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Food, nutrition, and diets at net zero. 10 years of Frontiers in Nutrition

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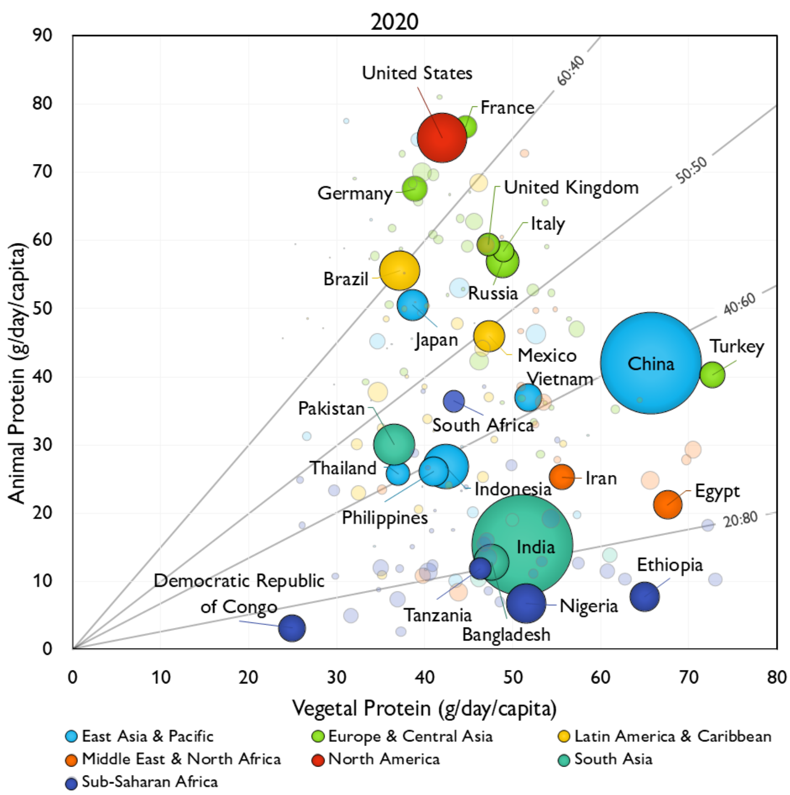

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Food, nutrition, and diets at net zero. 10 Years of Frontiers in Nutrition

Topic editor
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Editorial: Food, nutrition, and diets at net zero. 10 years of Frontiers in Nutrition

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Editorial on the Research Topic
Food, nutrition, and diets at net zero. 10 years of Frontiers in Nutrition

Ten years ago, in 2014, we launched Frontiers in Nutrition with a bold vision: to create a platform where rigorous science could bridge disciplines, from molecular mechanisms to consumer behavior. We aimed to foster an integrative approach to nutrition science— one that has since gained widespread recognition.

"*No subject pertains more to human life than nutrition.*" This statement from a decade ago still holds true, yet the questions we ask and the challenges we face continue to evolve (1).

Over this past decade, together with an extraordinary team of specialty chief editors, we have not only built a respected journal but also developed 14 specialty sections. These sections—spanning Clinical Nutrition, Food Chemistry, Nutrition and Microbes, Nutritional Epidemiology, and more—have become hubs of leadership in their respective fields. Every 5 years, our flagship editorial series, *Goals in Nutrition Science* (2, 3), has reflected the shifting landscape of the discipline, tackling topics from functional foods and nutrition methodologies to food security, ultra-processed foods (4), and cellular agriculture (5, 6).

As we enter our second decade, new frontiers await. The impact of artificial intelligence, the role of GLP-1 receptor agonists such as semaglutide (7), the growing concern over plastics in food (8), and the ever-present challenges of food security demand our attention. With the UN's Sustainable Development Goals set to conclude in 2030, we mark this milestone by presenting fresh perspectives on nutrition's role in shaping a future of zero hunger and net-zero emissions. This anniversary is not just a celebration—it is a call to action.

