various generations by taking into account the influence of socioeconomic status, familial factors, culture, and culinary traditions49. Socioeconomic status is important because people with lower socioeconomic class frequently encounter obstacles to changing to more nutritious eating habits, which include the costly nature of nutrient-dense foods and a lack of information about nutrition. They thus frequently eat meals high in sugar, salt, and fat, plus insufficient amounts of fruits and vegetables50. On the other hand, those with better socioeconomic class typically consume more fruits and vegetables every day. The food industry has moved its attention to the creation and advancement of fortified foods that not only have strong nutritional qualities but also have beneficial impacts on health by enhancing cellular processes and lowering the risk of diseases that are not transmissible51

1. **CONCLUSION**

Various propitious strategies for building a sustainable food future like green revolution, NutriCultivation and eco-productive farming failed to combat environmental degradation. A powerful approach towards accepting SFSC over the impediments of LFSC can balance these two challenges by intercession of the gaps among the farmer and the user, improving geographic vicinity and trackability.

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