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Nutrition in Abrupt Sunlight Reduction Scenarios: analysis and prevention of malnutrition in low-income regions

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Abstract

Purpose: An abrupt sunlight reduction scenario (ASRS) can be triggered by a nuclear war, a large volcanic eruption, or an asteroid strike, resulting in global agricultural collapse. A wide portfolio of resilient food interventions has been developed to address these issues, but even if they succeed in providing sufficient food energy for the global population, economic inequality could still result in fatal malnutrition in low-income countries (LICs).

Methods: Low-cost diets (<$1/person/day) based on ASRS-resilient foods were optimized to reduce malnutrition with sufficient energy intake. The generated dietary combinations were compared to dietary guidelines.

Results: The estimated diets were insufficient to achieve balanced diets, resulting in widespread malnutrition. We find that not only continued international trade but also significant food aid is needed to prevent widespread LIC starvation in a severe ASRS. Severe nutritional deficiencies are present: at the onset (Period 1), vitamins A, E, D, C, B3, B5, calcium, zinc, iodine, and selenium; and in the longer term (Period 2), vitamins E, D, K, B5, B6, B12, zinc, and selenium. Seaweed and single-cell proteins are resilient foods that contain notable quantities of many of these; however, large intakes of these are likely to be unfeasible without extensive processing.

Conclusion: To reduce the risk of malnutrition and mass starvation in a severe ASRS, LICs would need to develop the capability to ramp up resilient food production internally, perhaps through international cooperation, and/or establish international trade agreements for food and supplements in case of a disaster. Otherwise, if a global food shock occurs, they risk being left dependent on the mercy of catastrophe-stricken, wealthier nations.

Keywords

Global catastrophic risk; Existential risk; Resilient food; Food security; Nuclear winter; Low-Income Countries

Abbreviations

Abrupt Sunlight Reduction Scenarios (ASRS)

Single-Cell Protein (SCP)

Docosahexaenoic Acid (DHA)

Eicosapentaenoic Acid (EPA)

Sustainable Development Goal(s) (SDG, SDGs)

Low-Income Countries (LICs)

European Food Safety Authority (EFSA)

United States Department of Agriculture (USDA)

United States Dollar (USD)

1 Introduction

The global food system, which underpins human survival and well-being, has become increasingly vulnerable to a myriad of risks and challenges. Climate change, extreme weather events, crop pathogens, herbicide-resistant weeds, mass pollinator decline, and various other factors threaten food security, leading to widespread disruption and food insecurity [1]. The delicate balance of this system relies on consistent environmental conditions, such as sunlight, temperature, and precipitation, making it susceptible to both natural and anthropogenic factors [2].

Recent events such as the COVID-19 pandemic have exposed the fragility of food systems, revealing the urgent need for greater resilience against potential shocks. Supply chain disruptions coupled with widespread economic impacts have demonstrated the consequences of inadequate preparedness and adaptability. With nearly 25,000 individuals dying each day from hunger-related diseases, these impacts have been acutely felt in low-income regions since the onset of the pandemic [3]. These areas harbor over 103 million individuals already at risk, who face worsened food access challenges due to movement restrictions and industry closures—measures that, while medically wise to slow the spread of the virus and potentially control the pandemic, have negative effects on food security [4, 5]. The South Asian subcontinent, Western Africa, and Venezuela account for a significant portion of this economically at-risk population. Additional regions, including the Horn of Africa, parts of the Middle East, and Central Asia, particularly Iran, experienced an increase in the number of people suffering from food insecurity during the pandemic [4]. However, the global food supply, heavily reliant on modern agriculture, depends on stable environmental conditions, such as consistent sunlight, temperature, and rainfall, which are susceptible to disturbance by both natural events and human activities [6].

As extreme weather events and other environmental challenges become more frequent and severe, it is vital to understand and address the vulnerabilities of food systems, particularly in low-income countries (LICs), which may be disproportionately affected. Anthropogenic climate change further exacerbates these threats, increasing the likelihood of multiple bread basket failures, spiking food prices, and exacerbating food insecurity [7]. However, this is just one of the many threats that could result in a global catastrophic food failure, where food shortages overwhelm response capacities of governments and private sectors, necessitating extraordinary interventions [8].

Among these global catastrophic risks (GCRs), abrupt sunlight reduction scenarios (ASRS), pose a significant and potentially devastating threat to global food systems [9]. These GCRs include large volcanic eruptions, the direct impacts of exceptionally large asteroids or comets, and nuclear wars in which numerous cities have been targeted. In each scenario, large amounts of aerosol material or black carbon are projected and entrapped in the stratosphere, leading to a sudden and dramatic reduction in sunlight irradiation reaching the Earth's surface [6]. Such events could result in severe food shortages, potentially leading to mass starvation and destabilizing modern civilization. In the face of these unprecedented challenges, it is imperative to develop and implement resilient food solutions that can withstand extreme environmental changes and ensure human survival. A comprehensive approach to developing resilient food solutions should include the identification and scaling up of food sources that can thrive under the altered conditions of an ASRS, such as crops that require minimal sunlight, temperature, and precipitation, and food production techniques that can adapt to challenging environments.

Resilient food solutions are crucial for mitigating the consequences of GCRs, offering an avenue to maintain food availability and security despite the adverse conditions that may arise from these catastrophic events [6]. However, these solutions must not only be effective in providing adequate nutrition, but also affordable [9, 10], particularly for low-income populations in developing countries that may struggle to produce enough food for their populations during a catastrophic event. These countries, often characterized by high levels of poverty and malnutrition across different groups, limited infrastructure, and reliance on subsistence farming, face an array of challenges that make them particularly vulnerable to disruptions in the food supply [11].

Thus, this study aimed to analyze the nutritional feasibility of a diet comprising the lowest-cost resilient foods, with the aim of evaluating how well the diets that could emerge in this scenario would fulfill the nutritional needs of people in LICs in the event of ASRS. We analyzed the potential public health problems that could arise from these diets, such as malnutrition and related illnesses, and considered ways to address them. To assess the nutritional feasibility of a resilient food portfolio, this study examined the lowest-cost resilient foods outlined by [6]. This includes traditional and resilient food sources, such as cold-tolerant crops and greenhouse crops, as well as novel foods that are particularly resilient to ASRS, such as methane single-cell protein and seaweed.

This goal contributes to the understanding of the nutritional landscape under ASRS conditions to inform planning and preparedness efforts to ensure humanity's well-being in the face of severe food shocks. This analysis provides cost-effective options for relevant stakeholders that could help prevent the SDG 2 (Zero Hunger) from being derailed by ASRS.

2 Methods

2.1 Catastrophic Scenario Characterization

The ASRS analysis draws upon the nuclear winter climate model and crop model developed by [12] to characterize the climate and food system impacts in the post-disaster scenario and the food system intervention model developed by [10] to inform the choice of responses and expected food availability. The models project substantial disruptions to the food system owing to reductions in sunlight reaching cropland, temperature, and precipitation, with global starvation likely to follow a nuclear winter if the emergency response is not swift. However, even with a significant international response, the limited resources and capabilities needed to deploy resilient food solutions combined with economic inequalities would likely create a much more dire situation for LICs, some of which are already significantly food insecure. This analysis focused on exploring a scenario in which a significant global response to a nuclear winter has resulted in sufficient food production to cover people's energy requirements, but the food is distributed unequally, risking malnutrition over the vast swathes of the global population. This is analogous to the current situation in which more than enough food crops are produced to feed everyone in the world, but for economic and political reasons, nearly 30% of the global population experiences moderate or severe food insecurity [13].

The ASRS disruption would affect a number of cereals, oils, and vegetables that provide the majority of food to low-income consumers globally, which would be expected to see sharply reduced availability and higher prices during the disaster. As a result, low-income consumers may be unable to secure sufficient volumes of the foods they are currently reliant upon to meet their macro-and micronutrient requirements, and alternatives would be needed to meet the shortfall.

However, there are food types that are likely to be less disrupted by ASRSs as their production is less correlated with climatic conditions, which are broadly referred to as "resilient foods". These include high-tech foods such as single-cell protein (SCP) [14] and lignocellulosic sugar [15], as well as seaweed, where the ocean is projected to moderate the shock to temperatures. While these resilient foods are not necessarily cost competitive versus alternatives today, the fact that in an ASRS they can be scaled quickly, reliably produced, and affordable at the same time means that they may make a vital contribution to the nutrition of lower-income consumers worldwide, at a time when the price of traditional staples would be placed out of their reach [6].

Thus, the selection of resilient foods available to consumers in low-income regions is focused on those foods that could still be produced in those regions or could be produced in other regions and would be affordable enough to import even with greatly increased prices. We focus particularly on the latter type because most LICs are considerably dependent on imported foods [16].