The review article "*The role of algae, fungi, and insect-derived proteins and bioactive peptides in preventive and clinical nutrition*" explores the potential of algae, fungi, and insect-derived proteins and their bioactive peptides in nutrition (Yimam et al.). These alternative proteins offer sustainable, nutrient-rich sources with health benefits such as antimicrobial, anti-inflammatory, and antioxidant properties. Algae-derived peptides show promise in managing hypertension, obesity, type 2 diabetes, and certain cancers. Fungi, comprising mushrooms and derived mycoproteins, provide essential nutrients and may aid in cholesterol reduction, immune support, and metabolic health. Insects, rich in protein and essential amino acids, have been studied for antihypertensive, antimicrobial, and antioxidant effects. The review emphasizes the importance of bioactive peptides in modulating physiological functions and their potential in clinical nutrition. However, more human trials are needed to confirm benefits and determine dosages. The authors highlight research gaps in bioavailability, consumer acceptance, and regulations. Addressing these gaps could advance functional foods and sustainable diets, supporting both preventive and clinical nutrition.

The perspective article "*Diet, nutrition, and climate: historical and contemporary connections*" by Demmler and Tutwiler examines the links between nutrition and climate change, emphasizing integrated strategies for health and sustainability. Despite progress, micronutrient deficiencies persist, especially in Sub-Saharan Africa and South Asia. Food systems contribute to environmental degradation through deforestation, greenhouse gas emissions, and excessive water use. The authors highlight the need to integrate nutrition into climate policies and to strengthen food system resilience. Initiatives like the "Scaling Up Nutrition" movement and the "Food Systems Dashboard" help transform food systems, but stronger policies are required to align nutrition, climate, and equity goals. The paper calls for increased investment, better policy frameworks, and innovations in technology and data monitoring. Promoting biodiversity, addressing micronutrient deficiencies, and developing climate-smart crops are essential for sustainable agriculture. The authors reiterate that achieving resilient and equitable food systems requires collaboration across sectors, ensuring long-term solutions for both nutrition and climate challenges.

The perspective article "*Integrating food is medicine and regenerative agriculture for planetary health*" explores the intersection of Food is Medicine (FIM) and regenerative agriculture (RA) to improve health and sustainability (Rahman et al.). FIM initiatives, like produce prescriptions and medically tailored meals, promote nutrition equity, while RA enhances soil health, biodiversity, and reduces synthetic inputs. Current food systems contribute to greenhouse gas emissions, water use, and biodiversity loss while driving diet-related diseases. Integrating FIM and RA offers a synergistic approach to improving individual health and ecological wellbeing. The paper highlights real-world examples of RA practices in FIM programs, addressing challenges such as crop selection and logistics in rural areas. The authors call for collaboration among policymakers, healthcare providers, farmers, and researchers to strengthen links between agriculture and healthcare. Clear definitions of RA and stronger partnerships could create resilient food systems and improve health at individual and population levels, advancing planetary health.

In their original research study entitled "*The protein transition: what determines the animal-to-plant (A:P) protein ratios in global diets*" Drewnowski and Hooker examine global shifts in animal-to-plant (A:P) protein ratios, influenced by income levels. In high-income countries (HICs), about 65% of dietary protein comes from animal sources, with efforts underway to lower this for health and sustainability. In contrast, low- and middle-income countries (LMICs) are increasing animal protein consumption as incomes rise, following "Bennett's Law". Data from the FAO and World Bank show a strong correlation between national income and A:P ratios. By 2020, HICs had A:P ratios above 60:40, while countries like Brazil and China saw significant increases. The study highlights the challenge of global dietary recommendations, as HICs shift toward plant-based diets while LMICs increase animal protein intake. The authors stress that policies to reduce A:P ratios in HICs must account for economic forces shaping diets worldwide, ensuring strategies balance health, sustainability, and economic development across different regions.

Another research article, " *Ecological impact and the metabolic food waste of overweight and obese adult individuals living in North European and Mediterranean countries*", investigates the environmental impact of overeating through the concept of Metabolic Food Waste (MFW), which quantifies excess food consumption leading to excess body fat (EBF) and its ecological costs (Angelino et al.). Overeating not only harms health but also increases greenhouse gas emissions, water use, and land requirements for food production. The study analyzes dietary patterns in North European and Mediterranean countries, revealing how surplus food intake contributes to environmental degradation. Addressing overeating could reduce GHG emissions, conserve water, and promote sustainable land use. The research underscores the need for integrated strategies that link healthier eating habits with environmental sustainability, highlighting the interconnectedness of nutrition and ecological wellbeing.

