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Review Article

Food Systems, Climate Change, and Nutritional Security in the 21st Century

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Abstract

The global food system of the 21st century is at a serious crossroads, growing more stressed by the growing climate change and unable to provide adequate and fair nutritional security of the worldwide population. Although the global food production has grown since the Green Revolution, this agricultural growth has been achieved at the expense of environmental degradation, diets of homogeneity, and aggravation of micronutrient deficiencies due to increasing atmospheric CO_2, extreme weather and agroclimatic changes. The traditional measures of food security which are narrowly pegged on the sufficiency of calories overlooks the ever-increasing plight of the hidden hunger and diet-related noncommunicable diseases, which are both rising in the stress of climatic conditions. The review is critical because it is practicalized how climate adaptation plans and nutritional outcomes have become structurally disengaged by showing how techno-optimistic solutions have a tendency to ignore equity, cultural foodways, and metabolic well-being. We build an integrative strategy that places nutritional security as more of a downstream delivery as a design need of climate-resilient food systems. Based on the new evidence of the biogeochemistry, digital agrifood governance, marine micronutrient ecology, and circular metabolism, and epigenetic nutrition, we recognize five transformative pathways that redistribute justice, biological complexity, and intergenerational wellbeing. Such a policy move of decoupling the quantity of food and its quality is challenged in this analysis and it suggests a paradigm shift to food systems, which are capable of feeding people and the planet during a period of climatic uncertainty.

Keywords: Nutritional Climate Debt, Digital Food Sovereignty, Marine Micronutrient Collapse, Circular Nutrient Metabolism, Epigenetic Dietary Programming, Climate-Nutrition Nexus, Metabolic Equity.

1. INTRODUCTION

In the last century, world food systems have been shifting radically, moving away from projects, subsistence-based models into globalized and industrialized networks that encompass production, distribution, and consumption of millions of actors (Krätke *et al.*, 2014). This transformation, which was brought about by the Green Revolution and the ensuing development of agricultural science, had a drastic effect on both the volume of calories produced and the frequency of acute hunger in most areas, but also locked in structural injustices, environmental destruction, and nutritional disequilibrium. As yields increased, dietary variety generally decreased, and the homogenization of world cuisines based on a small range of energy-rich yet nutritionally deficient staples helped to create a paradoxical coexistence of undernutrition and obesity that is now seen as one of the defining problems of contemporary nutritional security (Saxena *et al.*, 2025). To add to these systemic vulnerabilities, climate change has become a destabilizing factor, destabilizing the very basis of agricultural production. Increasing temperatures, unpredictable precipitation patterns, extreme weather events, and changing agroecological zones are already reducing agricultural output, undermining the viability of livestock, and affecting fisheries, and they affect the populations which are low-income and agrarian-dependent. These climatic strains do not only threaten food supply, but also destroy access and use, because food quality, food volatility, and disruption of supply chains harm the nutritional sufficiency of diets on a global scale (Saccone *et al*., 2025). The environmental stressors and the socio-economic determinants further compound the already existing disparities to show how food insecurity is no longer a factor of scarcity, but rather a case of system inefficiencies, power imbalances, and policy failures that are inherent within the global food architecture.

Food systems in the past were determined by localized ecological conditions, cultural practices and cyclic rhythms of the seasons and promoted diverse cropping systems and cultures of food resiliency (Zuza *et al*., 2024). The period following the WorldWar-2, however, brought about a period of amplification, automation, and the opening of global trade without having the considerations of diversity and sustainability (Selcer *et al*., 2009). Although this model was effective in sustaining an increasing population, it was at a significant ecological cost, soils became depleted, water resources were degraded, and greenhouse gases were emitted in large amounts. Agriculture has today contributed almost a quarter of all emission in the world and this is a kind of feedback mechanism whereby food production leads to climate change which in turn compromises the very conditions that are required to support food production (Thakur *et al*., 2024). This vicious cycle is especially severe in the tropical and subtropical areas, where smallholder farmers as a significant portion of the global food production are increasingly threatened by heat stress, drought and pest attacks. In the meantime, urbanization and the shifting pattern of consumption have further separated consumers to food sources undermining traditional systems of knowledge and increasing reliance on shaky world supply chains susceptible to climatic and geopolitical disasters (Nikonenko *et al*., 2025).

Still, food security is evasively elusive to billions of people not just because of the caloric sufficiency, but also because of the regular availability of various, safe, and nutrient-intensive foods (Pingault *et al*., 2017). Micronutrient deficiencies can also be referred to as hidden hunger and it still remains even in situations of so-called food abundance which is a part of the disconnection of the quantity of food and the quality of this food. The decreases in protein, iron and zinc content of staple foods like rice and wheat due to climate changes also pose a significant risk to the nutritional performance of the vulnerable population, particularly women and children (Ebadi *et al*., 2025). Simultaneously, ultra-processed dishes rich in sugar, salt and non-nutritious fats have spread both in high- and low-income environments in increasing numbers across the globe, leading to the spread of diet-related non-communicable diseases. This twin malnutrition blow-out highlights the insufficiency of purely production-centered strategies and the need to implement integrated interventions, that is, to mitigate the food environment, consumer behavior, and structural determinants of health (Brouwer *et al*., 2021).