The scenario analysis was structured into two distinct periods: period 1, encompassing up to one year after the disaster, and period 2, covering the subsequent 2-3 year timeframe. Given that period 2 is primarily dependent on resilient food solutions, sensitivity analyses will be conducted to simulate scenarios of potentially limited access to one or more of these food solutions' options. The goal is to represent scenarios in which one or more food system interventions have failed to increase the availability of given foods and to better understand how much worse the situation would be if that happened.

2.2 Selection of low-cost resilient foods

The selection of low-cost resilient foods is influenced by several critical factors, primarily due to affordability in ASRS, and includes resource availability, scalability, cost-effectiveness, and nutritional adequacy. Resource availability and accessibility ensure that the selected food options are affordable enough to be imported or can be sourced and produced within the constraints of the affected regions, considering local agricultural practices and resource availability. Scalability and ramp-up speed are vital for quickly addressing the immediate needs arising from ASRSs and prioritizing foods that can be produced rapidly. Cost-effectiveness is crucial for low-income consumers, making affordable food options essential for widespread adoption. Additionally, leveraging existing infrastructure, such as biorefineries and breweries, can minimize setup costs and facilitate rapid production [15]. Deploying established agricultural interventions such as greenhouses and cold-tolerant crops enhances food production capabilities in the face of climate challenges. Based on these criteria, low-cost resilient food options, including crop relocation, greenhouses, animal offals, seaweed, single-cell proteins, and lignocellulosic sugar, have been identified as viable solutions (see Table 1).

Table 1. Proposed chronology of resilient foods' availability—in red: not available in significant quantities; in yellow: possibly available in significant quantities; in green: available

Food item	**period 1 Food stock Status (1 year)**		**period 2 Food stock status (2-3 Years)**		***Comments***
	Assumed food availability	***Limited amount selected for dietary combination (grams/person/day)***	***Assumed food availability***	***Amount selected for dietary combination (grams/person/day)***	
Sugar	Unrestricted	63.4	Unrestricted	195	Significant amounts of sugar could be produced, either via cold-tolerant beets or lignocellulosic biomass conversion
Soy flour (defatted)	Limited Amount	115	Unavailable		
Corn flour	Limited Amount	180	Unavailable		Representing early staple crop availability estimated from [10]
Vegetable oil (canola)	Limited Amount	13.6	Limited Amount	13.6	Reduced availability represented as half of current levels in Africa
Vegetables (potatoes)	Limited Amount	54	Limited Amount	54	Reduced availability represented as one

			third of current levels in Africa
Cattle organ meat	Limited Amount 10	Unavailable	Assuming significant slaughter in early period, combined with unaffordability of animal feed and meat imports later
Beans (whole soybeans)	Limited Amount 14.7	Unavailable	Reduced availability represented as half of current levels in Africa
Seaweed	Unavailable	Unrestricted 93.2	Significant amounts of seaweed could be produced affordably even in ASRS, but they would not be initially available.
Single cell proteins	Unavailable	Unrestricted 118	Significant amounts of SCP could be produced affordably even in ASRS, but they would not be initially available.
Wheat flour	Unavailable	Limited Amount 90	In period 2 wheat flour replaces corn flour (wheat is more ASRS-resilient), but with limited availability.

Table 2 summarizes the cost of the lowest cost-per-calorie unconventional resilient foods, some of which were not included in the analysis due to lack of data on the viability of deploying them rapidly. Lignocellulosic sugar [15], single cell protein [17], and seaweed [18, 19], which have all been included in the analysis as per table 1, have been estimated to have the potential for rapid deployment to produce food at an affordable cost in a global catastrophe.

Table 2. Costs of the most affordable resilient foods (in 2024 USD), not including conventional agriculture. Note: "Fresh" indicates significant water content as harvested, otherwise the cost reflects dry matter.

Resilient Food Technology	Species	Current Commodity Cost ($USD/kg)	Current Commodity Cost ($USD/person/day)	Estimated Retail Price to Consumers ($USD/person/day)	Cost comment
Lignocellulosic sugar	Granulated sugar	0.5	0.4	0.7	Production model cost estimate [15]
Leaf Protein Concentrate	Grass clover concentrate, powder	0.9	0.7	1.5	Production model cost estimate [20]
Synthetic fat from paraffin wax	Butter substitute, fresh	2.9	0.9	1.7	Production model cost estimate [21]
Single cell protein from methane	Microbial protein powder	1.6	0.9	1.7	Production model cost estimate [14]
Single cell protein from CO_2 and H_2, via gasification	Microbial protein powder	1.9	1.1	2.1	Production model cost estimate [17]
Single cell protein from methanol	Microbial protein powder	2.4	1.4	2.6	Reported price [22]
Amino acid synthesis	DL-Methionine powder	2.5	1.4	2.6	Wholesale, reported historical market price [22]
Greenhouses	Sweet potato, fresh	0.5	1.5	2.7	Production model cost estimate, Mississippi [23]
Seaweed	Japanese kelp, fresh	0.3	1.8	3.4	Wholesale, estimated from historical trade values (Average of global imports and exports) [24]

Comment	Selected representative of the product class.	Cost given for a commonly purchased form of the product, updated to 2024 USD	Amount required to fulfill a person's daily calorie requirement, at 2,300 kcal/person /day	Estimated as twice the value of the production cost, as a rule of thumb	Related to the origin of the cost given

2.2.1 *Land-based food solutions*

This category includes resilient foods produced on land, including grass-fed ruminants, crop relocation, greenhouses, cropland expansion, leaf protein, and mushrooms [6]. Meat, while locally available in small quantities, would likely become prohibitively expensive to import in an ASRS for economically disadvantaged populations due to a lack of animal feed. Thus, meat has been conservatively excluded from the available nutritional sources, although more affordable offals are included in small amounts. Mushrooms were excluded because of their high price per calorie.

First, crop relocation allows the adaptation of the global distribution of crops to suit changing climatic conditions and can significantly enhance food security in an ASRS. Potatoes, canola, and sugar beets were included in this analysis because of their tolerance to cooler conditions and low cost. Second, the rapid deployment of simple polymer-cover greenhouses can facilitate the cultivation of temperature-sensitive crops, improve yields, and enable crop growth in regions where they would otherwise be unviable. Low-tech, open-source greenhouse designs are available, and successful large-scale deployments have been documented. If implemented effectively, greenhouses could potentially contribute to approximately 30% of global food requirements within the first year of an ASRS [25]. Some limited amount of vegetables should remain available to low-income consumers, in part thanks to greenhouses. Finally, organ meats could be an affordable alternative to muscle meats. Despite a decline in consumption in developed countries, organs are a nutrient-dense food source, rich in protein, vitamins, and essential fatty acids.

2.2.2 *Water-based food solutions*

Water-based resilient food solutions include fishing, microalgae production, and farming of seaweed and bivalves. While many of these are at least partially feasible to scale in many low-income regions, the analysis considered only seaweed as it is the only one that is significantly likely to be importable at affordable prices in an ASRS. Seaweed presents a high potential for scalability, with the ability to meet 45% of global calorie demand in just around a year [19]. Its cultivation requires minimal technological resources and can be deployed rapidly. Seaweed can serve as a direct food source or be utilized in animal feeds, making it a versatile and cost-effective option in ASRSs. Seaweed could supply 10% of global caloric needs at $0.50/kg, while higher-cost production could meet even greater demands [18]. People can only consume a limited amount of fresh or rehydrated seaweed due to its low energy density, but the famously high levels of iodine and other mineral content present in large intakes of seaweed can be addressed with cooking (see supplementary section S1 on seaweed processing).

2.2.3 Food without agriculture: high-tech food solutions

There exist high-tech industrial solutions that allow for the production of food without agriculture or sunlight, including fermentation for production of single cell foods and for biosynthesis of key nutrients, and the nonbiological synthesis of food compounds such as from CO_2 [22]. Two were selected as affordable for their low unit cost and high level of technology readiness. First, Single-Cell Protein (SCP), which can be produced from methane or other feedstocks, is a rapidly scalable and protein-rich food source. SCP technologies can yield high-quality protein with minimal environmental impact, requiring less land, water, and inputs compared to traditional animal protein sources. Moreover, SCP can be produced in controlled environments, making it resilient to a wide variety of food system risks.

The estimated retail cost of methane SCP during catastrophe scenarios is between $3-5 per dry kilogram, making it a cost-effective solution, especially in terms of cost per protein considering it contains over 70% protein by mass [14]. Second, lignocellulosic sugar, which can be derived from agricultural residues or wood biomass, offers a scalable caloric source. It can be produced using repurposed industrial infrastructure, which minimizes setup costs and enhances feasibility. Its estimated retail cost in a catastrophe is $0.82/kg [15].