Finally, the review article "*Africa's contribution to global sustainable and healthy diets: a scoping review*" explores Africa's traditional diets and their role in health and environmental sustainability (Oniang'o et al.). Rich in whole grains, legumes, and indigenous foods, these diets support nutrition and agroecological practices that enhance biodiversity and soil health. However, dietary transitions toward processed, Westernized foods threaten food system independence and increase non-communicable diseases. Dependence on imported foods also heightens vulnerability to global market fluctuations, affecting food security. The review highlights the value of preserving traditional African diets to promote nutrition, sustainability, and food sovereignty. It calls for policies that integrate indigenous food systems into global health and environmental strategies, emphasizing Africa's contribution to sustainable diets.

Author contributions

JC: Writing – original draft, Writing – review & editing.

Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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The role of algae, fungi, and insect-derived proteins and bioactive peptides in preventive and clinical nutrition

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The current global trend in the nutrition, epidemiologic and demographic transitions collectively alarms the need to pursue a sustainable protein diet that respects ecosystem and biodiversity from alternative sources, such as algae, fungi and edible insects. Then, changing the nutrition reality is extremely important to impede the global syndemic of obesity, undernutrition and climate change. This review aims to synthesize the published literature on the potential roles of alternative proteins and their derived bioactive peptides in preventive and clinical nutrition, identify research gaps and inform future research areas. Google Scholar and PubMed databases from their inception up to 30 June 2024 were searched using keywords to access pertinent articles published in English language for the review. Overall, proteins derived from algae, fungi, and edible insects are high-quality proteins as animal sources and demonstrate significant potential as a sustainable source of bioactive peptides, which are metabolically potent and have negligible adverse effects. They show promise to prevent and treat diseases associated with oxidative stress, obesity, diabetes, cancer, cardiovascular disease (especially hypertension), and neurodegenerative diseases. Given the abundance of algae, fungi and insect peptides performed *in vitro* or *in vivo* animals, further clinical studies are needed to fully establish their safety, efficacy and practical application in preventive and clinical nutrition. Additionally, social and behavioral change communication strategies would be important to increase health awareness of nutritional benefits and promote consumer acceptance of alternative protein sources.

KEYWORDS

algae, fungi, insect, protein, peptides, cancer, cardiovascular disease, dementia

1 Introduction

Nutrition is a crucial pillar of human life, health and development (1, 2). Good nutrition ensures health and wellness at each stage of the human life cycle, such as pregnancy, infancy, childhood, adolescence, adulthood, and older age (3). Unfortunately, the double burden of malnutrition, i.e., concurrent manifestation of both undernutrition and overnutrition (overweight and obesity), may become manifest within the life course (4, 5). Although the burden of malnutrition mainly affects low and middle-income countries, countries passing the economic transitions also face the problem (6). Alongside, shifting of the overall dietary structure over time, i.e., the trend of the current nutrition transition, is associated with unrelenting non-communicable diseases (NCDs). Therefore, changing the nutrition reality is extremely important because a low-quality diet ignites a double burden of malnutrition (5, 7, 8).

By the year 2050, the world population is projected to be nearly 10 billion (9), the food demand is expected to increase by 56% (10), and animal-derived protein demand will be twofold (11), requiring a sustainable food system (12). Of significant concern, the increased consumption of red and processed meat globally contributes to an abrupt increase in the attributable burden of diet-related NCDs, including colorectal cancer, diabetes, and coronary heart disease, which are markedly risen in Northern and Eastern European countries as well as island countries in the Caribbean and Oceania (13). The demand and consumption of meat is also rapidly increasing in developing countries due to urbanization and rapid income growth (14).

Furthermore, raising livestock and animal meat consumption is associated with higher greenhouse gas emissions (15, 16), higher consumption of water and land use (17), human-induced terrestrial biodiversity loss (18, 19), contracting zoonosis and antibiotic resistance (20), and raised ethical concerns about animal welfare (21). These impacts clearly illustrate the need to pursue a sustainable healthy diet from alternative protein sources, such as algae, fungi, and edible insects, to achieve global food security without expanding crop or pastureland, deprived of increasing greenhouse gas emissions and without devaluing health (11, 17, 22–26). Figure 1 summarizes the relationship between obesity, undernutrition and climate change.

