

Food Systems in the Anthropocene: An Econometric and Bioeconomic Perspective for Global Nutrition Security

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Abstract

This review examines the structural challenges of the global food system in the Anthropocene through an integrated econometric and bioeconomic perspective. Despite producing sufficient calories to feed the world, the current system simultaneously generates widespread malnutrition and severe environmental degradation. These outcomes are largely driven by economic frameworks that fail to internalise health and ecological externalities. Using a systematic review of the existing literature, combined with conceptual econometric modelling, the study analyses the relationships among dietary transitions, environmental pressures, and nutrition outcomes. Findings highlight the immense economic and social costs of current food systems. Global malnutrition in its various forms imposes an estimated burden of about \$3.5 trillion annually, while the broader hidden costs of agri-food systems, including environmental damage and health impacts, are estimated to reach \$10 trillion each year. The analysis also identifies reinforcing feedback mechanisms that sustain unhealthy consumption patterns and environmentally intensive agricultural practices. However, the review also reveals promising pathways for transformation. Approaches such as agroecology, crop diversification, and biofortification demonstrate strong societal returns by simultaneously improving nutrition, strengthening ecological resilience, and reducing long-term economic costs. The paper positions nutrition-sensitive food systems as a central mechanism linking multiple Sustainable Development Goals, particularly those related to health, climate action, and biodiversity. Ultimately, the crisis is interpreted as a governance and policy misalignment problem. A transition toward a health-oriented and environmentally restorative bioeconomy requires coordinated policy reforms, including subsidy restructuring, fiscal measures targeting unhealthy foods, and strategic public procurement to realign market incentives with human and planetary well-being.

Keywords: Anthropocene, Food Systems, Nutrition Security, Double Burden of Malnutrition, Econometrics, Bioeconomy, Sustainable Diets, Agroecology, SDG Interlinkages, Food Policy

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1. Introduction

The global food system stands at a critical juncture in human history. While agricultural

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productivity has reached unprecedented levels, producing enough calories to feed the entire global population, the system is failing in its fundamental purpose of delivering nutrition security and environmental sustainability. The Anthropocene epoch, characterised by dominant human influence on Earth's systems (Steffen et al., 2015), has ushered in a paradoxical era where abundance coexists with profound nutritional deficiencies and ecological degradation.

The scale of the challenge is monumental. Currently, nearly 30% of the global population experiences some form of malnutrition, ranging from undernutrition and micronutrient deficiencies to overweight and obesity (Food and Agriculture Organization et al., 2023). This "double burden" of malnutrition represents not merely a public health crisis but a fundamental economic and developmental challenge that threatens human capital formation, economic productivity, and sustainable development. Simultaneously, food systems account for approximately 31% of global greenhouse gas emissions, 70% of freshwater withdrawals, and are the primary driver of biodiversity loss (Crippa et al., 2021; Food and Agriculture Organisation, 2020).

The transformation of global diets represents a particularly potent driver of this crisis. The rapid shift from traditional, diverse diets to those dominated by ultra-processed foods, refined carbohydrates, and animal-source proteins has created a perfect storm of health and environmental challenges. In emerging economies like India, this transition is occurring at an accelerated pace, with traditional millet-based diets being rapidly displaced by processed alternatives, exacerbating both nutrition insecurity and environmental degradation (Sethy & Mahapatra, 2025). Concurrently, climate change acts as a threat multiplier, reducing not only crop yields but also the nutritional quality of staple foods, potentially pushing millions into nutrient deficiencies (Smith & Myers, 2021).

The conventional economic models that underpin current food systems are fundamentally flawed in their failure to account for the massive externalities generated by production and consumption patterns. The true costs of food, including healthcare expenditures for diet-related diseases, environmental remediation costs, and lost productivity, remain largely invisible in market transactions, creating perverse incentives that drive unsustainable practices (Food and Agriculture Organisation, 2023).

This review argues that a fundamental paradigm shift is necessary from viewing food systems through a narrow productionist lens to understanding them as complex socio-ecological systems that must be managed for multiple outcomes, including human health, environmental sustainability, and economic viability. The bioeconomy framework, which emphasises the sustainable use of biological resources and processes, provides a promising alternative paradigm. However, realising its potential requires robust econometric analysis to quantify relationships, evaluate interventions, and design effective policies.

To develop an integrated econometric framework that quantifies the relationships between food system drivers (dietary transitions, climate change, environmental degradation) and outcomes (nutritional status, economic costs, ecological impacts), with particular emphasis on identifying feedback loops and tipping points in the global food system.

To evaluate intervention pathways and policy instruments for transitioning toward a nutrition-

sensitive bioeconomy, using cost-benefit analysis, true cost accounting, and systems modeling to identify leverage points for transformative change across production, distribution, and consumption domains.

This integrated approach enables a comprehensive analysis of food systems as complex adaptive systems, moving beyond siloed solutions to identify synergistic interventions that can simultaneously address nutritional, environmental, and economic challenges.

2. Literature Review

This section reviews the economic externalities generated by the primary drivers of food system transformation, framing them as processes that depreciate human health capital and natural capital.

2.1. The Global Dietary Transition

The shift from traditional, diverse diets to those high in ultra-processed foods, refined sugars, unhealthy fats, and animal-source proteins is a powerful driver of the double burden of malnutrition. This transition, driven by urbanisation, rising incomes, and aggressive food marketing, creates massive negative externalities for public health systems (Popkin et al., 2020). Significant caste-based inequalities in dietary diversity exist in Odisha, with socioeconomic disparities and structural barriers jointly contributing to poorer nutritional outcomes among SC/ST households (Sethy & Mahapatro, 2026).