2.3 Human nutritional needs

The recommended ranges for human nutrient intake align with those proposed by [9]. Nutrient intakes have been classified into three categories: adequate intake (AI), moderate-risk associated intake (MRAI), and severe-risk associated intake (SRAI). The lower AI values were determined using a conservative approach, selecting the most stringent values from the USDA [26], EFSA [27, 28], and WHO guidelines [29, 30]. Similarly, upper AI values were derived from the tolerable upper limits established by the USDA [26], EFSA [31], and WHO [29, 30]. Intakes falling outside of these adequate ranges were categorized as either moderate- or severe-risk associated intakes, based on the second most conservative value when available. In cases where more relevant figures were found in the literature, particularly in WHO emergency management handbooks [32, 33], those values were prioritized. If intake levels posed extreme health risks, such as poisoning or severe long-term damage, they were classified as the upper limit for SRAIs. Detailed referencing and further information are available in the Supplementary Information of Pham et al. (Table 'Human Nutritional Needs') [9].

Given the high rates of malnutrition and chronic diseases in LICs, the analysis will discuss the implications of nutrients that fall into Moderate-Risk and Severe-Risk intake levels. It will explore how the dietary changes from the ASRS could impact the health of vulnerable populations in these nations, where nutritional deficiencies and chronic illnesses are already significant issues. Table 3 provides the selected nutrients for analysis for the proposed low cost diets for periods 1 and 2 which are based on the selection from the previous analysis [9].

Table 3. Nutrients selected for analysis of foods and for which AIs, MRAIs and SRAIs were determined

Macronutrients					**Micronutrients**	
Protein		**Fats**		**Carbohydrates**	**Minerals**	**Vitamins**
9 Essential Amino Acids: Histidine, Isoleucine, Leucine, Lysine, Methionine, Phenylalanine, Threonine, Tryptophan, Valine	2 non-essential Amino Acids: Cysteine, Tyrosine	*2 Essential Fatty Acids: 18:2n-6 (Linoleic Acid, An Omega-6) and 18:3n-3 (Alpha-Linolenic Acid, an Omega-3)*	*Saturated Fats, Trans Fat*	*Sugars, Fiber*	Calcium (Ca), Iron (Fe), Magnesium (Mg), Phosphorus (P), Potassium (K), Sodium (Na), Zinc (Zn), Copper (Cu), Manganese (Mn), Selenium (Se), Iodine (I)	Vitamins A, E, D, C, B6, B12, K, Thiamin (B1), Riboflavin (B2), Niacin (B3), Folate (B9), Pantothenic Acid (B5)

2.4 Cost of diets

Economic as well as physical access to foods is required in order to meet the criteria of food security as laid out by the FAO [34]. While a detailed analysis of the prices is beyond the scope of this paper, we present a comparison below of the cost of each diet. These are based upon published estimates of break even costs for resilient foods, while the cost of conventional agricultural products such as cereals and vegetable oils use the average of 2020-2024 prices reported by the World Bank [35], scaled by a factor of the peak yield shock in year 2 - a factor of ~3.9 [10]. Finally, offal has been estimated from the average price of exports under the HS code 0206 (which covers edible offals) as reported by the UN COMTRADE database over the same period [36], which we then doubled to account for retail costs, further transport and cost rises post disaster. While prices will likely exceed these thresholds for many products, this analysis allows us to determine the minimum cost of diets, as prices must exceed costs to be sustainable over the length of the nuclear winter.

3 Results & Discussion

3.1 Proposed diet combinations based on resilient foods:

The proposed available foods in LICs were combined in diets aiming for as much nutritional completeness as possible, and their nutritional profiles were analyzed for potential deficiencies and excessive intake levels. The proposed dietary combinations are presented in Table 4, while the nutritional profile of each combination is detailed in Figure 1.

The included seaweed caloric share was within 10% (210 kcal/kg/day) in all periods (except period 2 C), to account for the difficulty in consuming large quantities of food with low energy density and high fiber content, despite the low cost and ease of production. The varieties of seaweed species used were emi-tsunomata, laver, and wakame; kelp was not included due to its high iodine content, although this could be partially addressed by boiling (see supplementary section S1 on seaweed processing techniques). As mentioned previously, lignocellulosic sugars can be used to achieve sufficient calories in the diet when the sugar beet supply is limited, but with regards to the nutritional analysis they are identical and represented as sugar.

Table 4. Mass and caloric intake per food item in each period's diet, based on availability as per table 1.

	period 1		***period 2***	
Unit	***g***	***kcal***	***g***	***kcal***
Single cell protein (from methane)	-	-	117	620
Canola oil	13.6	120	13.6	120
Cattle (organs)	10	14	-	-
Corn flour/ corn (whole grain)	180	650	-	-
Emi-tsunomata (dry)	-	-	7.7	20
Laver (dry)	-	-	26.2	55
Wakame (dry)	-	-	59.3	160
Potatoes	54	47	54	47
Soy flour	115	500	-	-
Soybeans	14.5	25	-	-
Sugar	193.5	745	195	750

Wheat flour	-	-	90.1	328

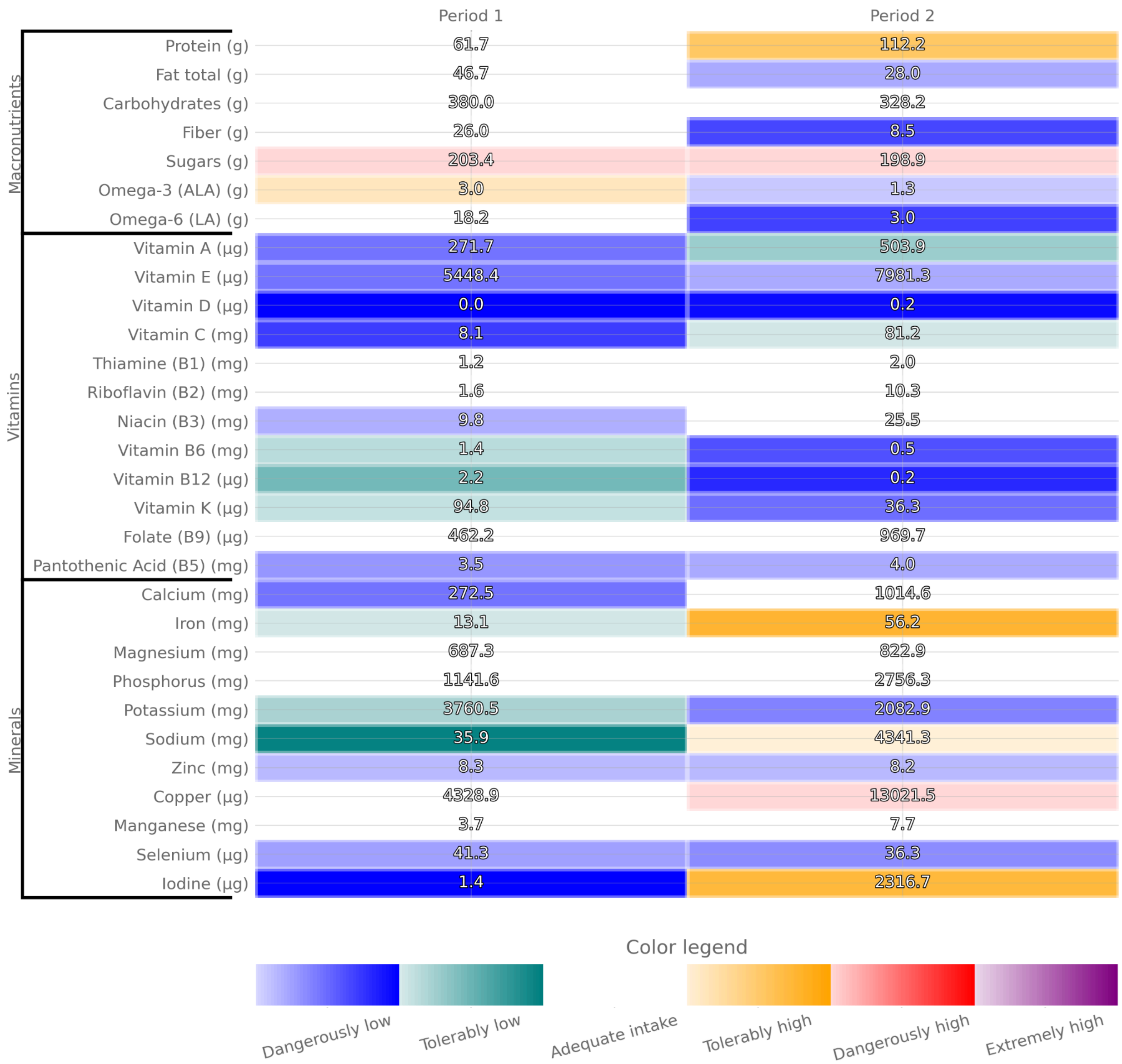

Figure 1. Colormap visualization of periods 1 and 2, showing which nutrients have an adequate intake, which ones are deficient, and which ones are overconsumed.

3.1.1 *Period 1*

During period 1, the included foods are organ meats, potatoes, a limited supply staple crops (corn, soy, and canola), and simple sugar. The energy requirements were primarily derived from corn

(~31%), soy flour (~24%) and sugar (~35%). Canola oil, potatoes, soybeans, and cattle organs constitute only the leftover 10%. This distribution aims to represent the very limited availability of vegetables, oil crops, and animal products in the proposed nuclear winter scenario.