A technological and institutional response to it is a wave of technological and institutional innovations, such as precision agriculture and climate-resistant crop varieties, digital marketplaces, and circular food economies, which provides opportunities to become more resilient, cut emissions, and improve nutritional outcomes (Putri *et al*., 2024). However, their scalability, equity and sustainability remain disputed, especially when they are implemented without proper consideration of local conditions, cultural behaviour and livelihoods of small holders. In addition, the existing knowledge base is limited in its integrative frameworks that may be applied to simultaneously consider the biophysical, nutritional, economic and governance aspects of food systems in times of climate stress, with crucial gaps in our comprehension of the scale and sector synergies and trade-offs (Zeng *et al*., 2025). With the planet nearing the ecological boundaries and the world population approaching ten billion by the middle of the century, the need to reenact food systems as adaptive, equitable, and nutrition sensitive systems has never been so much needed. This necessitates both the refining of the current tools and the development of transdisciplinary research to transcend agronomy, nutrition science, climate modeling, behavioral economics and policy analysis in a manner that can produce actionable insights to decision-makers (Hammond *et al*., 2012). The way ahead requires a paradigm shift to optimizing on the yield and non-optimizing on the planet, human well-being, and social justice based on strong evidence and inclusive governance. The purpose of the review, then, is to sum up the existing evidence on dynamic interconnections between food systems, climate change and nutritional security in the 21st century, and to establish the priority research areas that will enable transformative policies and practices to a sustainable and sustaining food future.

2. Metabolic Geographies of Food Systems

Modern food systems are being reconfigured silently, but radically, due to the disruption of the biogeochemical cycles underlining the availability and bioaccessibility of vital micronutrients caused by climatic changes shown in (Fig. 1). Conventionally, nutritional studies have assumed food composition as a static property, pegged in stagnant compositional databases, which do not acknowledge the dynamic interaction of the atmospheric chemistry, soil processes and plant physiology at varying climatic regimes (Silva *et al*., 2021). New findings indicate that high concentrations of CO_2 in the atmosphere that is set to reach above 550 ppm by the mid-century directly inhibit the build-up of zinc, iron, and protein in major cereal staple food crops such as rice, wheat, and maize, as physiological and biochemical processes that dilute the nutrient density, but leave biomass intact.

These decreases, which can be estimated by the means of the stable isotopic tracing and present in Earth system models simulating coupled carbon-nutrient dynamics, indicate a latent aspect of climate risk, the loss of nutritional quality at the molecular scale, regardless of the adequacy of caloric intake (Lumsden *et al*., 2024). It is not a uniformly distributed phenomenon; it is a spatially lumpy process, created by edaphic factors, genotypes of crops, and local climatic processes, creating an emergent set of so-called micronutrient desert areas on top of an already high malnutrition context and a low-nutritional diet. In order to predict and address these changes, it is necessary to conceptualize anew the study of the food system, which is no longer measured by agronomic yield and includes the metabolic interdependence of the human body and environmental chemistry (Ralhan *et al.,* 2024). This requires the combination of indicators of soil microbiome resilience such as nutrient mobilization and plant uptake with high-resolution climatic vulnerability indices to reflect local exposure to heat stress, changes in precipitation, and extreme events. This synthesis helps to map the area of nutritional risks in the future where the biogeochemical disruption is combined with the socioeconomic instability. More importantly, current dietary advice and community health nutrition systems are oblivious to these nutrient dilution impacts of climate, and are still issuing food-based prescriptions based on past nutrient levels that are no longer a reflection of what is being experienced on the ground (Worsley-Tonks *et al*., 2025).

This epistemic backwardness threatens to continue with suppressed hunger in the name of proper food consumption. In order to address this gap, we suggest to come up with the Nutrient Resilience Index as a spatially explicit, dynamic, measure that combines agroecological zoning with estimated human metabolic demand in a warming world. This index would render the concept of metabolic geography operational by matching the potential of regional food production with the caloric production, not with the potential of producing bioavailable micronutrients, as would be the case with a hypothetical future climate. It will require an interdisciplinarity radical that integrates biogeochemistry, nutritional epidemiology, critical geography, and Earth system modeling into a single analytical framework one that considers the nutrient flux of a warming Earth with its increasing perturbations.

Food systems can be redressed in the 21st century by being restructured around these kinds of integrative structures, this is the only way that food systems can be restructured on the basis of real nutritional security (Charlton *et al*., 2016).