Shifting towards alternative protein sources is vital to meet most of the United Nations' sustainable development goals and to achieve a net-zero greenhouse gas emission target indicated in the Paris Agreement (27). In accordance with this, in 2022, the sixth international panel on climate change urged governments to prioritize sustainable healthy diets to feed the projected population by 2050, while mitigating the effects of climate change (28). The environmental and nutritional advantage inspired the concept of a sustainable diet, i.e., a diet that respects biodiversity and ecosystems, that is nutritionally adequate, safe, healthy and at the same time culturally acceptable, and affordable, as highlighted by the Food and Agriculture Organization of the United Nations (29, 30). The role of a sustainable diet from plant origin on metabolic syndrome in humans is extensively explored (31–34). Emerging evidence also spotlights the potential role of alternative proteins (algae, fungi and insects) and their derived bioactive peptides, i.e., a group of biological molecules activated by extraction from parental proteins, to offer therapeutic advantages by modulating metabolic pathways (35). Particularly, bioactive peptides are known for their safety, tolerability, and minimal risk of adverse effects (36). The quests of these proteins and derived peptides in the context of preventive and clinical nutrition present a promising road to uncover innovative dietary strategies and therapeutic approaches. Given no previous review in the area, this narrative review aims to (1): explore the current research on the potential roles of alternative proteins and their derived bioactive peptides in preventive and clinical nutrition (2); identify gaps in the literature; and (3) inform future research.

2 Methods

Google Scholar and PubMed databases from their inception up to 30 June 2024 were searched using keywords to access pertinent articles

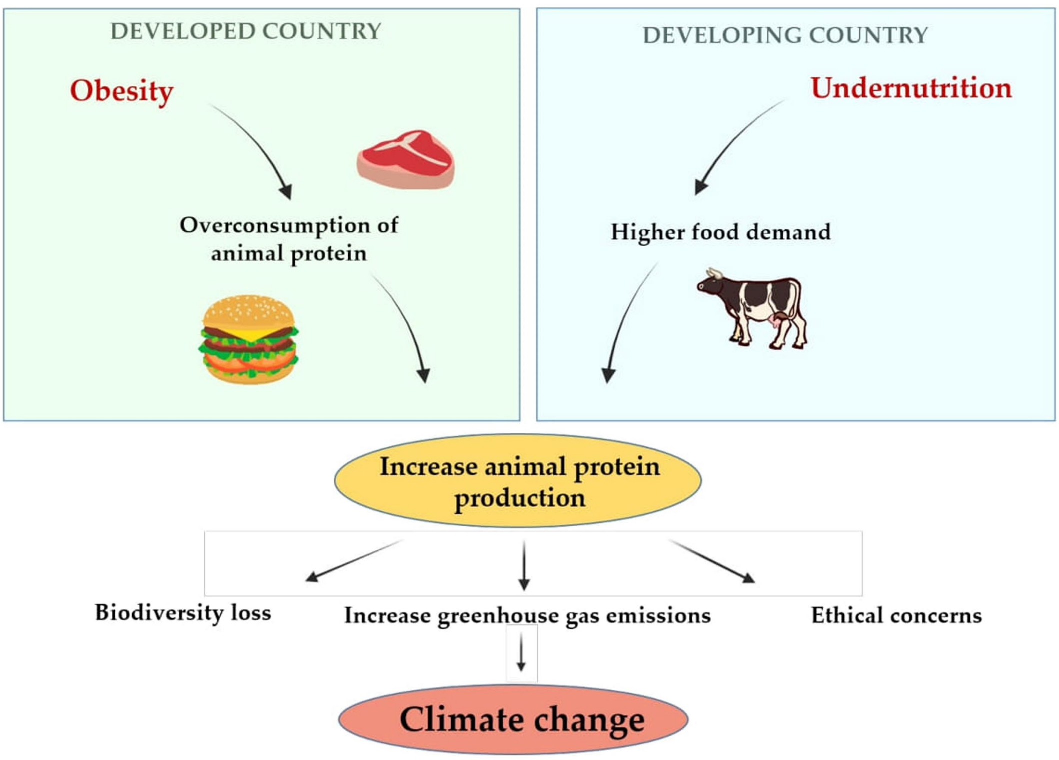

FIGURE 1
The relationship between obesity, undernutrition and climate change.

published in English-language for the review. The reference lists of included studies were additionally screened to locate further relevant literature. We used the following keywords for the review: "algae OR algal protein OR algae peptide + Y," "fungi OR fungal protein OR fungi peptide + Y," "Insect OR insect protein OR insect peptide +Y," where Y indicates hypertension, obesity, T2DM, dementia, cancer, and sarcopenia.