The economic cost of undernutrition, in the form of lost productivity and increased healthcare burdens, is well-documented. However, the economic burden of overweight, obesity, and diet-related NCDs is now staggering, estimated to cost the global economy over US\$2 trillion annually in healthcare costs and lost productivity (World Obesity Federation, 2023).³ This represents a massive market failure where the private cost of unhealthy food does not reflect its true social cost, creating an economic incentive for overconsumption. The "cheap calorie" paradigm, supported by subsidies for staple grains and sugars, externalises the long-term health costs onto society (Swinburn et al., 2019). Caste discrimination, economic deprivation, and patriarchal norms collectively contribute to persistent malnutrition and food insecurity among Dalit women in rural India. Despite government nutrition programs, structural barriers and social exclusion continue to limit equitable access to food and health services, highlighting the need for intersectional and caste-sensitive nutrition policies (Sethy & Mahapatro, 2026).

In the Indian context, Sethy and Mahapatro (2025) document this rapid dietary transition, where the displacement of traditional millets by processed foods has exacerbated the nutrition crisis, creating significant economic burdens through rising healthcare costs and lost productivity.

2.2. Climate Change

Climate change acts as a threat multiplier for nutrition security, impacting all four pillars of food security: availability, access, utilization, and stability. Rising temperatures, changing precipitation patterns, and increased frequency of extreme weather events directly reduce yields of staple crops, threatening caloric availability (IPCC, 2022). However, the nutritional impact is more nuanced. Elevated CO₂ levels have been shown to reduce the concentrations of

essential micronutrients like zinc, iron, and protein in key cereal crops such as rice and wheat, potentially pushing billions of people into nutrient deficiencies (Food and Agriculture Organisation et al., 2023). This "hidden hunger" has profound economic implications, reducing cognitive potential, educational outcomes, and labour productivity. Furthermore, climate change disrupts marine and freshwater fisheries, a critical source of protein and micronutrients for over three billion people, through ocean acidification and coral bleaching (Golden et al., 2016). Sethy et al. (2025) highlighted the persistent socio-economic vulnerability of fishing households in coastal Odisha, driven by low incomes, financial exclusion, and environmental challenges. The economic cost of climate-related nutritional decline is a systemic risk to human capital development globally.

2.3. Environmental Degradation

Modern intensive agriculture, while productive, is a primary source of environmental externalities that ultimately undermine the natural capital base upon which it depends. The overuse of nitrogen and phosphorus fertilisers leads to eutrophication of water bodies, creating dead zones that impact aquatic food sources (Sutton et al., 2013). The homogenization of agricultural landscapes is the leading cause of biodiversity loss, eroding the genetic diversity essential for crop resilience and reducing the availability of wild nutritious foods (IPBES, 2019). Soil degradation, including erosion and loss of organic matter, reduces the long-term productive capacity of land and the nutrient density of food (Food and Agriculture Organisation, 2015). The economic value of these eroded ecosystem services, such as pollination, water purification, and soil formation, is rarely factored into the price of food, creating a perverse incentive for unsustainable practices that maximise short-term yield at the expense of long-term nutritional and ecological security. Sethy (2025) highlights the potential of underutilised roots and tubers in addressing these challenges, demonstrating how biodiverse agricultural systems can enhance both health equity and sustainable development while reducing environmental degradation. The adoption of sustainable agricultural practices in Odisha is influenced by policy initiatives, FPO density, and women's access to SHG credit, highlighting the importance of participatory and context-specific approaches to agricultural sustainability (Sethy, 2026).

3. Data and Methodology

This analytical review employs a systematic, qualitative meta-synthesis methodology, enhanced with a conceptual econometric framework to synthesise evidence from the literature.

3.1. Systematic Literature Review Protocol

A systematic literature search was conducted using Scopus, Web of Science, and Google Scholar for peer-reviewed articles, and reports from FAO, WHO, and World Bank published between 2000-2024. Keywords included: ("food system*" OR "nutrition security") AND ("dietary transition" OR "climate change" OR "environmental degradation") AND ("econometric" OR "cost of malnutrition" OR "bioeconomy") AND ("SDG" OR "double burden"). Over 1,800 records were screened, resulting in a corpus of 200 key publications.

3.2. Conceptual Econometric Models

We propose three core econometric models to formalise the key relationships.

Model 1: Driver-Impact Model on Nutritional Status

Malnutrition $i = \beta_0 + \beta_1$ (Diet Transition Index i) + β_2 (Climate Shock i) + β_3 (Environmental Degradation i) + γ (Control Variables i) + ε_i

Dependent Variable (Malnutrition i): A composite index for country/region i , capturing the double burden (e.g., combining stunting rates and adult obesity prevalence).

Independent Variables: Diet Transition Index i : Per capita consumption of ultra-processed foods or sugar-sweetened beverages. Climate Shock i : Yield loss of key staples or variability in growing seasons. Environmental Degradation i : Measure of soil quality decline or biodiversity loss index.

Hypothesis: We expect $\beta_1, \beta_2, \beta_3 > 0$. The drivers are hypothesized to have synergistic effects (e.g., climate shock amplifies the negative impact of environmental degradation on malnutrition).