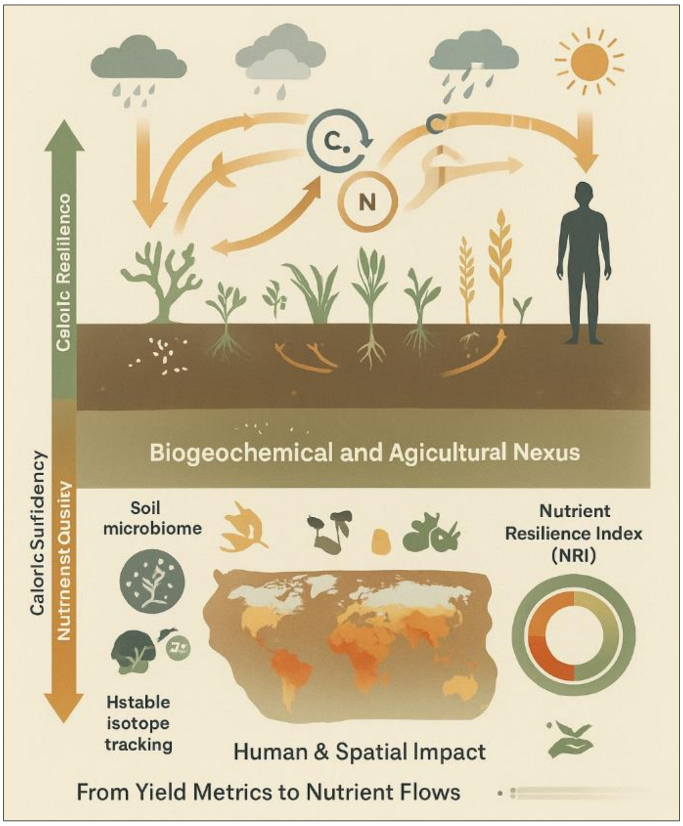

Fig. 1: Climate-induced biogeochemical disruptions are reshaping the metabolic geographies of food systems, decoupling caloric abundance from micronutrient sufficiency. The proposed Nutrient Resilience Index (NRI) integrates climate vulnerability, soil microbiome dynamics, and metabolic demand to map future nutritional risk zones and guide climate-smart nutrition policy

3. Algorithmic Food Sovereignty

The artificial intelligence and predictive analytics solutions to food systems have the potential to bring more efficiency, optimization of yields, and adaptation to the climate, but at the same time, they bring radical asymmetries of epistemic authority and power to make decisions (Yalamati *et al*., 2021). Since algorithmic systems are often deployed to make vital decisions, such as selecting a single seed type to plant, determining market-level logistics, and so forth, they tend to encode and scale up any existing biases, privileging data-saturated, high-input monocultures and ignoring low-input, biodiverse and native agroecological practices that have adapted over the centuries to local variability in climate. Not only is this technocratic drift distorting agronomic advice, but it is also actively undermining food sovereignty by replacing situated knowledge systems with black-box models, which are difficult to tell what they are based on and what they are being trained on, and which have normative priorities (Selgas-Cors *et al*., 2025).

In machine-based climate-resilient crop advisory systems, e.g. algorithms learned on commercially farmed data take a systematic under-liking in polycultural setups, landraces which are drought-resistant, and soils which are eco-protective of practices which do not fit traditional agricultural yield scales but are more nutritionally resilient and ecologically stable in stress. These omissions are not technical glitches but epistemic exclusions that go to more fundamental structural inequities of the determination of who determines what is resilience and what is efficiency in a warming world. Counterexamples, though, will indicate that AI does not necessarily qualify as a tool of epistemic centralization Community-led initiatives in the Sahel and the Andes illustrate how machine learning can be co-designed with pastoralists, smallholders, and Indigenous knowledge holders to generate hybrid forecasting tools that anticipate not only crop failure but also micronutrient shortfalls, drawing on both satellite-derived climate signals and generations of phenological observation (Gore *et al.,* 2024). Such platforms do not see data as a product that can be mined but rather as a resource of collective benefit that can be regulated by participatory protocols such that predictive products are provided in accordance with the needs of the local diet, cultural tastes, and ecological limitations.

Based on such innovations, an epistemic justice framework in digital food governance needs to be developed, which sets up non-negotiable principles of inclusive data sovereignty, algorithmic transparency, and nutritional fairness. This comprises of community rights to own, interpret, and control agricultural data, minimum disclosure of model assumptions and uncertainty limits, and measures of performance which prioritize dietary variety and the fulfillment of micronutrients over caloric quantity. More importantly, this form of governance should go beyond voluntary guidelines to binding policy tools. The agri-food AI can find an opportune way to be regulated through the Loss and Damage framework of the UNFCCC, which acknowledges that an algorithmic malfunction can be a kind of non-economic loss that undercuts cultural foodways, knowledge sharing, and resiliency in the disaster-prone regions. The integration of the concepts of epistemic justice in the international climate financing systems may precondition the AI implementation based on co-design, local validation, and fair distribution of benefits. To move to an algorithmic food sovereignty therefore, requires not merely technical solutions, but the reimagining of digital innovation as a practice of relationship, which is based on climate justice, data ethics and pluralistic epistemologies that keep food cultures resilient.

This is an integrative vision, developed at the boundary between science and technology studies, food systems governance and climate justice to turn AI into a field with no solution but a field of power, knowledge and food, which must be democratically negotiated shown in (Table. 1) (Rivera *et al*., 2019).