2.1 The role of algae-derived protein and bioactive peptides in preventive and clinical nutrition

Algae are protein-rich marine resources that have a rapid growth rate, can adapt to extreme and competitive environments, and contain numerous health-promoting compounds (37) and proteins, such as lectins, phycobiliproteins, mycosporine-like amino acids, derived hydrolysates, and bioactive peptides (38). Commercially available microalgae, such as spirulina (*Cyanobacterium Arthrospira platensis*) and *Chlorella vulgaris* contain up to 68% protein by dry weight (39, 40), whereas red algae contain up to 47% of protein (41). Proteins extracted from spirulina and chlorella have a high degree of *in vitro* digestibility and contain all essential amino acids (42, 43). Further studies assessing the *in vivo* digestibility of these proteins are necessary. Additionally, algae-derived bioactive peptides exhibited anti-microbial, anti-mutagenic, anti-inflammatory, anti-diabetic, anti-hypertensive, anti-oxidant, anti-tumor, neurophysiological and hepatoprotective activity (44–47). Figure 2 summarizes the role of algae, fungi and insect derived bioactive peptides in preventive and clinical nutrition.

2.1.1 Anti-sarcopenic effect of algae-derived protein and bioactive peptides

By the year 2050, the number of individuals aged 60 years and above will double (2.1 billion), particularly those over 85 years will triple (426 million) (48). Sarcopenia, the key hallmark of aging, refers to the progressive loss of muscle mass and loss of strength or performance (49). Sarcopenia negatively affects the quality of life of the individual (50, 51), burdens the public health sector (52, 53) and increases mortality rates (54, 55). Daily intake of adequate (30 g/meal) high biological value, leucine-rich proteins with physical activity is crucial to counteract sarcopenia by maximizing muscle protein synthesis (MPS) rate (56).

Food protein and their derived bioactive peptides could be a promising option in this regard (57, 58). For example, *Spirulina platensis*, is a potential protein supplement. A preceding study was conducted to examine the anti-sarcopenic effect of Spirulina protein hydrolysate (SPH) in dexamethasone-treated C_2C_{12} cells. The results indicated that SPH inhibits muscle atrophy mainly by activating the Akt/FoxO3a signaling pathway, specifically by increasing MyoD1, Myf5, and myogenin and decreasing Atrogin-1, MuRF-1, and FoxO3a (59). However, further studies on algae-derived peptides using animal models is required to affirm SPH as a solution for the prevention, and treatment of sarcopenia. Recently, randomized controlled trials performed among young adults (age: 22 ± 3 years) have shown that algae-derived protein (spirulina, and chlorella) ingestion stimulates muscle protein synthesis similar to mycoprotein (60). However, further research in older adults is warranted to translate into the prevention and treatment of sarcopenia.

2.1.2 Anti-obesity effect of algae-derived protein and bioactive peptides

Globally, obesity is a major public health problem primarily associated with the consumption of high-fat diets and ultra-processed foods (7, 61). It is attributable to the global incidence of cardiovascular disease, cancer, type 2 diabetes mellitus, osteoarthritis, work disability, and sleep apnea (62). As a consequence, algae-derived proteins and bioactive peptides could serve as anti-obesity agents (63, 64). In high-fat diet-fed mice, the anti-obesity effects of Spirulina-derived protein (SPP) or peptide (SPPH) are higher to the whole Spirulina (WSP), SPP is slightly lower than SPPH, under the same dose (2 g/kg per day). Overall, SPPH showed good anti-obesity effects, such as reduction of body weight (39.8% ± 9.7%), lowering serum glucose (23.8% ± 1.6%), decreasing total cholesterol (20.8% ± 1.4%), while positive drug Simvastatin (10 mg/kg per day) had the corresponding values: 8.3 ± 4.6, 24.8 ± 1.9% and − 2.1% ± 0.2%, respectively. SPPH anti-obesity effects modulate the

