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## Review Article

# A review on sustainable food systems (SFS) on the light of physics principles

Dr. Barnali Barman

Department of Physics, Seva Bharati Mahavidyalaya, Kaggari, Jhargram, West Bengal, India

\*Corresponding author, E-mail: [barnalibarman91@gmail.com](mailto:barnalibarman91@gmail.com)

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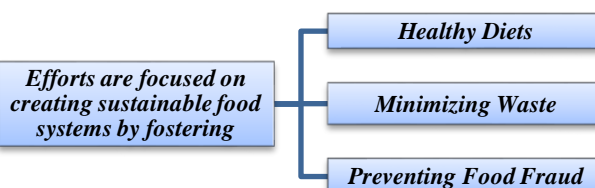
### ABSTRACT

Aiming for a resilient and sustainable food chain, the Farm to Fork Strategy addresses key challenges under the Green Deal by fostering environmentally friendly production, securing food availability and promoting sustainable practices across the entire food supply chain including processing, retail and food services. Efforts are focused on creating sustainable food systems by fostering healthy diets, minimizing waste and preventing food fraud. This transition is enabled by targeted research, investment and capacity building. The past few decades have seen an exponential rise in publications dedicated to sustainability science. Paralleling this, intense global discussions have focused on food and bioeconomy systems, fueled by a growing consensus that the status quo is unsustainable due to issues like climate change, biodiversity loss and the emergence of pandemics like COVID-19. Advances in Food Science and Technology (FST) are crucial for developing sustainable food systems (SFS), with a key focus on improving food quality through plant-based alternative proteins to support healthier, more sustainable diets. Achieving Sustainable Food Systems (SFS) requires conceptualizing their nature and understanding how Food System Transformation (FST) developments can serve as leverage points. Physics principles can guide this process, with some literature offering a unique perspective: using a physics-based approach to gain first-order insights into the interactions between food agents and system dynamics. The transformation of resources into consumed or recycled food functions as an open thermodynamic system, heavily reliant on principles well-understood by food scientists. The history of cooking demonstrates that variables such as temperature, pressure, time and mass transfers connect the disciplines of food chemistry, microbiology and physics.

## 1. Introduction

A review of Sustainable Food Systems (SFS) through the perspective of basic physics reveals that, the current food system, which operates as a linear chain focused on exponential growth, is unsustainable and leading toward disordered states, such as climate change and biodiversity loss. By applying physical principles [1], food systems are re-envisioned as Open Thermodynamic Systems (OTS) and Complex Adaptive Systems (CAS) that must balance within a "sustainability zone" between "frozen states" (static, inflexible) and "chaos" (uncontrolled, chaotic waste). A Sustainable Food System (SFS) is a collaborative network that delivers food security and nutrition for all without compromising the economic, social and environmental bases for future generations. Unlike conventional linear "farm-to-table" models, an SFS takes a holistic, systems-based approach

to ensure that the way we produce, process, distribute and consume food is resilient to shocks like climate change while remaining profitable and equitable. For a food system to be truly sustainable, it must balance three core dimensions (i) Economic Sustainability: The system must be profitable throughout all stages from small holder farmers to large retailers ensuring long-term viability and job creation, (ii) Social Sustainability: It should provide broad-based benefits, including food security, nutritious diets and fair labor practices (e.g., safe working conditions and equal rights), (iii) Environmental Sustainability: The system must have a neutral or positive impact on the environment by protecting biodiversity, conserving water and reducing greenhouse gas emissions.



Food Science and Technology is a multidisciplinary field that combines biology, chemistry, Physics, engineering and nutrition to study the nature of food and improve its production, preservation and safety [2-7]. While the terms are often used together, they represent two distinct stages of the food system (i) Food Science: The study of the physical, biological and chemical makeup of food. Scientists research how food components react to processing, storage and heat to ensure safety and high quality, (ii) Food Technology: The practical application of that scientific knowledge to develop, preserve, package and distribute safe and nutritious food products. Over the past few decades many Research and Publications have done on Sustainable Food Systems [8-17]. To achieve Sustainable Food Systems (SFS), it is essential to define their structure and identify how Food System Transformation (FST) acts as a leverage point. Physics offers a unique, foundational approach to this, providing first-order insights into how food agents and system dynamics interact [1].