The macronutrient intake was roughly 70% carbohydrate, 19% fat, and 11% protein intake, not quite achieving the recommended distribution of 45-65% carbohydrates, 20-35% fat, and 10-35% protein [37]. The lack of other options resulted in a very high sugar intake (35%+) in order to meet the required energy intake to avoid starvation. Protein consumption was quantified at ~1 gram per kilogram of body weight per day, aligning with established adequate intake guidelines [38]. Most micronutrients were within AI, or MRAI limits, except for vitamin A, E, D, C, B3, and B5; as well as iodine which were in the SRAI range. Although Omega 6 fell within the MRAI ranges, the ratio of omega-6 to omega-3 was 6:1, higher than the ideal 1:1 - 1:4 [39].

3.1.2 *Period 2 baseline (access to a variety of low-cost resilient foods)*

The baseline diet of period 2 represents a scenario in which people would still be able to consume the same amount of limited vegetables and vegetable oils as in period 1 (respectively represented by potatoes and canola oil). Instead, the basis of the diet is those food alternatives that are resilient and can be produced in surplus amounts. Seaweed and SCP are expected to make significant contributions to the diet in this baseline period 2 diet scenario, which represents a successful production ramp up of these low-cost resilient foods. The sensitivity analysis in the next section will challenge this assumption.

Sugar from beets or lignocellulosic sources is the main source of energy intake (~40%) due to a lack of other food sources. Single-cell protein provides the majority of the dietary protein and ~30% of the daily caloric intake. Wheat flour contributes ~16% of the total energy followed by seaweed (primarily wakame) constituting ~10% of total calories. Canola oil and potatoes remain consistent in providing a small amount of total calories as in period 1. The macronutrient profile shows significant deficiencies. Vitamin B1, B2, B3, and B9 were within the adequate intake limits, but the rest of vitamins intakes were within MRAIs (vitamins A and C) and SRAI limits (vitamins E, D, K, B6, B12, and B5). Several minerals also fell within SRAIs ranges with potassium, zinc, and selenium in very low quantities but copper overconsumption due to the high SCP intake. The intakes of Omega 3 and Omega 6 were also dangerously low, within SRAIs.

3.2 Sensitivity Analysis of Nutritional Combinations

This analysis tests extreme scenarios of disruptions in infrastructure, a lack of timely aid deployment, trade restrictions, failure to successfully ramp-up production, and/or failure to secure import of the available foods. Hence, in a severe nuclear winter it is likely that LICs would have to rely on a more limited number of options. Modified versions of period 2 are explored below to understand how these limitations would affect the nutritional profile of the low-income populations under more extreme scenarios. Scenario 2A will assume the ability to obtain sufficient supply of wheat flour to cover the population's energy requirements but a complete lack of any resilient food alternative, representing a scenario with sufficient availability of cold-tolerant wheat but a failure to deploy resilient foods. Scenarios 2B through 2D will assume widespread accessibility to only one of the food alternatives, respectively: sugar, seaweed, or SCP. One particularity of the seaweed-centered scenario 2C is that the limit of ~10% seaweed is removed, to better understand the potential of seaweed if it could be consumed in large quantities. The food amounts used in each scenario are shown in Table 5, and the resulting intake levels for each dietary combination are shown in figure 2.

Limited access to resilient foods results in significant changes to macronutrient and micronutrient profiles in each period 2 alternative scenario. Vitamins A, E, D, B5, B6, B12, and K remain within SRAI levels except under unlimited access to seaweed, where intake status improves to within AIs and MRAIs ranges. Omega 3 and 6 levels maintain critical status across all scenarios, remaining within SRAI ranges. Levels of vitamins B1, B2, and B3 are severely low in scenarios 2A (wheat flour) and 2B (sugar) but adequate in 2C (seaweed) and 2D (SCP). Regarding trace element intakes, scenarios 2A and 2B result in severely low intakes of most or all minerals, while scenario 2C is adequate except for a severely high iodine intake, and scenario 2D is low on potassium, manganese, selenium and iodine.

Table 5. Distribution of caloric and weight intake of resilient foods in case of limited access to food alternatives in period 2: only one resilient food is available in addition to the limited baseline food supplies.

Period 2 scenario:	***Scenario A (unlimited wheat flour supply)***		***Scenario B (unlimited access to sugar)***		***Scenario C (unlimited access to seaweed)***		***Scenario D (unlimited access to single cell protein)***	
Unit	***g***	***kcal***	***g***	***kcal***	***g***	***kcal***	***g***	***kcal***
Single cell protein (methane)	-	-	-	-	-	-	305	1605
Canola oil	13.5	120	13.5	120	13.5	120	13.5	120
Emi-tsunomata (dry)	-	-	-	-	250	648	-	-
Kelp (dry)	-	-	-	-	39	100	-	-
Laver (dry)	-	-	-	-	150	317	-	-
Wakame (dry)	-	-	-	-	200	540	-	-
Potatoes	54	47	54	47	54	47	54	47
Sugar	-	-	401	1605	-	-	-	-

Wheat flour	531	1933	90	328	90	328	90	328

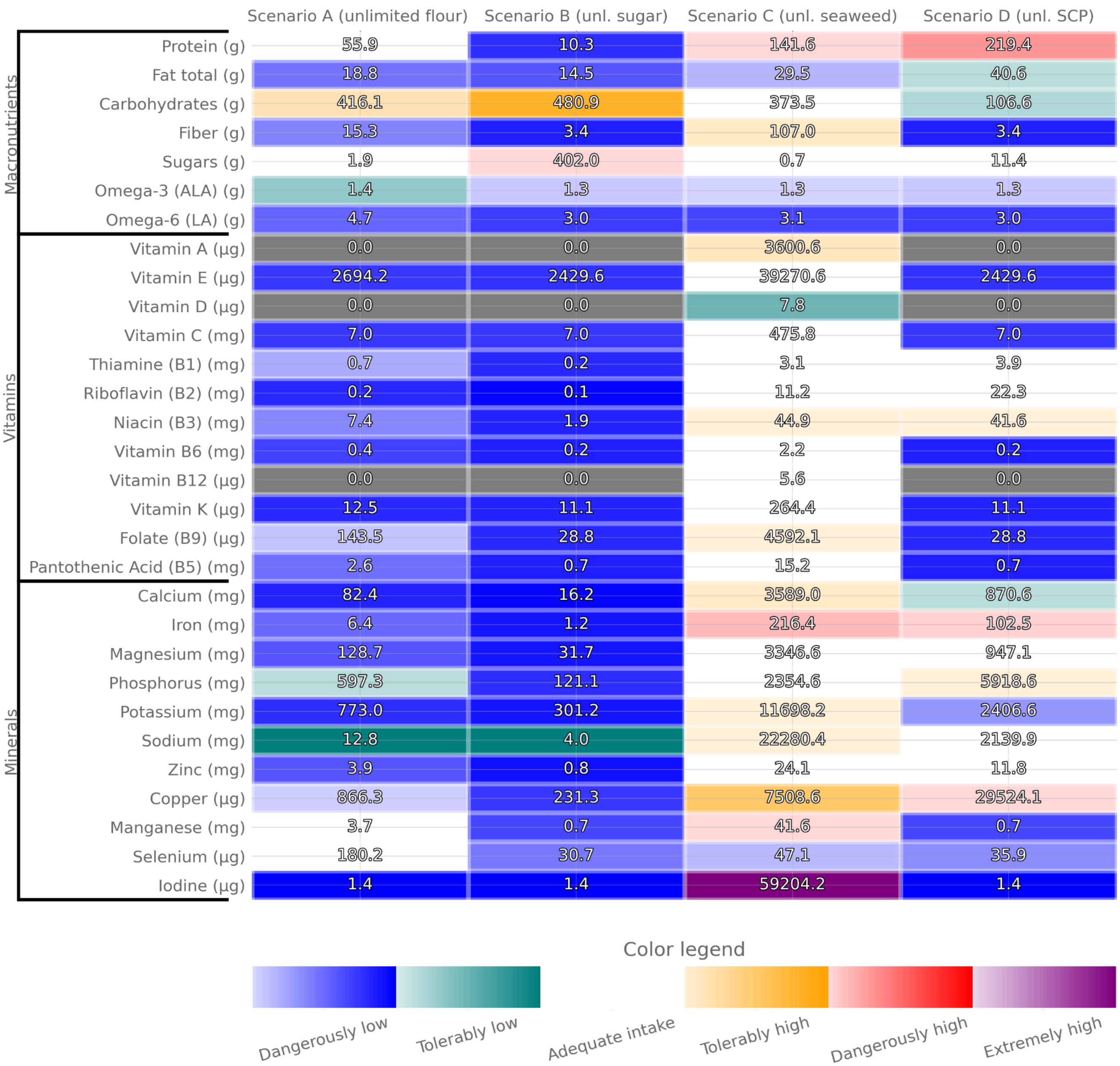

Figure 2. Colormap visualization of the limited period 2 scenarios, showing which nutrients have an adequate intake, which ones are deficient, and which ones are overconsumed.