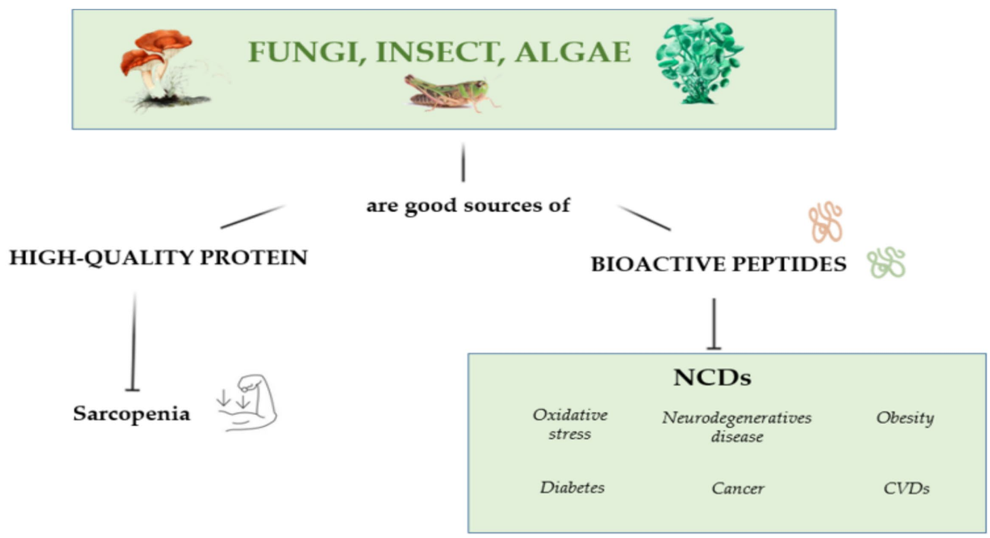

FIGURE 2
The possible positive effects of fungi, insects and algae in preventive and clinical nutrition.

expressions of key genes in the brain (Acadm, Gcg) and liver (Retn, Fabp4, Ppard, and Slc27a1), which are linked with lipid metabolism and accumulation (65). A peptide, CANPHELPNK, identified from enzymatic hydrolysates of *Spirulina platensis* protein showed the best anti-proliferative activity on preadipocytes 3 T3-L1 (60.08%), which was close to that of Simvastatin (70.32%), at 2 mg/ml. Furthermore, the two peptides NPVWKRK and CANPHELPNK were also demonstrated to significantly reduce the accumulation of triglyceride at 600 μg/ml, with 23.7 and 19.5%, respectively compared with control (66). Moreover, in high fat diet-fed rats, supplementation with *Chlorella vulgaris* effectively reduced total serum lipids, liver triglycerides, and cholesterol (67).

Intriguingly, a systematic review and meta-analysis of randomized controlled trials in humans showed that spirulina supplementation significantly reduces body weight, body fat percentage, and waist circumference (68). It also decreases triglycerides and total cholesterol levels in patients with type 2 diabetes, metabolic syndrome, overweight, or obesity (69). Spirulina is "generally recognized as safe" for human consumption (70). Nevertheless, rare potential adverse effects, such as acute rhabdomyolysis (71) and anaphylaxis (72) were reported. Therefore, an allergy risk assessment before supplementation is strongly suggested.

2.1.3 Anti-hypertensive effect of algae-derived proteins and bioactive peptides

Hypertension shares a large quota as a risk factor for CVD (73). It is further leads to end-stage renal disease, stroke, disability, dementia and mortality (74–76). To lessen hypertension, angiotensin-converting enzyme (ACE) inhibition using synthetic drugs is the basic step, despite undesirable side effects, including dry cough, angioedema, disturbance, and skin rash are associated with the drug (77). Therefore, pursuing anti-hypertensive bioactive peptides from natural food sources, such as algae has paramount importance (78).

In silico and *in vitro* assessment showed that bioactive peptides (Alcalase, bromelain, papain, pepsin) of *A. platensis* demonstrated ACE inhibitory activity (80% inhibition rate at a level of 1.0 mg/ml) (79). Moreover, oral administration of protein hydrolysate from *Chlorella Vulgaris* (5 mg/kg of body weight) to spontaneously hypertensive rats (SHR) effectively reduced the systolic blood pressure by 50 mmHg, verifying the potent antihypertensive effects of certain peptides, equivalent to synthetic drugs (80). Interestingly, a systematic review and meta-analysis of randomized controlled trials in humans showed that chlorella supplementation (4 g/day) for 8 weeks and more, significantly reduced total cholesterol, low-density lipoprotein, systolic and diastolic blood pressure in hypertensive patients (81).