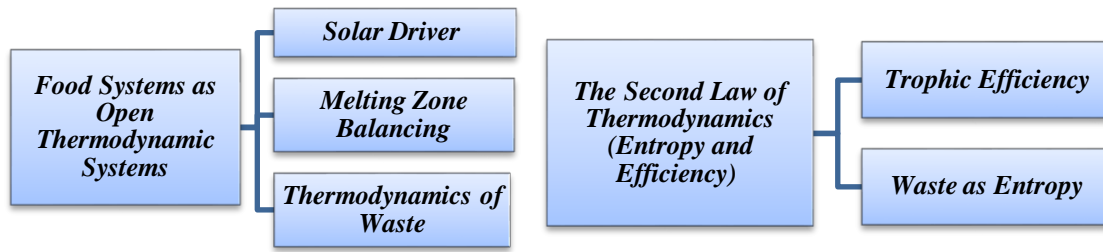
## 2. Literature Review

By reviewing some literature main outcomes related to some papers are drawn about Sustainable Food Systems. Bridging science, policy and practice require a unified yet diverse approach to forge sustainable food systems, building intentionally on decades of transdisciplinary progress [18]. To support the Sustainable Development Goals (SDGs), the scientific community must pivot toward actionable, data-driven approaches. This involves a four-part strategy like (i) Develop Quantifiable Metrics: Define concrete indicators for tracking progress on each SDG to ensure they are measurable, comparable and actionable, (ii) Establish Monitoring Mechanisms: Implement robust data acquisition, analysis and interpretation systems in collaboration with governments to track these indicators in real time, (iii) Evaluate Progress Regularly: Utilize evidence-based reporting to assess trends, synergies and trade-offs, allowing for adjustments in policy and strategy (iv) Enhance Infrastructure and Access: Build necessary technological, scientific and knowledge-sharing infrastructures to ensure Earth observation data and research findings are open and accessible to all. To bridge the science-policy gap, we must actively integrate these monitoring and evaluation tools into decision-making processes at all levels from local to global to accelerate the transition to sustainability [19]. The 2030 Agenda for food and agriculture necessitates a complete transformation of current systems, as continuing down the current path is no longer a viable option. We must pivot from conventional agricultural practices to sustainable ones to reach the 2030 Sustainable Development Goals [20]. Building stronger, more sustainable food systems demands a harmonious blend of global supply chains and local sourcing [21]. Transition from a focus on "having enough food" to managing the entire food system. Merge efficiency with affordability, social equity and environmental health. Replace fragmented trade with seamless end-to-end linkages.

Transform traditional value chains into sustainable, circular loops. Move from narrow, targeted fixes to integrated systemic governance [22]. Some papers provide the idea of SFS based on four fundamental physical forces; this model defines the basic boundaries of SFS. These forces collaboratively ensure the stability of both independent and interacting systems within the sustainability zone [1]. Food ingredients behave as biopolymers, allowing synthetic polymer theories to be applied to food systems. Additionally, the complex structural behavior of food is best understood through the lens of soft matter physics [23]. Turning food waste into new food resources, demonstrates the power of a circular bioeconomy which tackles critical waste issues while creating a sustainable, closed-loop system [24]. Some articles investigate how mimicking natural systems (bio-inspiration) can revolutionize materials sustainability by reimagining design, production and usage paradigms. Spanning fields like healthcare and structural engineering, it promotes adopting closed-loop natural cycles focused on circularity, longevity and parsimony to advance efficient recycling, reuse and material longevity [25]. As agriculture and food systems are major global energy consumers and greenhouse gas (GHG) emitters, implementing energy-efficient strategies is crucial to balance productivity with sustainability. Integrating renewable energy and digital technologies significantly boosts efficiency, environmental performance and yield. The new innovations support various SDGs, ensuring sustainable food production [26].