Table 1: Algorithmic Food Sovereignty Governing AI-Driven Food Systems in an Era of Climate Uncertainty

Dimension	Current Challenges	Risks	Solutions / Future Directions	Examples
Data and Ownership	AI in agriculture relies heavily on large-scale data collected by private platforms, often excluding smallholder farmers and Indigenous data networks. This centralization limits transparency and local agency in data use.	Concentrated data ownership reinforces digital colonialism, undermining local control and adaptive food strategies, especially in climate-stressed regions.	Promote data sovereignty frameworks emphasizing community-owned databases, open-access climate models, and participatory sensing systems to democratize data control.	The Digital Green project in India co-develops AI tools with farmers, ensuring shared data access and local governance.
Algorithmic Bias	Machine learning models trained on industrial agriculture datasets prioritize yield maximization and	Bias perpetuates monocultural optimization and resource misallocation, reducing resilience in	Develop inclusive AI architectures that integrate multi-scalar agroecological data and bias auditing	The CGIAR AI4Ag project applies bias audits to regional crop models, ensuring

Dimension	Current Challenges	Risks	Solutions / Future Directions	Examples
	uniformity, neglecting agroecological diversity and marginal contexts.	diverse ecological zones and reinforcing inequitable decision-making.	mechanisms; encourage contextual AI training across heterogeneous landscapes.	adaptive decision support for African and Asian smallholders.
Knowledge Systems and Agroecology	AI frameworks often privilege techno-scientific knowledge over Indigenous, experiential, and local ecological wisdom, marginalizing plural epistemologies.	This erasure weakens agroecological innovation, alienates farmers from digital tools, and disrupts co-evolution between human knowledge and ecological complexity.	Implement hybrid epistemic platforms integrating local agroecological data with AI analytics; support co-design workshops bridging scientific and Indigenous expertise.	The Andean Open Knowledge Network combines local soil data with AI-driven nutrient mapping for climate-resilient cropping.
Governance and Policy	Regulatory mechanisms lag behind technological deployment, with few policies addressing AI's implications for food sovereignty, equity, or sustainability.	Unregulated AI adoption risks corporate monopolization, data misuse, and policy capture, limiting inclusive decision-making in climate adaptation.	Establish polycentric governance models linking local councils, national AI ethics frameworks, and global climate policy dialogues; require algorithmic transparency and accountability.	The EU's "Farm to Fork" digital governance strategy integrates ethical AI assessments into sustainable agriculture policy.
Ethical and Social Impacts	AI-driven food systems can exacerbate inequality by displacing labor, automating value chains, and privileging techno-capital over social equity.	Socio-technical exclusion leads to digital disenfranchisement, loss of traditional livelihoods, and erosion of community food rights under algorithmic control.	Foster just AI transitions emphasizing labor inclusion, ethical algorithm design, and social impact monitoring; embed participatory ethics boards in agritech innovation.	Sahel community-based AI cooperatives use local data for drought prediction while maintaining community ownership and labor equity.

4. The Thermal Nutrition Nexus

The increasing temperatures on the planet are creating a hidden but significant nexus between the environmental temperature stress and human nutritional physiological functions, and this is beyond the traditional temperature-only analyses of food production losses. Although climate models consistently simulate falls in crop output when it gets hotter, it does not consider the converse effect, in which heat stress also decreases food supply and the ability of the body to use it, which overlooks a positive feedback loop in which temperature stress causes a reduction in food supply and reduce the efficiency of the body to consume it at the same time (Muhammad *et al*., 2025). Occupational health, clinical nutrition, and environmental physiology all point in the same direction empirical evidence on occupational temperature effects has implicated occupational temperatures as suppressing appetite, changing the preference towards lighter and less nutrient-dense foods, and impairing gastrointestinal performance, which lowers the absorption of certain important micronutrients including iron, zinc, and B vitamins. These physiological responses, which are developed to reduce endogenous heat generation during a digestive process called diet-induced thermogenesis are maladaptive in situations where caloric and micronutrient intake is already marginal.

Emerging global temperatures are creating an unprecedented but imperative nexus regarding heat-stressing the environment and human nutritional physiology, which is out of a standard analysis involving food production losses alone. Although climate models are habitually used to predict decreases in crop yields in a warming context, they mostly ignore the response of thermal stress to human dietary behavior, digestive effectiveness and metabolic demand thus ignoring a positive feedback loop in which thermal stress itself reduces food supply and decreases the efficiency with which it is consumed (Muhammad *et al*., 2025). All the empirical data of occupational health, clinical nutrition and environmental physiology point toward a universal pattern: chronic exposure to high ambient temperatures inhibits appetite, alters macronutrient intake patterns towards decreasing fat intake and increasing protein intake, as well as increases nutrition intake with the goal of maintaining homeostatic temperature and immune functions and cell repair when thermostress occurs. This interaction forms what we call the systematic gaps in the dietary nutrient intake of populations in the warming regions due to the increased metabolic rates, compared with the nutritional content of accessible food supplies.