2.1.4 Anti-diabetic effect of algae-derived protein and bioactive peptides

Type 2 diabetes (T2DM) is a metabolic disorder that accounts for more than 90% of patients with diabetes, which leads to microvascular (neuropathy, retinopathy and nephropathy) and macrovascular (CVD) complications. In addition, T2DM has a significant impact on patients' lives and puts a huge burden on healthcare systems (82, 83). The existing anti-diabetic agents are often associated with side effects (84); as a result, there is a growing interest in the use of food protein/peptides as a potential remedy for the prevention and management of T2DM (85), especially in its early forms.

Bioactive peptides derived from various algae species, such as *A. platensis* (79, 86, 87), *Chlorella* sp. (88), and *P. palmata* (89), have demonstrated anti-diabetic bioactivities via inhibiting Dipeptidyl peptidase IV (DPP-IV), and carbohydrate-digesting enzyme inhibition, i.e., α-amylase and α-glucosidase, thereby reduced the postprandial blood glucose absorption. Literature has shown that *Spirulina platensis*-derived anti-hyperglycemic peptide exhibited the best inhibition on α-amylase (62%), α-glucosidase (90%) and DPP-IV (49%) (87). Thus, the inhibitory activity of α-glucosidase was remarkably higher than α-amylase (87). This could be useful to decrease side effects due to the abnormal bacterial fermentation of undigested saccharides in the colon, which commonly occurs following excessive inhibition by α-amylase (90).

In streptozotocin-induced diabetic mice (SIDM), oral administration of *P. palmata* crude protein hydrolysate influenced the incretin system by directly upregulating the secretion of glucagon-like peptide 1 (GLP-1) and glucose-dependent insulinotropic polypeptide (GIP) (89).

2.1.5 Anti-dementia role of algal proteins

Among individuals diagnosed with dementia, a neurodegenerative disease, such as Alzheimer's disease (AD) shares a large part (60%), which arises when nerve cells in the central nervous system gradually lose function due to proinflammatory stimulus that facilitates the generation of neurotoxicity substances, and eventually die (91, 92). Neurodegenerative disease affects the patient's quality of life (93), increases the burden for caregivers (94) and poses a higher economic cost (95). Though the available treatments may relieve symptoms, no known curative treatment is found for neurodegenerative diseases. As a consequence, food-derived peptides could have the potential to mitigate neurological inflammation, thereby improving cognitive performance (91, 96). A previous study indicated that dietary administration of 1 and 2% *Spirulina platensis* for 16 weeks in high fat diet fed mice significantly improved spatial learning and memory performance via inhibiting Aβ accumulation, tau-hyperphosphorylation, and neuroinflammation in the hippocampus (97). This study provides further evidence for the application of *Spirulina platensis* derived protein as a functional supplement for the treatment of AD. In support, the effects of spirulina intake (500 mg/day spirulina powder versus placebo twice a day for 12 weeks) among 60 patients with AD significantly improved their cognitive function, as evidenced by the mini-mental state examination score (MMSE). Additionally, spirulina intake decreased high-sensitivity C-reactive protein, fasting glucose, insulin resistance, and increased insulin sensitivity compared with the placebo (98).

2.1.6 Anti-cancer role of algae-derived protein and bioactive peptides

Cancer is the leading cause of death next to CVD (99). Cancer metastasis to vital organs of the body usually results in massive tissue destruction, loss of life-sustaining functions, and death (100). The investigation of anticancer drugs derived from natural products has become a hot topic in the field of cancer research because of their lower economic cost and fewer side effects (101, 102).

Dietary algae such as *Chlorella vulgaris* (103), *Chlorella pyrenoidosa* (104), *Spirulina platensis* (105), and *Enteromorpha prolifera* (106) have shown significant anticancer bioactivities. Literature has shown that enzymatic hydrolysates of *A. platensis* protein at a concentration of 0.5 mg/ml exhibited comparable inhibitory effects against breast cancer cells (MCF-7), lung cancer cells

(A549), gastric cancer cells (SGC-7901), colon cancer cells (HT-29), and liver cancer cells (HepG2) compared to the positive control drug 5-flurouracil (5-FU) (105, 107, 108). Moreover, the protein-derived peptide from *Chlorella vulgaris* stops human AGS gastric cancer cells after G1 phase (103). Papain hydrolysate purified from *Chlorella pyrenoidosa* showed anti-proliferation activity against HepG2 (104). Recently, heptapeptide (GPLGAGP) isolated from hydrolysates of *Enteromorpha prolifera* showed the most potent inhibitory activity against NCI-H460 lung cancer cells (106).