3.2.1 *Scenario 2A (unlimited wheat flour supply)*

Scenario A depends heavily on wheat flour, 531 g/person/day, that makes the diet high in carbohydrates exceeding 80%. Due to lack of protein alternative sources, the caloric share of protein drops to only account for 11% of total energy intake while fat intake remains within comparable percentage to full access scenario accounting for 8%. This scenario aims to represent a situation in which large amounts of wheat can be produced locally or imported, since some wheat varieties are somewhat resilient to ASRS, but the catastrophe makes it hard to produce vegetables or meat, vastly reducing availability. This diet may not be life-sustaining.

3.2.2 *Scenario 2B (unlimited access to sugar)*

The sole introduction of sugar from lignocellulosic material or beets would push the sugar intake, protein and fat to SRAI ranges, disrupting the whole caloric distribution of macronutrients. The daily sugar intake is 410 g which accounts for over 75% of total energy intake and raises the carbohydrates share to over 90%. The total percentage of fat would fall below 5% in addition to an alarmingly low protein intake that is less than 1%. The resulting diet is probably not survivable.

This scenario aims to represent a situation in which large amounts of lignocellulosic sugars or beet sugars can be produced locally or imported, since both of these are resilient to ASRS, but the catastrophe makes it hard to obtain vegetables or meat, vastly reducing availability.

3.2.3 *Scenario 2C (unlimited access to seaweed)*

This scenario aims to represent a situation in which large amounts of seaweed can be produced locally or imported, but the agricultural disruption makes it hard to produce or import other foods. Unlimited access to seaweed provides a comparable caloric share from carbohydrates and proteins to the baseline scenario. By removing the limitation on seaweed intake, seaweed primarily replaces the sugar present in the period 2 baseline, resulting in improved outcomes for many nutrients.

Note that consuming this much fresh seaweed directly is probably not feasible at the population level, as its low energy density would require each person to ingest tens of kilograms of fresh seaweed per day, beyond practical limits of stomach volume and chewing time. To make this possible nutrient extraction techniques such as the ones discussed in the supplementary section S1 on processing techniques for seaweed would be needed, but whether this can be achieved during a global catastrophe at an affordable cost remains speculative. This scenario is primarily for the illustrative purposes of the sensitivity analysis.

3.2.4 *Scenario 2D (unlimited access to single cell protein)*

Higher intake of SCP significantly improves the fat caloric share to MRAI ranges, accounting for ~21% of total energy intake. On the other hand there is a marked increase of protein intake that constitutes 51% of total energy intake which is within SRAI range. Moreover, this scenario provides the lowest percentage of carbohydrates accounting for only 27% that falls within the MRAI ranges.

3.3 Comparison of nutritional balance and adequacy between scenarios

3.3.1 *Macronutrient balance*

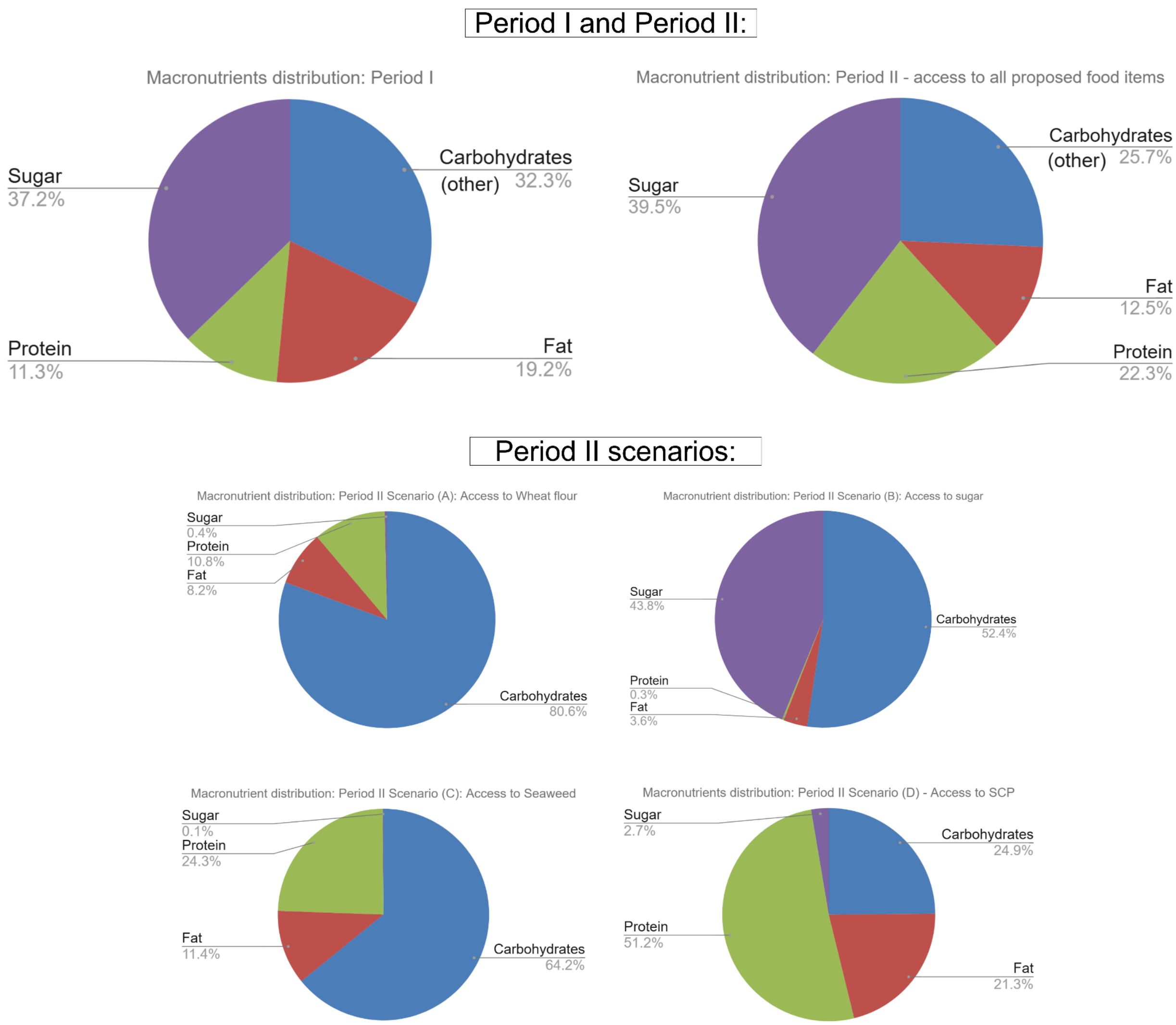

Figure 3. Macronutrient distribution of the diets in the two baseline periods and the 4 proposed alternative scenarios for period 2.

While caloric needs are met, all scenarios exhibit significant deviations from WHO-recommended balances, with critical health implications. Protein extremes (as low as 2% of total energy intake in scenario 2B, as high as 51% of total energy intake in 2D), fat deficiencies (4-21%), and sugar overloads (up to 44%) threaten long-term physiological function, necessitating policy interventions. The caloric distribution of fat is marginally adequate only in period 1 and SCP-centered diets (scenario 2D), which put the population in LICs at risk of essential fatty acid deficiency and fat-soluble vitamin deficiencies during a nuclear winter. Proteins exhibited variable MRAI, and SRAIs across all scenarios except in the seaweed-centered diet (scenario 2C). The SCP-centered diet exceeds safe protein limits (>35%) [40], and the sugar-centered (scenario 2B) diet fails catastrophically. Severe low protein intake for long periods can lead to catabolic, muscle wasting complication (e.g. kwashiorkor) and excessive intake will lead to renal complication in the long run. Carbohydrates were within the AIs except in the sugar-centered diet where the sugar intake fell within the SRAIs that put vulnerable populations at risk of metabolic syndromes (e.g. higher rate of cardiovascular diseases, obesity, hyperlipidemia, etc.).