According to current global estimations, such as those of the IPCC and the High-Level Panel of Experts on Food Security and Nutrition (HLPE) are stuck on continentally static, temperate-zone baselines of dietary energy needs that do not consider climate-adjusted changes in human energy spending and nutrient bioavailability (Manica *et al*., 2018). Subsequently, the nutritional risk in tropical and subtropical areas where the heat stress is the most severe and the adaptive capacity the most limited is underestimated in vulnerability indices in a systematic way. Such negligence requires a basic review of dietary reference scales in climate risk models with region-specific modification of ambient temperature, humidity, and exercise patterns. In addition to recalibration, it is necessary to actively plan diets, making them rd and, in most cases, less nutrient-dense, and weakens the performance of the gastrointestinal tract, decreasing the absorption of essential micronutrients like iron, zinc, and B vitamins. The physiological mechanisms of such adaptation are adjusted to the endogenous heat generation during digestion process referred to as diet-induced thermogenesis that are maladaptive in situations where caloric and micronutrient consumption is marginal.

The idea of thermally adaptive diets is the result of food patterns being strategically designed to be highly nutritionally dense and, in terms of thermic effect, hydration capability, and bioavailability of micronutrients under heat stress. The emphasis of such diets is on easy-to-digest proteins, complex carbohydrates with moderate fibers, and water-dense fruits and vegetables with high concentrations of micronutrients and the exclusion of energy-dense and highly processed foods that increase thermal load (MacLaughlin *et al*., 2022). To achieve this vision, the approach should be integrative in nature and combine human physiology, climatology, behavioral nutrition and food systems modeling in order to simulate not only what can be produced in future conditions, but also what the human body can actually consume, absorb and use, under those same conditions. Food systems can only be truly brought to make the leap between the thermal conditions of the environment and the metabolic needs of the warming world by sealing the loop between the two (Lumsden *et al*., 2024).

5. Blue-Zone Disruption

The famous Okinawa, Sardinia, and Nicoya, among other Blue Zones of the world, are long-standing living laboratories of human longevity, where diets based on place, high in legumes, whole grains, wild greens, and fermented products overlap with high social cohesion and minimal environmental impact to provide outstanding health results. However, these nutritional-cultural ecologies have recently been put in acute danger by both the globalized food markets and by the increasing pace of climate change, which is serving as a catalyst of the dietary Westernization by destabilizing the ecological and social frameworks that support traditional foodways (Feldman *et al*., 2023). The ethnographic fieldwork and high-resolution remote sensing are suggesting a disturbing convergent: increasing sea temperatures and ocean acidification are destroying the seaweed and fish stocks in Okinawa; extended droughts in Sardinia are killing the ancient olive groves and sheep farming in pastures; unpredictable rain patterns in Nicoya are destroying the milpa system, a biodiverse maize-bean-squash polyculture upon which the diet and cultural identity depend.

The biophysical shocks not only diminish food supply, but also break up the cross-generational transmission of food culture, dislocate food rites of passage, and undermine food provisioning networks that facilitate communities in adapting to local environmental uncertainty and facilitating metabolic adaptation (Raubenheimer *et al*., 2012). This memory serves as an underappreciated climate resiliency resource, which provides alternatives to industrialized diets with low-emission, nutrient-dense foods, and cushions against chronic disease and acute food insecurity. Nevertheless, its vulnerability is amplified by the homogenizing logic of global supply chains that bombard local markets with cheap, ultra-processed imports in times of and after climate derailments and take advantage of interim loopholes in the conventional food access. The effects are dual: a quantifiable deterioration of population health, including increased obesity, diabetes, and cardiovascular disease and an invisible increase in the carbon footprint of the diet, as food of foreign origin, with high energy content, and low adaptability over time and place replace low-adaptability, low-carbon-footprint foods.

According to quantitative studies, rehabilitating climate-resilient traditional diets in such areas can prevent thousands of disability-adjusted life-years at the same time as halving or half of food-system emissions relative to present-day trends of westernization. This twofold advantage needs to be safeguarded by more than nostalgia; it needs positive action in the form of policy innovation. An effective toolkit should be implemented within the current international frameworks especially the UN Decade on Ecosystem Restoration and the Globally Important Agricultural Heritage Systems (GIAHS) of the FAO to legally identify, map and support intangible food heritage as a vital climate adapting infrastructure. These steps involve community-based seed and recipe banks, climate-guided agroecological zoning, which emphasizes the importance of heritage crops, and subsidies that incorporate the purchase of local food in the state institutions (Radeny *et al*., 2020).

Basing itself on medical anthropology, nutritional epidemiology, cultural heritage research and climate adaptation science, this approach repositions dietary tradition as a historical process and as a changing and adaptive approach to health and pathophysiology in a period of planetary disruption. Protecting Blue Zones shown in (Fig.2) is not simply the preservation of the longevity enclaves but the protection of a model of food sovereignty in which culture, ecology, and nutrition all develop together to oppose homogenization and failure (Logan *et al*., 2015).