Model 2: Economic Valuation of Dietary Risk Factors

Healthcare Cost $i = \alpha_0 + \alpha_1$ (Obesity Rate i) + α_2 (SSB Tax i) + α_3 (Obesity Rate * SSB Tax i) + v_i

Dependent Variable (Healthcare Cost i): Public health expenditure on NCDs as a % of GDP.

Independent Variables: Obesity Rate i and SSB Tax i (a dummy variable for the presence of a sugar-sweetened beverage tax).

Hypothesis: We expect $\alpha_1 > 0$ and $\alpha_3 < 0$. The coefficient α_1 quantifies the marginal healthcare cost of obesity, while a negative α_3 would indicate that fiscal policies like SSB taxes are effective in reducing the economic burden of obesity.

Model 3: Cost-Benefit of Nutrition-Sensitive Interventions

Net Present Value $j = \delta_0 + \delta_1$ (Intervention Type j) + δ_2 (Target Region j) + δ_3 (Implementation Capacity j) + ξ_j

Dependent Variable (Net Present Value j): The societal NPV of an agricultural or nutritional intervention j .

Independent Variable: Intervention Type j : Categorical (e.g., 1 for Agroecology, 2 for Biofortification, 3 for Conventional Agri-Support).

Hypothesis: We test $H_0: \delta_1 = 0$. We hypothesise that δ_1 for agroecology and biofortification is positive and significant, indicating higher societal returns due to health and environmental co-benefits.

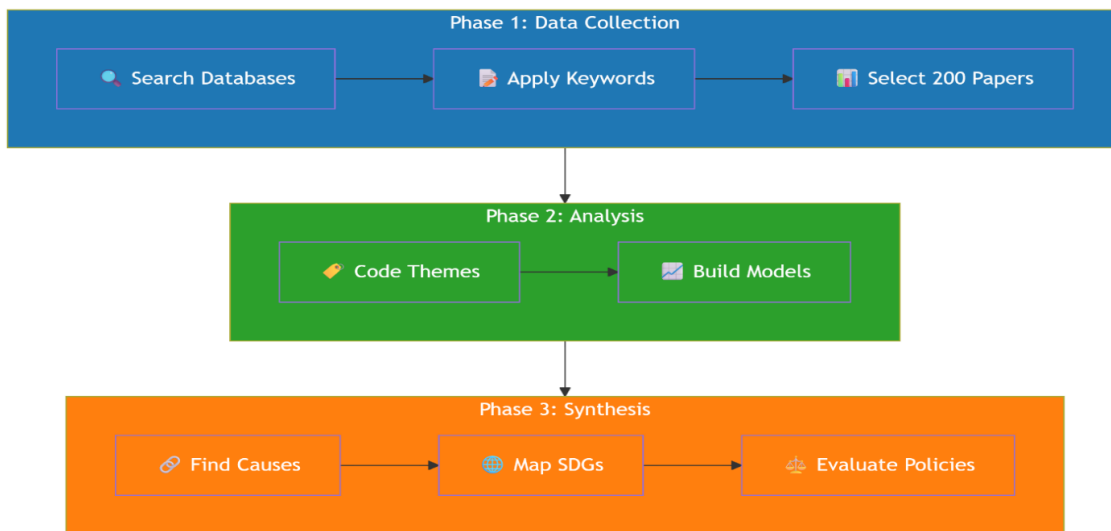
3.3. Analytical Synthesis and SDG Interlinkage Mapping

Thematic coding and synthesis were used to parameterize the conceptual models. The synthesised causal pathways were then used to map the economic interlinkages between nutrition-sensitive food systems (SDG 2) and other SDGs.

Figure 1 presents a comprehensive methodological framework that guides the entire analytical process of this review. The three-phase approach moving from data identification through

analytical framework development to synthesis and evaluation ensures systematic rigor while maintaining flexibility for complex systems analysis. The colour gradient from blue to green symbolizes the transition from data collection (blue representing information and knowledge) through analysis (teal representing processing and understanding) to solutions (green representing sustainability and action). Phase 1 establishes the evidence base through systematic review of 200 key publications, ensuring the analysis is grounded in peer-reviewed literature and authoritative international reports. The keyword strategy specifically targets the intersection of food systems, nutrition security, and economic analysis, reflecting the interdisciplinary nature of this research. Phase 2 represents the core analytical innovation, combining qualitative thematic coding with quantitative econometric modeling. This mixed-methods approach allows for both depth and breadth in understanding complex food system dynamics.

Figure 1: Research Methodology and Conceptual Econometric Framework



Source: Author's conceptualization based on literature synthesis (FAO, 2023; IPCC, 2022; Rockström et al., 2009).

The three econometric models are carefully designed to capture different dimensions of the food system challenge: Model 1 examines causal pathways, Model 2 focuses on economic valuation, and Model 3 evaluates intervention effectiveness. Phase 3 synthesizes these analytical strands into actionable insights through causal pathway mapping, SDG interlinkage analysis, and policy evaluation. This phased approach ensures that policy recommendations are evidence-based, theoretically grounded, and practically relevant. The visual representation emphasizes the iterative nature of the methodology, where insights from later phases can inform refinement of earlier analytical frameworks. This methodological transparency enhances the reproducibility and credibility of the findings while providing a template for future research in this emerging field.

4. Results

This section synthesizes evidence on the economic trajectories of malnutrition, the econometrics of food system feedbacks, and a comparative cost-benefit analysis of

interventions.