Historical and modern populations have occasionally subsisted on extreme diets, though such extreme macronutrient imbalance is rare and typically driven by environmental or socioeconomic constraints. Extreme dependence on carbohydrate rich staples at the expense of other nutrients has historically resulted in chronic malnutrition. Evidence of carbohydrate-based diet include cassava-dependent communities in sub-Saharan Africa, where children exhibited high rates of stunting (30–40%), vitamin A deficiency (15-20%) and protein-energy malnutrition despite caloric adequacy [41, 42], and the traditional Kitavan diet (70–80% carbohydrates from tubers, low in refined starch and sugar), which avoided metabolic disease but sustained low life expectancy due to infectious diseases [43]. The pre-1950 Okinawan diet, rich in sweet potatoes, and Omega-3 from fish was associated with longevity, but it combined the sweet potato dependency with micronutrient-dense foods (green leafy vegetables, soy, and modest fish) to offset low protein (9%) and fat (6%), suggesting low protein alone did not impede healthy aging [44]. Historical crises, such as the Irish Potato Famine and wartime China, as well as other historical evidence, demonstrated that monocrop reliance on starchy staples can lead to scurvy, protein deficiency, and/or beriberi due to micronutrient deficiencies, even when calories were sufficient [45]. Modern epidemiological data reveal that refined high-carbohydrate diets (e.g., white rice in Asia) correlate with rising type 2 diabetes and cardiovascular disease [46, 47], while traditional whole-food versions (e.g., Kitava's high-fiber tubers) show metabolic resilience [43]. Critical trade-offs include micronutrient deficiencies (vitamin A, B vitamins, iron) and insufficient protein (<10% energy), exacerbating anemia and growth impairment. Sustained high-protein diets (≥50% of energy) pose significant metabolic risks, with no documented long-term survivorship in human populations. Indeed, studies suggest the physiological ceiling (probably around 35–45 % of energy) is set by hepatic urea-cycle capacity, such that higher intakes become self-limiting as protein intoxication lowers intake [48]. The traditional Inuit diet—the closest natural example—reached only 35–45% protein, primarily from marine and animal sources; it also was correlated with glucose intolerance and elevated inflammatory markers, but causation remains unclear [49].

In terms of micronutrient intakes, period 1 is characterized by critical population-wide risks of deficiencies in vitamins A, C, and E as well as Iodine. These deficiencies can lead to severe health consequences such as blindness, immune failure, scurvy, and cognitive decline. Additionally, slower-onset but severe risks are identified for vitamin D and B12 deficiencies, particularly affecting vulnerable groups.

Period 2 shows improvements in some areas, with vitamin A, C, and iodine levels becoming tolerable, and niacin (B3) reaching adequate levels, thanks to seaweed and SCP. However, new concerns arise with very low levels of vitamins D, B6, B12, K, and omega-3/6 fatty acids. This shift highlights a transition from acute starvation threats to chronic "hidden hunger" issues. Comparing this to a previous analysis [9] that had a much more diverse array of resilient foods available (not limited to low-cost foods) shows the same deficiencies (vitamins D, E, K) with the added burden of deficiencies in vitamin B12 and omega fatty acids, due primarily to the low availability of vegetables, vegetable oils, and animal products.

Additional challenges were revealed when accounting for the possibility of limited accessibility to resilient food solutions. Period 2 scenarios could lead to long-term disabilities due to a deficiency in fat-soluble vitamins (A, D, E, K), as the diets are not rich in fat, with only the speculative seaweed-heavy diet of scenario 2C avoiding this. This applies to the SCP-rich scenario (2D) as well, however if SCP production was available, one way to address this issue could be growing agriculture-independent microbial food varieties rich in fat rather than the protein focused one used in this analysis, for example genetically modified hydrogenotrophs [50]. Unfortunately, the SCP's high content of copper and iron limits how much can be safely consumed without additional post-processing or modification of the organism to reduce their content. The diet where sugar is the only resilient food that works in period 2 (scenario 2B) poses a deadly threat, potentially resulting in mass-scale exacerbation of existing morbidities that might significantly impact the mortality rate without adequate fortification given that all vitamins and trace element status are within SRAIs, particularly in regions already facing malnutrition challenges, as sugar cannot cover any of the deficiencies created by the very low availability of food, providing only energy. Similarly, diets based on wheat flour (scenario 2A) fail to provide most essential micronutrients in the absence of fortification, as wheat flour does not address the dietary deficiencies present in the baseline combination of foods with very little availability of vegetables and animal foods (save for protein and a few minerals). While seaweed-centered diets (scenario 2C) address numerous deficiencies, they remain speculative since they would at a minimum require proper cooking and likely significant processing (see supplementary section S1 on seaweed processing techniques) to achieve a sufficiently high energy density while enabling a good micronutrient intake and minimizing overconsumption of certain nutrients (e.g. iodine). For example, while iodine can be reduced significantly by boiling, manganese toxicity would remain an issue for which boiling would probably not suffice, requiring processing of the seaweed at higher levels. More details about the implications of the micronutrients status of these proposed diets are discussed in the supplementary material.

Across the two periods, LICs are challenged by dual crises of imbalances and deficiencies starting from period 1, compounded with the risk of extreme macronutrient imbalances in period 2. Even with full access to low-cost resilient food solutions, the limited diversification still requires ample supplementation to avoid exacerbation of existing nutrition-related morbidities, increasing disease burden and possibly mortality in LICs.

The sensitivity analysis illustrates how a varied selection of resilient foods results in much better nutritional combinations: while the diets in which only one resilient food is available all result in significant issues, the period 2 baseline diet combining availability of multiple resilient foods fares much better. This is in accordance with the well-known principle of dietary diversity and nutrient complementarity, whereby combining foods with differing nutrient profiles offsets the deficiencies of any single item and yields a more balanced, resilient diet. One exception is the seaweed-centered diet, but it can be argued to have significant diversity stemming from the different seaweed species with diverse nutritional properties.

The low availability of vitamin A in the proposed scenarios is particularly alarming, with seaweed as practically the only source. It could push vitamin A deficiency prevalence from current levels—15% of the world's children [51]—to potentially catastrophic levels. This would result in increased mortality, especially childhood death, and increased prevalence of measles and diarrheal illnesses. Zinc supplementation (e.g. through mineral supplements, SCP, or seaweed) would be important in period 2 given zinc's critical role in immune function and growth, as deficiency is already present at ~20% in low income countries [52], and zinc supplementation decreases pneumonia prevalence by 41% in children [53].

The projected micronutrient deficiency patterns would strain healthcare systems in low income countries through multiple pathways, with current estimates suggesting micronutrient deficiencies contribute to approximately 1.1 million disability-adjusted life years annually. ASRS scenarios could massively exacerbate this burden, requiring massive investments in supplementation programs and clinical management of deficiency diseases. The economic impact extends beyond healthcare costs to include reduced productivity from cognitive impairment (particularly from B-vitamin deficiencies), increased infection rates requiring treatment, and long-term developmental consequences affecting human capital formation.

3.4 Interventions for addressing nutritional deficiencies in ASRS

This section focuses on how the nutritional inadequacies identified as particularly important for LICs in severe abrupt sunlight reduction scenarios could be addressed using ASRS-resilient sources of nutrients. Table 6 summarizes the identified deficiencies, their potential health outcomes, and the interventions that could be implemented. The supplementary material discusses in more depth the risks associated with inadequate intake levels of micronutrients. For a broader discussion of interventions to reduce the risk of famine in ASRS and other catastrophic scenarios, not limited to LICs, see the literature review by [6].

Table 6. Micronutrient deficiencies that could be present in diets resilient to ASRS and selected potential sources and mitigation strategies. Similar information about ASRS mitigation can be found for other micronutrients that are commonly problematic in famines and displaced persons but were not highlighted by the analysis in table 4 of [9].

	Deficiency	**Primary source**	**Potential implication**	**Interventions for addressing in**

	status			ASRS (i.e. local production or food aid)
Vitamin A	Severe deficiency in period 1 and scenarios 2A, 2B, and 2D	Period 1: Cattle organs Period 2: Seaweed (exclusive)	-Would escalate an already existing global health issue -Childhood blindness, impaired immunity. High child mortality -Growth failure	-Dairy, liver, fish, -Fortification/supplementation (industrial synthesis)
Vitamin E	Severe deficiency in all periods and scenarios	Period 1: Soy flour and canola oil Period 2: Seaweed	-Retinopathy in premature infants -In children: anemia, neurologic deficit. -In adults: atopic dermatitis and psoriasis, spinocerebellar ataxia	-Vegetable oil (canola, soybean, corn), -Fortification/supplementation (industrial synthesis) -Prioritization of pregnant and nursing women to receive fortification and supplementation in case of limited supply
Vitamin D	Severe deficiency in all periods and scenarios	Period 1: Cattle organs (exclusive) Period 2: Seaweed (exclusive)	-Would escalate an already existing problem in low income countries -Deficiency could be developed within weeks -Strong evidence for causing negative skeletal effects from infancy to adulthood	-Sunlight exposure (if ultraviolet light levels allow) -Ultraviolet light-treated biological food sources (mushrooms, yeast, lichen), fatty fish (mackerel, salmon, sardines), dairy, kelp
Vitamin C	Severe deficiency in period 1 and scenarios 2A, 2B, 2D	Period 1: Potatoes Period 2: Seaweed	-Deficiency could be developed within weeks to months that could lead to scurvy	-Potatoes, some seaweeds -Fortification/supplementation (industrial synthesis)
Niacin (B3)	Severe deficiency in period 1 and scenarios 2A and 2B	Period 1: Soy and corn flours Period 2: Seaweed	-Incidence is very rare among normal population -Could lead to Pellagra disease, with high case-fatality within weeks to months if untreated	-Potatoes, whole wheat, barley, brown rice, mushrooms, fish, meat, organs, dairy, single cell protein