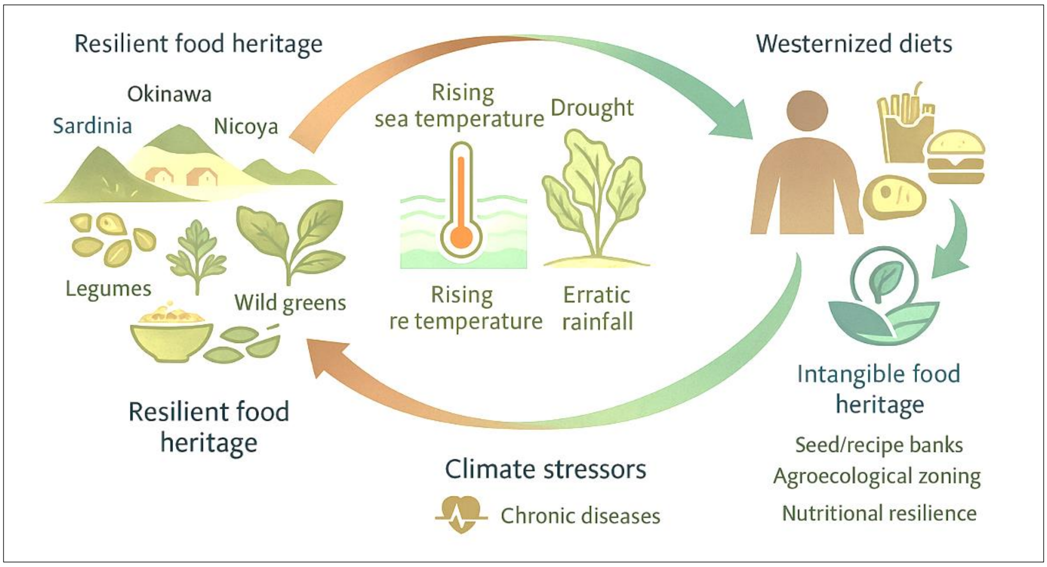

Fig. 2: Climate change disrupts traditional Blue Zone food systems, eroding nutritional cultural memory and accelerating dietary Westernization. Environmental stressors undermine local diets, health, and sustainability, highlighting the need to safeguard heritage-based food resilience for planetary and human well-being

6. Atmospheric Nutrition

Food security models have been built around the availability, access and consumption of food but have track systematically ignored an overall environmental intermediary that silently impairs the nutritional value of food as well as the human body ability to exploit it: the air we breathe. The deteriorating air quality, a combination of fossil fuel burning, industrial agriculture, and pollution events contributed to by climate, is becoming an important but not explained factor in determining nutritional insecurity (Raza *et al*., 2025). Not only is ground-level ozone and fine particulate matter (PM2.5) a respiratory/cardiovascular-health hazard, but the biochemical integrity of the food system at several levels is literally interfered with by the two.

Chronic exposure to ozone in plants inhibits photosynthetic rate and secondary metabolic processes resulting in quantifiable losses in health-promoting phytochemicals flavonoids, carotenoids, and glucosinolates in fruits and vegetables, thereby reducing their antioxidant and anti-inflammatory activity. At the same time, air pollutants weaken some of the most important physiological processes in humans, which are the metabolism of micronutrients: exposure to PM2.5 under the sun has been associated with lower levels of cutaneous vitamin D synthesis and systemic inflammation due to inhaled pollutants may suppress iron absorption and break the homeostasis of zinc, worsening micronutrient deficiencies despite a nutritionally adequate intake. These two mechanisms that lead to the reduction of food quality at the source and impairment of metabolic use in the consumer hold what we refer to as atmospheric nutrition, a latent dimension of dietary risk that is not reflected in the standard food security measures and agricultural planning (Smith-Spangler *et al*., 2012).

As a way of making this invisible danger visible, we suggest a project on developing an Atmospheric Nutrition Risk Index, which is a spatially dynamic tool merging a high-resolution forecast of air pollution with fine-grained dietary intake data across urban-rural gradients and thereby increase the nutritional vulnerability of hotspots where bad air quality meets monotonous or marginal diets. This type of index would allow making specific interventions, whether it is timing the harvests to avoid peak ozone days or focusing on indoor air filtration during nutrition programs (Nassikas *et al*., 2024). More importantly, this nexus requires a unified policy formulation. The strategies to minimize ammonia emissions, which are the leading contributors to secondary PM2.5, to the expansion of urban green areas to filter the pollutants and supply local, nutrient-rich food, and enhance dietary diversification to mitigate the pollution-related loss of nutrients bring about co-benefits. However, the existing climate mitigation roadmaps, especially national net-zero plans, are still in silos, the air quality and nutrition are viewed as different areas. This breaking down does not consider the nutritional externality of emission control: e.g. allowing incentives to encourage synthetic fertilizer application with no requirements on volatilization can inadvertently increase the formation of PM 2.5 and, by extension, nutrient status at the population level.