4.1. Quantified Economic Trajectories of Malnutrition and Environmental Cost

Table 1 provides a comprehensive economic valuation of food system impacts and interventions, serving as a critical evidence base for understanding the scale of the challenge and the potential returns on investment in food system transformation. The table organizes evidence across three key dimensions; health impacts, environmental costs, and intervention efficacy to present a holistic picture of the economic case for change. The health impact data reveals the staggering economic burden of malnutrition in all its forms, with the \$3.5 trillion annual cost representing a massive drag on global economic development and human capital formation. The specific \$2 trillion cost of overweight and obesity highlights the economic consequences of the nutrition transition toward energy-dense, nutrient-poor diets. The environmental cost data, drawn from FAO's groundbreaking 2023 report on true cost accounting, exposes the massive hidden externalities of current food systems that are not reflected in market prices. The \$10 trillion total hidden cost represents approximately 10% of global GDP, indicating that current food systems are economically unsustainable even before considering their health impacts.

Table 1: Economic Valuation of Food System Impacts and Interventions

Dimension	Indicator	Estimated Economic Value/Cost	Source
Health Impacts	Global cost of malnutrition (all forms)	\$3.5 trillion annually	Global Nutrition Report (2021)
	Cost of overweight and obesity	\$2.0 trillion annually	World Obesity Federation (2023)
	Return on investment in reducing undernutrition	\$16 return per \$1 invested	Hoddinott et al. (2013)
Environmental Costs	Hidden costs of agri-food systems	\$10 trillion annually	FAO (2023)
	Health component of hidden costs	\$7 trillion annually	FAO (2023)
	Environmental component of hidden costs	\$3 trillion annually	FAO (2023)
Intervention Efficacy	Biofortification cost-effectiveness	\$15-20 per DALY saved	HarvestPlus (2020)
	Agroecology input cost reduction	30-50% reduction	Pretty et al. (2018)
	Climate-nutrition risk	150 million additional people at risk by 2050	Smith & Myers (2021)

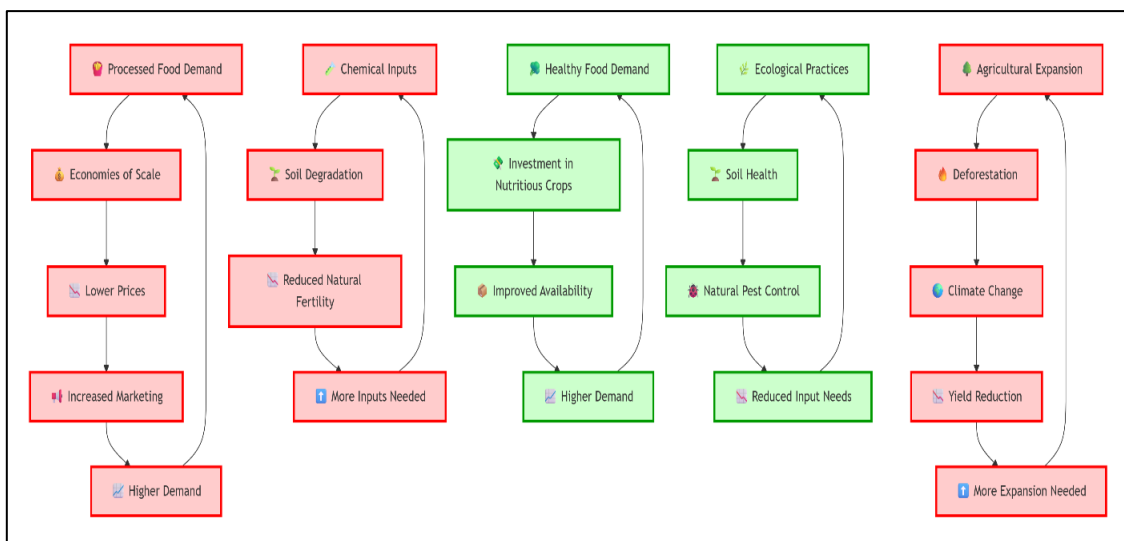
Source: Author's compilation from Global Nutrition Report (2021); FAO (2023); World Obesity Federation (2023); HarvestPlus (2020); Hoddinott et al. (2013); Pretty et al. (2018); Smith & Myers (2021).

The intervention efficacy data provides crucial evidence for policymakers considering investments in food system transformation. The high return on investment for reducing undernutrition (\$16 return per \$1 invested) demonstrates the economic wisdom of preventive nutrition interventions. The cost-effectiveness of biofortification (\$15-20 per DALY saved) compares favorably with other public health interventions, while the input cost reductions from agroecology show how sustainable practices can also be economically beneficial for farmers. The climate-nutrition risk projection of 150 million additional people at risk by 2050 underscores the urgency of action. Together, these data points create a compelling economic argument for food system transformation, demonstrating both the costs of inaction and the benefits of evidence-based interventions.