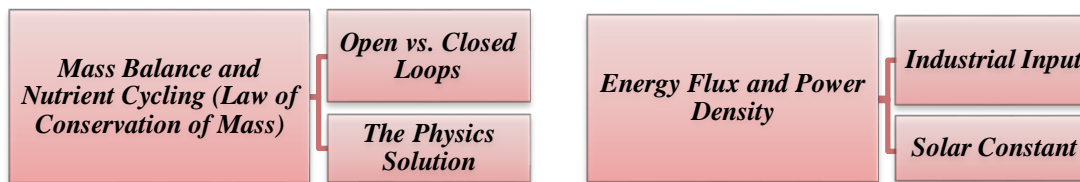
## 3. Methodology

A review of Sustainable Food Systems (SFS) on the light of physics [1], reveals that the current global food infrastructure is largely an unsustainable, fossil-fueled thermodynamic system that needs to transition toward solar-driven, circular and highly efficient network structures which moves the conversation from policy and ethics to the fundamental laws of energy and matter. Physics, particularly thermodynamics, complex adaptive systems (CAS) theory and soft matter physics provides a foundational framework to evaluate and redesign food production, processing and distribution to remain within planetary boundaries. From a physics perspective, a sustainable food system is an open thermodynamic system one that exchanges energy and matter with its surroundings fueled primarily by solar energy. Sustainable systems rely on photosynthesis to convert solar energy into biomass, balancing the expanding "solar force" (production growth) with the "gravitational force" (natural resource limits and recycling nutrients). Sustainable food systems operate in a "melting zone" (a safe and just operating space) between highly rigid, frozen states (e.g., rigid monoculture chains) and pure chaos (e.g., inefficient, wasteful, over-dispersed chains). The second law of thermodynamics implies that, without energy efficiency, food production produces high-entropy outputs (greenhouse gases, food waste, heat). Reducing this requires shifting from linear chains to closed-loop food webs (industrial ecology).



A food system is an energy conversion process. The Second Law states that in every energy transfer, some energy is lost as heat (entropy). Physics explains why plant-based diets are more sustainable. Each step up the food chain (from grain to cattle) loses roughly 90% of the available energy. A

system that minimizes these steps reduces total entropy production. Food waste isn't just lost calories; it represents the "embodied energy" (transport, refrigeration, processing) that has been irreversibly dissipated.

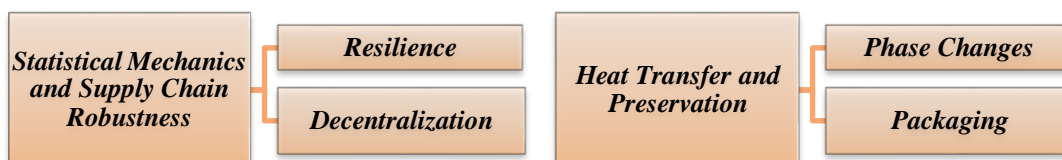


In a sustainable system, the input of matter must equal the output plus accumulation. Current food systems are "linear" (extractive). Nutrients are taken from the soil, processed and eventually dumped into oceans or landfills.

flux. Physics-based innovations, like vertical farming, attempt to optimize Photosynthetic Photon Flux Density (PPFD) to maximize caloric output per square meter using controlled light wavelengths.

Transitioning to a circular model (composting, anaerobic digestion) aligns with the conservation of mass, ensuring that nitrogen, phosphorus and carbon remain within the system's boundary rather than becoming pollutants. The sustainability of a food system is often a function of its Energy Return on Investment (EROI). Modern SFS analysis critiques the fact that we often spend 10 units of fossil fuel energy to produce 1 unit of food energy. SFS aims to shift back to primary solar

Physics models of complex systems help us understand food security. A sustainable system acts like a stable physical lattice. Over-centralized systems (huge monocultures) have low modularity. If one node fails, the whole structure collapses. Physics suggests that a distributed network of local food hubs creates a more stable, lower-energy state that is more resistant to external shocks (e.g. climate change, fuel spikes etc.).



A major pillar of SFS is reducing post-harvest loss. Using physics to improve refrigeration (latent heat storage) and drying techniques (evaporative cooling) reduces the energy required to keep food stable. Moving away from polymers to biodegradable materials involves understanding the molecular permeability of gases like oxygen and ethylene to slow down biological decay.

2. How can we ensure sustainable land and water management to combat degradation and depletion in vulnerable locations?
3. To what extent will economic disparities and lack of employment continue to obstruct access to adequate food?
4. How does climate change threaten agricultural production and rural livelihoods as well as what role can farm play in reducing greenhouse gas emissions?