The genuine food future must thus overcome these disciplinary lines with the atmospheric chemistry, nutritional biochemistry, environmental health, and food policy coming into one structure that sees clean air as not a luxury but as a pillar of health in the diet. Then, and only then, can food security be refined, to include not only what we consume, but the conditions of the atmosphere in which it is cultivated, consumed and metabolized as well (Ayeni *et al.*, 2024).

CONCLUSION

The 21st-century food crisis has ceased to be characterized by the lack only and changed into the destabilizing combination of climate disruption, nutritional degradation and systemic injustice inherent to the world food systems. They occur due to the degradation of crop micronutrients and changes in heat-sensitive metabolic demands, the loss of dietary cultural memory, and the loss of nutrients through air pollution, which is the growing evidence of a multidimensional threat that is not limited by the conventional paradigms of yields. It is impossible to solve this complexity by gradually adjusting to it; we must radically reorient towards climatically resilient, nutrition sensitive and epistemically inclusive food systems. Three imperatives will be essential to the future: the interdisciplinary research that encompasses biogeochemistry, human physiology, data justice, and cultural ecology; the implementation of the policies, which would incorporate the climate mitigation, air quality regulation, and dietary health; and the multi-sectoral governance, in which smallholder knowledge, Indigenous practices, and urban-rural synergies are centralized. It is with this concerted, systems-based transformation that we are only able to achieve nourishment, beyond calories, resiliency, and justice in a planetary change.

REFERENCES

- Ayeni, O., Ogunmefun, O., Afolabil, O., Adeniyi, F., & Akpor, O. (2024, November). Food Insecurity and the Global Environment: The Role of Food Loss and Waste. In *2024 IEEE 5th International Conference on Electro-Computing Technologies for Humanity (NIGERCON)* (pp. 1-8). IEEE.
- Brouwer, I. D., van Liere, M. J., de Brauw, A., Dominguez-Salas, P., Herforth, A., Kennedy, G., ... & Ruel, M. (2021). Reverse thinking: taking a healthy diet perspective towards food systems transformations. *Food Security*, *13*(6), 1497-1523.
- Charlton, K. (2016). Food security, food systems and food sovereignty in the 21st century: A new paradigm required to meet Sustainable Development Goals.
- Ebadi, A. G., & Selamoglu, Z. (2025). Climate Change, Food Security, and Human Health: A Comprehensive Analysis of Global Problems and Sustainable Nutritional Plans. *Wah Academia Journal of Health and Nutrition*, *1*(3), 39-46.
- Feldman, C. H., & Wunderlich, S. (2023). Cultural food distancing: a conceptual discourse on the evolution of seminal to present and future models of traditional food practices. *British Food Journal*, *125*(5), 1936-1952.
- Gore, S., Patil, D., Mahankale, N., & Gore, S. (2024). Satellite imaging for precision agriculture enhancing crop management, soil condition and yield prediction. In *Emerging Trends in Smart Societies* (pp. 420-423). Routledge.
- Hammond, R. A., & Dubé, L. (2012). A systems science perspective and transdisciplinary models for food and nutrition security. *Proceedings of the National Academy of Sciences*, *109*(31), 12356-12363.
- Krätke, S. (2014). How manufacturing industries connect cities across the world: extending research on 'multiple globalizations'. *Global networks*, *14*(2), 121-147.
- Logan, A. C., Katzman, M. A., & Balanzá-Martínez, V. (2015). Natural environments, ancestral diets, and microbial ecology: is there a modern "paleo-deficit disorder"? Part II. *Journal of Physiological Anthropology*, *34*(1), 9.
- Lumsden, C. L., Jägermeyr, J., Ziska, L., & Fanzo, J. (2024). Critical overview of the implications of a global protein transition in the face of climate change: Key unknowns and research imperatives. *One Earth*, *7*(7), 1187-1201.
- Lumsden, C. L., Jägermeyr, J., Ziska, L., & Fanzo, J. (2024). Critical overview of the implications of a global protein transition in the face of climate change: Key unknowns and research imperatives. *One Earth*, *7*(7), 1187-1201.
- MacLaughlin, H. L., Friedman, A. N., & Ikizler, T. A. (2022). Nutrition in kidney disease: core curriculum 2022. *American Journal of Kidney Diseases*, *79*(3), 437-449.
- Manica, M., Guzzetta, G., Poletti, P., Filipponi, F., Solimini, A., Caputo, B., ... & Merler, S. (2018). Modelling Aedes albopictus dynamics and related Arbovirus outbreaks risk in central Italy. *ISTISAN CONGRESSI*, (18/C5), 97.
- Muhammad, S., Maridevaru, M. C., Roy, S., Chen, D., Zeng, W., Sun, L., ... & Guo, B. (2025). Piezodynamic Therapy: Unleashing Mechanical Energy and Featuristic Next Generation Therapeutic Paradigms for Glioblastoma. *ACS nano*.
- Nassikas, N. J., McCormack, M. C., Ewart, G., Balmes, J. R., Bond, T. C., Brigham, E., ... & Kipen, H. M. (2024). Indoor air sources of outdoor air pollution: health consequences, policy, and recommendations: an official American Thoracic

Society workshop report. *Annals of the American Thoracic Society*, *21*(3), 365-376.