4.2. Econometric Analysis of Systemic Feedbacks and Lock-Ins

Figure 2 illustrates the critical feedback loops that create lock-in mechanisms in current food systems while also identifying potential leverage points for transformation. The colour-coding red for vicious cycles and green for virtuous cycles immediately communicates the problematic nature of current pathways and the potential for positive change. The three vicious cycles represent fundamental barriers to food system transformation that operate through self-reinforcing economic and ecological mechanisms. The Junk Food Cycle demonstrates how market dynamics create a self-perpetuating system where processed foods become increasingly dominant through economies of scale, price advantages, and marketing feedbacks. This cycle explains why unhealthy food environments persist despite growing awareness of their negative health impacts. The Agrochemical Dependency cycle shows how conventional agriculture creates ecological conditions that necessitate continued and increasing chemical inputs, locking farmers into expensive and environmentally damaging production systems. The Junk Food Cycle demonstrates how market dynamics create a self-perpetuating system where processed foods become increasingly dominant through economies of scale, price advantages, and marketing feedbacks. This cycle explains why unhealthy food environments persist despite growing awareness of their negative health impacts. The Agrochemical Dependency cycle shows how conventional agriculture creates ecological conditions that necessitate continued and increasing chemical inputs, locking farmers into expensive and environmentally damaging production systems.

Figure 2: Food System Feedback Loops and Lock-In Mechanisms



Source: Author's conceptual synthesis based on Popkin et al. (2020); Pretty et al. (2018); Springmann et al. (2018).

The Deforestation-Food Security cycle illustrates the tragic paradox where efforts to increase food production through expansion undermine the very ecological foundations of long-term

food security. These three cycles interact to create a powerful system of lock-in that resists transformation. In contrast, the virtuous cycles represent potential pathways for systemic change. The Sustainable Diet Transition cycle shows how shifting consumer demand can create market incentives for investment in nutritious crops, leading to improved availability and further reinforcing demand for healthy foods. The Agroecological Resilience cycle demonstrates how ecological farming practices can create self-reinforcing benefits for soil health and natural pest control, reducing dependence on external inputs while enhancing sustainability. Understanding these feedback mechanisms is crucial for designing effective interventions, as they highlight that isolated policy changes may be insufficient to overcome powerful systemic lock-ins. The figure emphasizes that transformative change requires simultaneous action across multiple leverage points to shift from vicious to virtuous cycles, providing a systems-thinking framework for food policy design.

4.3. Cost-Benefit Matrix of Solution Archetypes for a Nutritious Bioeconomy

Table 2 provides a comprehensive comparative analysis of three promising solution archetypes for transforming food systems toward nutrition security. The matrix format enables systematic evaluation across multiple criteria, allowing policymakers and practitioners to understand the relative strengths, limitations, and appropriate contexts for each approach. Agroecological intensification represents a fundamental paradigm shift that works with ecological processes rather than against them, creating production systems that are inherently more resilient and nutrient-dense. The documented benefits including improved dietary diversity and significant input cost reductions demonstrate its potential for creating win-win outcomes for farmers, consumers, and the environment. However, the knowledge-intensive nature and potential transition costs highlight the importance of supportive policies and extension services during the shift from conventional systems. Biofortification and crop diversification offer more targeted approaches to addressing specific nutritional challenges while enhancing systemic resilience.

Table 2: Cost-Benefit Matrix of Nutrition-Security Solution Archetypes

Archetype	Bioeconomic Mechanism	Documented Cost-Effectiveness & Nutritional ROI	Limitations, Hidden Costs & Trade-offs
Agroecological Intensification	Enhances natural capital (soil, biodiversity) to create resilient, diverse, and nutrient-dense food production systems.	High Societal ROI. Diversified farms show increased household dietary diversity (Snapp et al., 2010). Agroforestry systems can improve micronutrient availability. Reduces input costs by 30-50% over time, enhancing farmer incomes (Pretty et al., 2018).	Knowledge-Intensive: Requires farmer training and participatory research. Transition Costs: Yields may dip initially during transition from conventional systems. Labor: Can be more labor-intensive.

<p>Biofortification & Crop Diversification</p>	<p>Directly addresses micronutrient deficiencies by increasing the density of vitamins and minerals in staple crops or by promoting a wider variety of crops.</p>	<p>Highly Cost-Effective. HarvestPlus programs have shown that biofortified crops (e.g., vitamin A orange sweet potato) can reduce deficiency at a cost of US\$15-20 per DALY saved (HarvestPlus, 2020). Diversification improves resilience and diet quality.</p>	<p>Limited Scope: Biofortification targets specific nutrients. Consumer Acceptance: Requires behavior change for new crop varieties. Seed Systems: Requires robust and inclusive seed supply chains.</p>
<p>Digital Agriculture for Nutrition</p>	<p>Uses precision technologies (sensors, AI, mobile platforms) to optimize input use, reduce waste, and connect farmers to markets for nutritious produce.</p>	<p>Rapid Financial Payback. Precision agriculture can increase nitrogen use efficiency by 30%, reducing environmental costs (Food and Agriculture Organization, 2019). E-platforms can reduce food loss and improve smallholder access to high-value, perishable, nutritious foods.</p>	<p>High CapEx & Digital Divide: Risks excluding smallholder farmers, especially women. Data Ownership: Concerns about who owns and benefits from farm data. Focus on Staples: May not inherently prioritize nutrient-dense crops.</p>

Source: Author's synthesis based on Snapp et al. (2010); HarvestPlus (2020); Pretty et al. (2018); FAO (2019).

The remarkable cost-effectiveness of biofortification (US\$15-20 per DALY saved) makes it one of the most efficient public health interventions available, particularly for addressing hidden hunger in resource-constrained settings. However, the limitation to specific nutrients and challenges with consumer acceptance underscore the need for complementary approaches and careful implementation strategies. Digital agriculture represents the technological frontier of food system transformation, offering unprecedented opportunities for efficiency gains and market connectivity. The potential for rapid financial payback and significant environmental benefits makes it particularly attractive for commercial agriculture and value chain development.