Panthotenic acid (B5)	Severe deficiency in period 1, period 2 baseline, and scenarios 2A, 2B and 2D	Period 1: Soy and corn flours Period 2: Seaweed	-Adrenal insufficiency -Neuropathy and fatigue, in worst cases resulting in neuro-degenerative disorders -Impaired immune system	-Some seaweeds, organ meats, mushrooms, dairy, potatoes -Fortification/supplementation (industrial synthesis)
Vitamin B6	Severe deficiency in period 2 baseline and scenarios 2A, 2B, and 2D	Period 1: Soy and corn flours Period 2: Seaweed	-Would escalate an already existing problem in low income countries -Critical for perinatal period and prevention of preeclampsia -Low levels can lead to microcytic anemia -In infants: deficiency could affect their hearing and could cause seizures	-Potatoes, some seaweeds (e.g. nori), some single cell proteins -Fortification/supplementation (industrial synthesis)
Vitamin B12	Severe deficiency in period 2 baseline and scenarios 2A, 2B, and 2D	Period 1: Cattle organs (exclusive) Period 2: Seaweed (exclusive)	-Deficiency would escalate one of the most common vitamin deficiencies globally - Main cause for megaloblastic and peripheral neuropathy	-Meat, organ meats, fish, some single cell proteins -Fortification/supplementation (industrial synthesis)
Vitamin K	Severe deficiency in period 2 baseline and scenarios 2A, 2B, and 2D	Period 1: Soy flour Period 2: Canola oil	-Deficiency rarely causes symptoms - Only symptomatic in certain groups with an underlying condition. Causes acute hemorrhagic deaths in newborns -Major implications are of lower probability at a population level	-Canola oil, some seaweeds (e.g. kelp), fermented foods (soybeans, etc.)
Calcium	Severe deficiency in period 1 and scenarios 2A, and 2B	Period 1: Soy flour Period 2: Seaweed	-Deficiency would escalate an already high global deficiency - In children the major implication is rickets -In adults, specifically, elderly would increase osteoporosis, increased risk of falling, and	-Dairy -Fortification/supplementation (mining, bone meal)

			tetany	
Zinc	Severe deficiency in period 1, period 2 baseline, and scenarios 2A and 2B	Period 1: Soy and corn flours Period 2: Single cell protein	-Would escalate an already existing problem in low income countries -Disruptions in immune system leading to higher risk of disease -Stunting and growth failure in children	-Meat, organs, shellfish, dairy, single-cell protein -Fortification/supplementation (mining)
Iodine	Severe deficiency in period 1 and scenarios 2A, 2B and 2D	Period 1: Potatoes (exclusive) Period 2: Seaweed	-Deficiency would escalate an already existing problem -Could be detrimental to fetal development and cause mental impairment that could be irreversible -In adults, deficiency mainly causes goiter, and evidence shows it can cause intelligence reduction	-Seaweed, fish, shellfish, dairy, -Fortification/supplementation (mining) -Iodized table salt could fulfill the iodine requirement gap
Selenium	Severe deficiency in period 1, period 2 baseline, and scenarios 2B, 2C, and 2D	Period 1: Corn flour Period 2: Wheat flour	-Deficiency would escalate an already existing problem -Disruptions in immune system leading to higher risk of disease -Strongly associated with Preeclampsia	-Dietary sources: seafood, lean meat, dairy products, eggs, fortification -Fortification/supplementation (mining)

Wherever wheat flour intakes are used to represent the availability of wheat, it's worth noting that wheat germ and bran which are not included would contribute to the intake of vitamins B5 and B6, among others. However, they are not major components: the composition of a wheat kernel typically includes approximately 14–16% bran and 2–3% germ by weight [54]. While the presence of these components in wholewheat flour would improve the overall nutritional profile, switching white flour for wholewheat flour cannot provide sufficient amounts of B5 and B6 to meet dietary needs in period 2 with the available amount (90 grams of flour). Additionally, it may not be feasible to secure wholewheat flour instead of white refined wheat flour, due to issues such as shorter ambient shelf life, higher packaging needs, elevated insect/mold risk, and slower downstream preparation. Aid agencies such as the World Food Program generally default to fortified white flour for food aid purposes [55]. Fortification of white flour, if feasible in an ASRS, is a well-established method which would help with many of the deficiencies identified here.

Another way to address B vitamin deficiency is the broader use of fermentation technologies. This work was limited to methane SCP due to its lower cost, but including other resilient microbial foods would bring in a much more complete nutritional profile. For example, hydrogen SCP could bring in some vitamins lacking from the methane SCP such as A, D, B5, B6, B9, B12, and K. Adding microalgae such as spirulina would incorporate much needed essential fatty acids and vitamins C and E. Taking a broader look than SCP, biomanufacturing techniques are already used extensively for vitamin supplement production and would likely be fundamental in an ASRS, even if they generally rely on non-resilient agricultural sugar sources as a feedstock that could be scarce. For more discussion of industrial synthesis of single cell proteins and vitamins resilient to ASRS, see the review on the topic by [22].

As scenario 2C shows, different seaweed species have varied and complementary nutritional properties that can make significant contributions to a diet. One important way to address nutritional deficiencies in an ASRS could be selecting for cultivation those seaweeds richest in nutrients of concern. For example, regarding omega-3s the macroalga *Bifurcaria bifurcata* contains 1% DHA+EPA on a dry weight basis [56], and the more commonly eaten Dulse and Wakame contains 0.5% and 0.6% EPA, respectively [56, 57]. This is higher than lean fish such as cod or yellowfin tuna, which are ~0.4% DHA+EPA, although lower than fatty fish [58, 59]. *Hydropuntia edulis* boasts an impressive vitamin C content of ~5 mg/g of dry weight, comparable to grapefruit [60]. Nori (laver) contains 1560 µg of vitamin A equivalents per 100 g dry weight, comparable to other vitamin A-rich foods such as sweet potato or butter. However, there are some important caveats: some vitamins in seaweed (e.g. C) degrade rapidly after harvest, can vary significantly by season, and often are less bioavailable than those found in traditional sources. Further research that incorporates these issues is warranted regarding how to leverage the nutritional potential of seaweeds in ASRS in an effective manner.

3.5 Cost of diets

Table 7 summarizes the results of the analysis to estimate the diets' costs. The lowest cost estimate diet would be around US$0.49 per person per day (period 2, Scenario B, where there is unlimited access to comparatively cheap lignocellulosic sugars). Meanwhile, the majority of our other diets are in the range of around US$0.7-0.9, while the highest cost diet would be Scenario C, due to the high comparative cost of seaweed as a source of macronutrition.

Overall, this analysis suggests food affordability would be under very serious pressure. While it is not impossible to achieve dietary combinations for less than a dollar a day per person using resilient foods under many assumptions, the resulting diets would not be nutritionally complete, requiring potentially costly supplementation. In contrast, a previous analysis estimated that a nutritionally complete ASRS diet would cost $1.73/person per day [61], likely pricing out nearly 40% of the global population, in agreement with the results of the current work.

Table 7. Cost per kg of dietary items and estimated diets by period and scenario.

Cost per kg		**Period 1**		**Period 2**		**Scenario 2 A**		**Scenario 2 B**		**Scenario 2 C**		**Scenario 2 D**	
Unit	USD/ kg	g	USD/ kg	g	USD/ kg	g	USD/ kg	g	USD/ kg	g	USD/ kg	g	USD/kg
Single cell protein (from methane)	$1.7			117	$0.20							305	$0.52
Canola oil	$5.3	13.6	$0.07	13.6	$0.07	13.5	$0.07	13.5	$0.07	13.5	$0.07	13.5	$0.07
Cattle (organs)	$4.2	10	$0.04	-									
Corn flour/ corn (whole grain)	$1.0	180	$0.19	-									
Emi-tsunomata (dry)	$3.4			7.7	$0.03					150	$0.51		
Laver (dry)	$3.4			26.2	$0.09					200	$0.68		
Wakame (dry)	$3.4			59.3	$0.20					54	$0.18		
Potatoes	$0.5	54	$0.03	54	$0.03	54	$0.03	54	$0.03	54	$0.03	54	$0.03

Soy flour	$2.4	115	$0.28	-									
Soybeans	$1.9	14.5	$0.03	-									
Lignocellulosic sugar	$0.7	193.5	$0.14	195	$0.14			401	$0.28				
Wheat flour	$1.2			90.1	$0.11	531	$0.65	90	$0.11	90	$0.11	90	$0.11
Cost of diet			**$0.77**		**$0.86**		**$0.74**		**$0.49**		**$1.58**		**$0.73**

3.6 Policy implications: international cooperation, trade, and food aid

The analysis reveals that abrupt sunlight reduction scenarios would trigger cascading micronutrient deficiencies, undermining decades of progress in health and poverty reduction. Like pandemic risks, these global catastrophic threats are neglected in current SDGs. They are non-linear in impact as nutrients imbalances could precipitate mortality spikes comparable to infectious disease outbreaks. Their impact is potentially intergenerational, especially during childhood, when there is a higher risk of development of irreversible complications that may permanently reduce future productivity. These harms threaten the chances to achieve SDG 2 (Zero Hunger). Addressing these micronutrient deficiencies requires partnering across the entire fortification and supplementation value chain to close acute micronutrient gaps after ASRS, including: pharmaceutical, millers/refiners, premix manufacturers, humanitarian buyers, and regulators working under SDG 2 and SDG 17 (Partnership for the Goals).