- Nikonenko, U., Chornenka, O., Mandzinovska, K., & Struk, N. (2025). Innovation and new challenges in the world: proposals to redesign food supply and production chains to resist geopolitical and climate disruptions in a forward-looking way. *Clío. Revista de Historia, Ciencias Humanas y Pensamiento Crítico.*, (10), 187-212.
- Pingault, N., Caron, P., Kalafatic, C., Allahoury, A., Fresco, L. O., Kennedy, E., ... & Zurayk, R. (2017). Nutrition and food systems. A report by the High Level Panel of Experts on Food Security and Nutrition of the Committee on World Food Security.
- Putri, N. S. (2024). Circular Economy on Agricultural Product: Assessing Food Security Resilience and Sustainable Growth. *SUKUK: INTERNATIONAL JOURNAL OF BANKING, FINANCE, MANAGEMENT AND BUSINESS*, *3*(I), 16-28.
- Radeny, M. A., Mungai, C., Amwata, D., Osumba, J. J., & Solomon, D. (2020). Climate change, agriculture, food and nutrition security policies and frameworks in Kenya.
- Ralhan, N. (2024). The Dilemmas of Food Systems Transformation: From Concept to Impact. In *The Climate-Health-Sustainability Nexus: Understanding the Interconnected Impact on Populations and the Environment* (pp. 73-93). Cham: Springer Nature Switzerland.
- Raubenheimer, D., Simpson, S. J., & Tait, A. H. (2012). Match and mismatch: conservation physiology, nutritional ecology and the timescales of biological adaptation. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *367*(1596), 1628-1646.
- Raza, A. (2025). Air Quality Under a Changing Climate: Trends and Implications for Respiratory Diseases. *Journal of Environmental Science and Health*, *1*(1).
- Rivera, M., Pinto Correia, T., Guarin, A., & Hernandez, P. (2019). SMALL FARMS AS POTENTIAL INTERVENTION POINTS TO IMPROVE THE SUSTAINABILITY OF FOOD SYSTEMS SESSIONS.
- Saccone, D., & Vallino, E. (2025). Global food security in a turbulent world: reviewing the impacts of the pandemic, the war and climate change. *Agricultural and Food Economics*, *13*(1), 47.
- Saxena, V., Jasrotia, A., Sharma, S., & Khapre, M. (2025). Double Burden of Malnutrition as a Rising Public Health Problem: Indian Scenario. In *Handbook of Public Health Nutrition: International, National, and Regional Perspectives* (pp. 1-28). Cham: Springer Nature Switzerland.
- Selcer, P. (2009). The view from everywhere: disciplining diversity in post–World War II international social science. *Journal of the History of the Behavioral Sciences*, *45*(4), 309-329.
- Selgas-Cors, M. (2025). Sociotechnical Transformation: A Systematic Review on the Impact of Artificial Intelligence on Society and Organizations. *FinTech and Sustainable Innovation*, 1-16.
- Silva, L. C., & Lambers, H. (2021). Soil-plant-atmosphere interactions: structure, function, and predictive scaling for climate change mitigation. *Plant and Soil*, *461*(1), 5-27.
- Smith-Spangler, C., Brandeau, M. L., Hunter, G. E., Bavinger, J. C., Pearson, M., Eschbach, P. J., ... & Bravata, D. M. (2012). Are organic foods safer or healthier than conventional alternatives? A systematic review. *Annals of internal medicine*, *157*(5), 348-366.
- Thakur, A., Kumari, D., & Kumar, P. (2024). Climate Change and Agriculture: Assessing the relationship between agricultural practices, greenhouse gas emissions, and climate change. *A Comprehensive Exploration of Soil, Water, and Air Pollution in Agriculture*, *155*.
- Worsley-Tonks, K. E., Angwenyi, S., Carlson, C., Cissé, G., Deem, S. L., Ferguson, A. W., ... & Hassell, J. M. (2025). A framework for managing infectious diseases in rural areas in low-and middle-income countries in the face of climate change—East Africa as a case study. *PLOS global public health*, *5*(1), e0003892.
- Yalamati, S. (2024). The Contribution of Artificial Intelligence to Foster Sustainable Food Systems in Agriculture. In *Artificial Intelligence and Machine Learning for Sustainable Development* (pp. 236-248). CRC Press.
- Zeng, R., Abate, M. C., Cai, B., Addis, A. K., & Derebe Dereso, Y. (2025). A systematic review of contemporary challenges and debates on Chinese food security: integrating priorities, trade-offs, and policy pathways. *Foods*, *14*(6), 1057.
- Zuza, E. J., Lambert, K., Macmillan, T., Chiyemura, F., Araya, Y., Bowskill, V., ... & Bhagwat, S. (2024). Crop species diversity: A key strategy for sustainable food system transformation and climate resilience. *Food and Energy Security*, *13*(3), e558.