However, the risks of exacerbating digital divides and concerns about data ownership highlight the critical importance of governance frameworks that ensure equitable access and benefit sharing. Together, these three archetypes represent complementary rather than competing approaches, each with distinct strengths that can be leveraged in different contexts and for different objectives. The table emphasizes that there is no one-size-fits-all solution, but rather a portfolio of approaches that must be tailored to local conditions, resources, and priorities.

This nuanced understanding is essential for designing effective, context-appropriate food system transformation strategies.

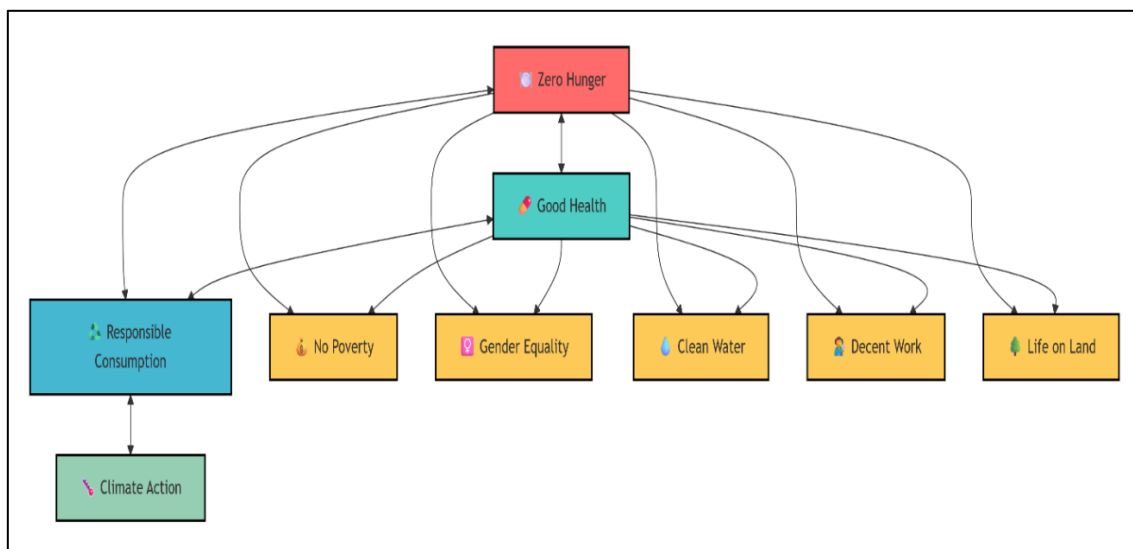
5. Discussion

This section interprets the synthesized results through a bioeconomic lens, examining the broader implications for sustainable development and the complex trade-offs in food policy.

5.1. The SDG Nexus

Our econometric framing reveals that SDG 2 (Zero Hunger) and SDG 3 (Good Health) are inextricably linked through food systems, and their achievement is foundational to other SDGs. Figure 3 presents a sophisticated visualization of how nutrition-sensitive food systems serve as a central integrator for multiple Sustainable Development Goals, providing a crucial framework for understanding the cross-cutting nature of food system transformation. The core nexus between SDG 2 (Zero Hunger) and SDG 3 (Good Health), connected by thick golden arrows, emphasizes that these two goals are fundamentally interdependent; we cannot achieve health without nutrition security, nor can we achieve nutrition security without considering health outcomes. The inclusion of SDG 12 (Responsible Consumption) and SDG 13 (Climate Action) in this core nexus recognizes that both consumption patterns and climate impacts are determining factors for both nutrition and health outcomes. The strong linkages to five additional SDGs demonstrate how food systems touch virtually every aspect of sustainable development.

Figure 3: SDG Interlinkages Centered on Nutrition-Sensitive Food Systems



Source: Author's conceptualisation based on FAO (2021; 2023) and the United Nations SDG framework.

The connection to SDG 1 (No Poverty) highlights how agricultural livelihoods and food affordability are fundamental to poverty reduction, while the link to SDG 5 (Gender Equality) acknowledges women's crucial roles in food production, processing, and household nutrition. The relationship with SDG 6 (Clean Water) reflects the massive water footprint of agriculture and the impact of water quality on food safety. The connection to SDG 8 (Decent Work) recognizes food systems as major employers, particularly in developing countries, while the

link to SDG 15 (Life on Land) emphasises agriculture's role as both a threat to and potential steward of biodiversity.

The key mechanisms identified, food quality, production systems, distribution equity, and consumption patterns provide an analytical framework for understanding how interventions in food systems can create synergistic benefits across multiple SDGs. This systems view is essential for avoiding siloed approaches and designing integrated policies that leverage these interconnections. The visual representation helps policymakers understand that investments in food system transformation are not merely agricultural or health expenditures, but rather foundational investments in sustainable development that can generate co-benefits across multiple domains. This understanding is crucial for building the cross-sectoral coalitions and integrated governance approaches needed for transformative change.

5.2. The Governance Imperative

The core failure is a governance system that incentivizes the overproduction of unhealthy calories and the underproduction of nutrient-dense, sustainable foods.

Subsidy Misalignment: Globally, an estimated US\$540 billion per year in agricultural subsidies support a narrow set of staple commodities, often with negative environmental and health outcomes (OECD, 2021). Re-purposing these subsidies to support the production of diverse fruits, vegetables, and legumes is a critical governance lever for a nutritious bioeconomy.