#### 4. Discussion

To account for an uncertain future, planners often use foresight exercises to evaluate different scenarios against a range of potential risks. The core challenge for future food systems is ensuring 10 billion people can access nutritious, sustainable diets by 2050 [19]. This must be achieved despite rising demand for resource intensive foods and the need to supply non-food agricultural commodities, raising several critical questions:

1. What strategies can be used to moderate food demand and encourage eco-friendly eating?

#### *For Food Demand Management and Changing Peoples Dietary Preferences:*

- Leveraging awareness and regulation to manage consumer demand helps contain agricultural expansion.
- Reducing malnutrition including undernutrition, micronutrient deficiencies and obesity requires educating consumers to make better dietary demands.
- Food prices should reflect fair market value.
- Balancing international trade is essential for high-income countries to optimize production, address dietary shifts and fill food deficits.

**Advancing food security and nutrition through poverty reduction and equitable policies:**

- To eliminate undernourishment, we must actively reduce poverty and social disparities.
- Sustainable agriculture offers a dual solution to hunger and ecological decline.
- A more equitable distribution of wealth makes nutritious, healthy food affordable for all.
- Sustainable agriculture can simultaneously optimize profitability and sustain rural livelihoods.
- Growing enough food is necessary, but no longer sufficient to guarantee that everyone has equal access to it.

**Implementing Sustainable Strategies to Combat Land Degradation and Water Scarcity:**

- Sustainable agricultural intensification provides the best balance between meeting food demands and reducing land degradation.
- Sustainable land management preventing damage while rehabilitating degraded areas tackles limited land resources.
- Optimizing water consumption is increasingly essential for sustainability.
- High-level implementation necessitates significant investment.

**The Nexus Between Agricultural Productivity and Environmental Stewardship:**

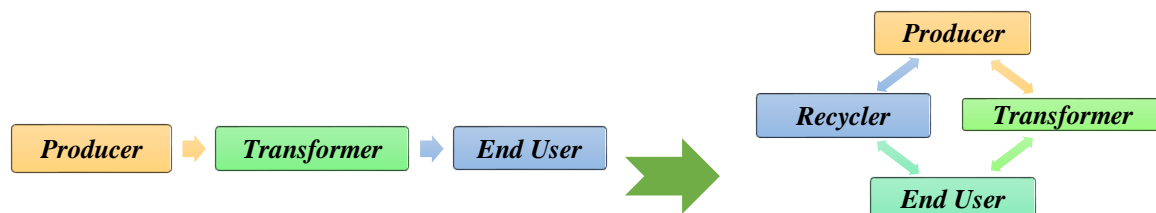
- Failure to address climate change in agriculture will incrementally reduce yields while worsening economic disparity and poverty.
- Climate change poses a systemic threat that transcends agricultural productivity.

- Agricultural sector reforms are only part of the solution; drastic, economy-wide Green House Gases (GHG) reductions are mandatory.

**5. Conclusions**

To transition from our current "linear" (take-make-waste) systems to sustainable ones, several strategies are employed: Using practices like Organic Farming, Regenerative Agriculture and agroecology to restore soil health and reduce chemical use. Designing "zero-waste" systems where food by-products are upcycled into new products, energy or animal feed instead of ending up in landfills. Addressing the fact that roughly one-third of all food produced is currently lost or wasted. Encouraging a shift toward Plant-Based Foods (like legumes, nuts and vegetables) which typically require significantly less land and water than animal-based products. Supporting local food chains and seasonal eating to reduce "food miles" and support local economies, though the environmental benefit depends on the specific product and transport mode.

- Why it matters: Our current food systems are a major driver of the climate crisis, accounting for roughly one-third of global greenhouse gas emissions and 70% of the world's freshwater usage. A sustainable transformation is considered critical to achieving the UN Sustainable Development Goals, particularly SDG-2 (Zero Hunger).
- From the physics perspective, a Sustainable Food System is one that: Minimizes entropy (lowers waste and trophic loss), Closes mass loops (recycles nutrients), Maximizes Energy Return on Investment [EROI] (uses renewable energy over fossil inputs), Increases system modularity (ensures structural stability).



**Key Takeaways and Future Directions:** A review of these principles suggests that for systems to become sustainable, they must replace singular linear food chains with diverse, interconnected networks of food actors. Stop aiming for endless growth and instead balance expanding solar energy (biomass) with binding forces (soil health, carbon capture). Utilize low-cost sensors and artificial intelligence to monitor energy and mass flows in real-time to allow for immediate, targeted adjustments in processing and waste reduction.

**Authors' contributions**

The author reviewed and approved the final version of the manuscript for publication.

**Conflicts of interest**

The author declares no conflict of interest.

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**Data availability**

No new data were created.

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