Several policy recommendations have been developed in recent years to implement an effective response to a global shock of this magnitude [6]. This includes how governments should develop rapid response and contingency protocols involving cross-sectoral participation between food ministries, civil protection, trade ministries, and other key actors.

Strengthening food resilience and response capabilities prior to an ASRS could be critical to prevent cascading failures and maintain cooperation. Similar to [61], this work finds that severe ASRS malnutrition is unavoidable without maintaining trade and ramping up international aid during the catastrophe. Aid plays a pivotal role in combating micronutrient deficiencies, particularly in LICs that lack the infrastructure and resources to implement comprehensive nutrition programs independently. Cooperation with high-income countries with stronger tech capacity would enable technology transfer and local food production during catastrophes. By investing in local food systems and promoting agricultural diversification, aid organizations can help build resilience against future shocks, ensuring that communities are better equipped to meet their nutritional needs.

International cooperation is essential to deploy investments in LICs towards faster response during a global catastrophic food crisis. Prior to a shock, it can also help mobilize resources from the international community for development policy and preparedness initiatives to fill the urgent need for evaluation and prioritization of resilient food solutions for an ASRS, promote the creation and distribution of effective disaster response plans, and integrate these initiatives with global frameworks. Policies that support continued global trade and cooperation are essential, as uncertainty in coordinating between trading blocs following an ASRS will significantly impact the global capacity to respond.

3.7 Limitations of the study and future work

The most important limitation of the study is the capacity to anticipate the diet expected to be available in LICs during a severe ASRS. Future research will be focused on the economics and feasibility of resilient food scaleup to yield results that help better estimate the basket of food that would be available in particular regions. The results of such analysis could then be analyzed using the methodology of the current article and [9] to estimate what dietary inadequacies may arise. The analysis would then also allow for examining the scenario in concrete regions rather than just in low income countries as a general group. Another type of future work that would be valuable is researching the magnitude of the public health impacts from the severe deficiencies identified in this work as likely to be present in an ASRS, such as the degree of increased mortality, disability, and reproductive complications at a population level arising from the inadequate diets shown in Figure 1, as a step towards prioritizing the cost-effectiveness of specific resilient food interventions.

[9] analyzed in more detail a scenario where 150 million tonnes of soot is released into the atmosphere from nuclear warfare, examining one of many potential sunlight reduction effects. Constrained by the lack of empirical data, it leaned on climate models to estimate global dietary impacts; the study acknowledged significant uncertainties such as the variability in soot dispersal and its effects on climate and weather patterns. Further uncertainties include the impact on global industry, trade, and international relations, noted to be similar to disruptions observed during the COVID-19 pandemic. Moreover, the study assumed international cooperation and an intact industrial infrastructure. The current study is grounded in these uncertainties, alongside other unexplored factors that will be discussed further below. [6] describe these uncertainties in depth and propose a comprehensive research agenda to address them.

Future work could include disambiguation efforts. Similar to [9], this work focused on one subset of adequate nutrition, using 2100 kcal for the global body weight average of 62 kg. Future analysis could incorporate different age and sex groups, as well as physical activity level. Other open questions include: 1) cultural acceptance of unfamiliar food items as seaweed, SCP, and offal would be in many cultures, 2) the adequate preservation of foods such as offal, 3) the nutritional bioavailability and bioaccessibility of the proposed foods, nutrient-nutrient interactions including supplements, anti-nutrients, and changes in the gut microbiome due to shifting from the normal diet, 4) behavioral considerations, such as how people in LICs sometimes prioritize more expensive foods with lower nutritional value over cheaper nutrient-dense foods due to factors like taste and social status despite low budgets [62, 63].

4 Conclusion

In the absence of significant food aid and with disruptions in international trade, the consequences of a severe ASRS would be catastrophic for low-income populations. Diets were constructed based on ASRS-resilient foods for potentially under $1/person/day, but the limited choice of foods results in nutrient intake imbalances. Low-cost resilient foods combined with a very small supply of traditional vegetable and animal foods cannot provide a complete diet in a severe nuclear winter scenario.

Vitamins E, D, and K were identified as particularly lacking, same as a similar study that used a wider variety of food options, but more severely in this work. Vitamin A, C, and B3 deficiencies, of extreme concern for children and adults, were present in period 1 and and most period 2 scenarios, with seaweed as the only widely available source due to the very limited availability of vegetables and animal foods. Period 2 (baseline) and most period 2 scenarios present deficiencies in B5, B6, B12 as well, the latter two particularly severe in children, again with seaweed as the only significant source. Deficiencies in calcium, zinc, and selenium are present and can be quite severe, but mineral deficiencies are logistically easier to address via supplementation and fortification. Iodine deficiency (present in period 1) could be resolved through seaweed supplementation or iodized table salt. Seaweed overall showed significant nutritional potential but presents considerable barriers to consumption in large quantities that would require extensive food processing to overcome.

A sensitivity analysis was run involving 4 alternative scenarios of period 2 where most of the proposed resilient foods were unavailable but dietary energy intake was met. It shows that if resilient food responses to a severe ASRS failed to provide multiple dietary options, the resulting diets are inadequate to the point of being potentially unsurvivable in LICs, especially those that are net food importers. This strengthens the conclusion that international trade and food aid would be indispensable to prevent the starvation of large swathes of the global population in a severe ASRS. Even if enough food was produced to fulfill the global population's dietary requirements, economic inequality would likely result in LIC starvation absent monumental foreign aid efforts.

Future work should focus on combining nutritional assessment methodologies as used in this work to integrated assessment models of nuclear winter responses, such as [10], to explore particular scenarios and systematically find robustly useful mitigation strategies against malnutrition in ASRS.

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Data availability

Not applicable

Conflict of interest

All authors declared no conflict of interest.

SUPPLEMENT: Seaweed processing techniques to mitigate safety concerns

Seaweed bioaccumulates chemical elements that harm human health in elevated quantities, including iodine, arsenic and other heavy metals. To enhance the safety and digestibility of seaweed, various processing techniques can be employed. Washing, heating, fermentation, soaking, and cooking are methods that can significantly influence the nutritional profile and safety of seaweed products. For example, boiling kelp (kombu) for 15 minutes can remove up to 99% of the iodine content, while Sargassum loses ~40% [1], though there can be significant variation [2]. Soaking *Sargassum fusiforme* at room temperature can reduce total arsenic levels by 32-60% [3], while 3-4 gentle boils for 30 minutes each at ≥90°C can remove up to 92% of arsenic [4]. However, arsenic consumption remains a concern in scenarios as explored in this work involving large seaweed intakes for prolonged periods of time, necessitating more research before large seaweed intakes can be recommended.

The seaweed-centered diet of scenario 2C showed iodine and manganese as trace elements consumed in dangerously high amounts. Boiling seaweed is a useful way to tame excess iodine as it is stored as free, water-soluble ions, but manganese is different: it is architecturally embedded in the algal cell wall as a structural cross-linking cation and is far less water-soluble. Household boiling alone cannot reduce it to safe levels; meaningful reduction would require acid, chelators, or limiting seaweed to a modest share of the overall diet. Other problematic metals not analyzed as part of the diet, such as cadmium, lead, or mercury, are as recalcitrant as the manganese and would not be significantly affected by boiling, limiting the safe amount of seaweed in the diet absent extensive processing [2].

More intensive processing is possible to reduce unwanted compounds and facilitate consumption of larger amounts of seaweed, but it would increase product cost, impacting its potential as a useful resilient food intervention for LICs. For example, the seaweeds could be dried and broken down into a flour [5] that is subjected to separation processes (e.g. ion-exchange, membranes, or acid leaching) specifically targeting divalent metals to reduce ash content. Another approach is the extraction of particular nutrients such as proteins and lipids from the seaweed [6], involving techniques such as: conventional solvents, enzymes, ultrasound, microwave, pH-shift, pulsed electric field, and physical pre-treatments [7] [8] [9]. More research is needed in seaweed processing techniques to ascertain how large the potential of seaweed is for ASRS response, involving the analysis of different processing techniques for different species of interest and their associated capital and operational costs.

Additionally, fermentation can enhance the digestibility of seaweed by breaking down antinutritional factors that can impair protein absorption [10]. However, challenges related to the complex composition of seaweed, including the presence of resistant components like alginate and fucoidan, can hinder effective fermentation [11]. Factors such as high buffering capacity and limited water-soluble carbohydrates also pose challenges for achieving optimal fermentation conditions.

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