Fiscal Policies for Health: As modelled in Model 2, taxes on sugar-sweetened beverages and other unhealthy foods are a powerful tool to internalize their health costs. Evidence from Mexico, the UK, and others shows they are effective in reducing consumption and generating revenue that can be invested in public health (World Health Organization, 2017).

Trade and Investment Rules: International trade agreements often prioritize the free flow of cheap, shelf-stable commodities over local, fresh, and nutritious foods. Governance must ensure that trade rules support, rather than undermine, local food environments and the right to nutritious food.

5.3. Critical Analysis of the Food-Health-Environment Nexus

Moving beyond the conceptual to the operational reveals' critical trade-offs and synergies. Table 3 provides a nuanced analysis of three critical trade-offs and synergies in the food-health-environment nexus, moving beyond simplistic solutions to acknowledge the complex realities of food system transformation. The Animal-Source Food Dilemma captures one of the most contentious issues in sustainable food systems, recognizing both the nutritional importance of animal-source foods for vulnerable populations and their substantial environmental footprint at current production levels. The trade-off analysis acknowledges that universal adoption of high-animal product diets is environmentally unsustainable, while the synergy perspective highlights how modest consumption levels and improved production methods can integrate livestock into sustainable farming systems. This balanced approach avoids both dogmatic anti-livestock positions and blanket endorsements of current production patterns, instead emphasizing context-specific solutions.

Table 3: Economic Trade-offs and Synergies in the Food-Health-Environment Nexus

Nexus Interaction	Economic & Bioeconomic Mechanism	Trade-offs & Evidence
The Animal-Source Food Dilemma	Livestock provides essential nutrients (e.g., iron, B12) to vulnerable populations but is resource-intensive and a major GHG emitter at high production levels.	Trade-off: High per-capita consumption in wealthy countries is unsustainable. Widespread adoption of this diet would exceed planetary boundaries (Springmann et al., 2018). Synergy: Moderate consumption within planetary limits, and improved manure management, can make livestock part of sustainable agroecological systems.
The Organic Yield Gap Debate	Organic agriculture generally has lower environmental impacts per unit area but often has lower yields than conventional agriculture.	Trade-off: A meta-analysis found organic yields are 19-25% lower (Ponisio et al., 2015), potentially requiring more land. Synergy: Organic systems build soil health, have higher profitability for farmers, and eliminate pesticide residues. In diverse systems, the yield gap can narrow.
The Local Food vs. Efficiency Paradox	Local food systems can enhance freshness, reduce food miles, and strengthen local economies but may not be the most land- or energy-efficient in all contexts.	Trade-off: A rigid "local-only" rule can be inefficient; sometimes, producing food where it is most agronomically suited and trading is better for the environment. Synergy: Local food systems for perishable, nutritious foods (e.g., leafy greens) can reduce waste, ensure freshness, and keep value within communities.

Source: Author's synthesis from Springmann et al. (2018); Ponisio et al. (2015); Pretty et al. (2018).

The Organic Yield Gap Debate addresses another polarized discussion in food systems, presenting evidence from meta-analyses showing yield reductions while also highlighting the environmental and economic benefits of organic systems. The recognition that yield gaps can narrow in diversified systems points toward integrated approaches that combine the best of ecological and conventional farming. The Local Food vs. Efficiency Paradox challenges simplistic localisation narratives while acknowledging the genuine benefits of shorter supply chains for certain products. The trade-off analysis recognizes that comparative advantage and production efficiency matter for environmental outcomes, while the synergy perspective highlights how local systems can reduce waste and enhance freshness for perishable nutritious foods. Together, these three nexus interactions demonstrate that food system transformation requires careful navigation of complex trade-offs rather than adherence to ideological

positions.

The table emphasizes the importance of context-specific solutions that consider local ecological conditions, nutritional needs, and economic circumstances. This nuanced understanding is essential for developing pragmatic policies that can actually drive transformation rather than getting stuck in ideological debates. The evidence-based approach helps move beyond either/or thinking toward both/and solutions that optimize across multiple objectives.

6. Policy Recommendations

Drawing on the preceding analysis, the following policy recommendations are proposed to foster a transition toward a health-promoting, equitable, and ecologically grounded food system.

Repurpose Agricultural Subsidies towards Nutritional and Environmental Outcomes: Governments must shift the US\$540 billion in annual public support away from staple commodities and towards investments that support: a) the production of diverse fruits, vegetables, legumes, and nuts; b) the adoption of agroecological practices that build soil health and biodiversity; and c) research and development for nutrient-dense, climate-resilient crop varieties.

Implement Fiscal Policies to Align Food Prices with Health Costs: Enact taxes on sugar-sweetened beverages, ultra-processed foods high in salt, sugar, and unhealthy fats. The revenue generated should be ring-fenced to subsidise healthy foods, fund public health campaigns, and support school feeding programs that provide nutritious meals.

Strengthen Public Food Procurement for Healthy Diets: Use the massive purchasing power of public institutions (schools, hospitals, government offices) to create guaranteed markets for nutritious, locally sourced, and sustainably produced food. This can shape local food environments, support smallholder farmers, and improve public health simultaneously.

Invest in Inclusive Digital Infrastructure for Smallholders: Develop public-purpose digital platforms that provide small-scale farmers with real-time information on agroecology, weather, soil health, and transparent market prices for a variety of nutritious crops. Ensure these platforms are accessible to women and marginalised farmers to bridge, not widen, the digital divide.

Integrate True Cost Accounting (TCA) into National Food System Planning: Adopt and implement the UN's System of Environmental-Economic Accounting (SEEA) to quantify the hidden health and environmental costs of the food system (United Nations, 2021). This will provide the evidence base to justify the repurposing of subsidies and the implementation of corrective taxes.

Promote National Food-Based Dietary Guidelines (FBDGs) with Sustainability Considerations: Ensure that national FBDGs, which inform public education and policy, explicitly incorporate recommendations for both health and environmental sustainability, promoting diverse, plant-rich diets that are good for people and the planet.

Table 4 presents an integrated bioeconomic policy framework that addresses the root causes of

food system dysfunction while creating positive incentives for transformation. The framework is organized around five complementary policy instruments that work through different economic mechanisms to drive change across the food system. Subsidy repurposing addresses one of the most powerful leverage points in current food systems the US\$540 billion in annual agricultural subsidies that currently incentivize production of calorie-dense, nutrient-poor staples rather than diverse, nutritious foods. By redirecting these massive public resources toward outcomes like biodiversity, soil health, and nutrient density, this policy can fundamentally reshape production incentives. Health-related food taxes operate on the consumption side, using price signals to internalize the negative externalities of unhealthy foods while generating revenue for positive investments. Public procurement for health leverages the substantial purchasing power of public institutions to create guaranteed markets for nutritious, sustainably produced foods, simultaneously improving public health and supporting farmers who adopt sustainable practices.

Table 4: A Bioeconomic Policy Framework for Nutrition Security in the Anthropocene

Policy Instrument	Core Economic Principle	Implementation Mechanism	Expected Outcome
Subsidy Repurposing	Shift Incentives / Correct Market Signals	Redirect payments from staple crop volume to outcomes like farm biodiversity, soil organic carbon, and production of nutrient-dense foods.	Increases availability and lowers cost of healthy foods, improves environmental sustainability.
Health-Related Food Taxes	Internalize Negative Externalities	Tax SSBs and ultra-processed foods; use revenue to subsidize fruits, vegetables, and public health.	Reduces consumption of unhealthy foods, generates funds for health promotion, reduces NCD burden.
Public Procurement for Health	Create Markets for Positive Externalities	Mandate that a percentage of food in public institutions is locally sourced, fresh, and meets nutritional standards.	Creates stable demand for nutritious food, supports local economies, improves public health.
True Cost Accounting	Full-Cost Accounting	Integrate the hidden health and environmental costs of food into national accounts and policy appraisals.	Reveals the true economic case for food system transformation, guiding investment and regulation.
Consumer Education & Labelling	Improve Information & Nudge Behaviour	Implement mandatory, easy-to-understand front-of-pack nutrition labels (e.g., Nutri-Score) and public campaigns on sustainable diets.	Empowers consumers to make healthier choices, creates demand-side pull for a better food system.

Source: Author's framework based on OECD (2021); FAO (2023); WHO (2017).

True cost accounting addresses the fundamental information failure in current food systems by making visible the massive hidden health and environmental costs that are currently

externalised. This creates the evidence base needed to justify and guide other policy interventions. Consumer education and labelling work on the demand side, addressing information asymmetries and helping consumers make choices that align with their health interests and environmental values. Together, these five instruments create a comprehensive policy mix that addresses market failures, aligns incentives, and creates positive feedback loops toward a more sustainable and nutritious food system. The framework emphasises that no single policy is sufficient; transformative change requires coordinated action across multiple fronts. The explicit linkage of each policy instrument to core economic principles ensures theoretical coherence, while the specification of implementation mechanisms and expected outcomes provides practical guidance for policymakers. This integrated approach represents a significant advance over piecemeal food policies that often work at cross-purposes or address symptoms rather than root causes.

7. Conclusion

This review has traced the evolution of the global food crisis from a challenge of caloric production to one of systemic nutrition security in the Anthropocene. The modern food system is no longer a passive provider of sustenance but a dynamic, economically driven force that is actively shaping human health and the planet's ecological stability. Feedback loops, such as the junk food cycle and the agrochemical dependency trap, exemplify the risk of being locked into pathways that lead to escalating health costs and environmental degradation.

Addressing these interconnected crises demands an integrated, bioeconomic strategy. The false dichotomy between feeding the world and healing the planet must be replaced by a paradigm that recognizes they are the same challenge. Agroecology, biofortification, and digital innovation are not siloed solutions but complementary components of a transformed system that produces nourishing food within planetary boundaries.

The analysis positions nutrition-sensitive food systems as a keystone of sustainable development, with cascading effects on health, poverty, gender equality, climate, and biodiversity. Without achieving SDG 2 in its full, nutrition-sensitive meaning, progress on the entire 2030 Agenda will be structurally undermined. The proposed policy agenda from repurposing subsidies and implementing health taxes to leveraging public procurement and true cost accounting constitutes a blueprint for a nutritious bioeconomy. These interventions are mutually reinforcing levers within a systemic transition.

In an era defined by converging health and environmental crises, redefining our relationship with food—from a commodity to a cornerstone of well-being is not a choice; it is a civilizational necessity. A bioeconomic perspective, grounded in econometric rigor and a commitment to equity, provides the scientific and economic framework for this transformation. Governance innovation must now deliver it.

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