2.2 The role of fungi-derived protein and bioactive peptides in preventive and clinical nutrition

Fungi are suitable alternative sources of food for humans which have a low environmental footprint, and could be a solution for a sustainable future for our planet (109–113). Mycoprotein, which is a proteinaceous wholefood produced from the continuous fermentation of the filamentous fungus *Fusarium venenatum*, is the most popular example that is commercialized and sold in different countries (UK, USA, Belgium, Germany, Denmark, Ireland, France, the Netherlands, Switzerland, Sweden etc.) as an ingredient in products marketed under the brand name Quorn™ (114). Mycoprotein product contains high-quality protein (11.5%), fiber (6%) composed of glucan-chitin matrix, sugar (0.8%), fat (2.9%), and minerals, such as selenium (20%), zinc (less bioavailable than meat), iron (lower than meat), manganese, calcium, and phosphorus, and a source of vitamin B2 (115). Also, it is devoid of trans-fats and cholesterol. Due to its healthy nutritional profile, the consumption of mycoprotein is increasing worldwide (112). For example, including mycoprotein in the daily diet helps maintaining glycaemic control (116). Furthermore, edible mushrooms have tremendous health benefits including anti-inflammatory, antioxidant, anti-cancer, anti-diabetic and anti-obesity properties (117, 118).

2.2.1 The role of fungi-derived protein and bioactive peptides in weight management

Owing to its sufficient amount of fiber and high protein content, mycoprotein plays a vital role in fighting hunger, decreasing body weight, and reducing energy intake. Literature have shown that mycoprotein ingestion reduces energy intake and increases satiety effects in obese and overweight individuals (119, 120). A study with 36 overweight and obese adults showed that 132 g energy-matched mycoprotein-based preload meal compared to a chicken meal for 180 min reduced energy intake by 10% (120). This could partly be due to the thermogenic and satiety effect of mycoprotein (121). Further longer-term studies are needed to investigate the potential of mycoprotein in the prevention of obesity and T2DM.

Interestingly, *Ganoderma lucidum*—a medicinal mushroom—showed anti-obesity activities by modulating the gut microbiota (decreased the ratio of Firmicutes to Bacteroidetes and levels of Proteobacteria) in high-fat diet (HFD)-fed mice, suggesting as a prebiotic to reduce weight (122). The finding also showed that supplementation of water extract of *Ganoderma lucidum* mycelium to HFD-fed mice daily for 2 months by oral gavage results in a dose-dependently decreased weight gain and both epididymal and subcutaneous fat accumulation, and reduced inflammation and insulin resistance compared with untreated controls. Given scarce studies in the area, extensive research and clinical studies demonstrating the safety and effectiveness of fungi-derived bioactive peptides are worthy of further investigation.

2.2.2 The role of fungi-derived protein and bioactive peptides in improving cardio-metabolic health

Mycoprotein ingestion also advantageously modifies blood lipid profiles, as indicated by studies (123, 124). The greatest benefits have been observed in subjects with elevated cholesterol levels at baseline (124). A study conducted on 17 healthy participants indicated that ingestion of mycoprotein-containing products (191 g) per day for 3 weeks reduced total cholesterol, lowered low-density lipoprotein and improved high-density lipoprotein by 13, 9, and 12%, respectively (125). A randomized trial was conducted in a home setting among 72 overweight, hypercholesterolaemic adults showed that mycoprotein ingestion for 4 weeks reduces serum cholesterol, low-density lipoprotein level, blood glucose, and C-peptide concentrations by 6, 10, 13 and 27%, respectively (123). This implies that mycoprotein may improve peripheral insulin sensitivity, suggesting a role in preventive and clinical nutrition in reducing the risk of obesity and diabetes mellitus in adults. However, further investigation is warranted to consolidate this evidence. Consumption of edible mushrooms decreases plasma triglyceride, total cholesterol, and low-density lipoprotein (126). Moreover, bioactive peptides obtained from different edible mushroom species, such as *Pholiota adiposa, pleurotus cornucopiae, Hypsizygus marmoreus, Agaricus bisporus, Tricholoma giganteum*, *Ganoderma Lucidum*, and shiitake mushroom (*Lentinula edodes*) exhibited ACE inhibitory activities (127–133). A detailed summary of the beneficial effects of bioactive peptides has been provided in Table 1.

2.2.3 The role of fungi-derived protein and bioactive peptides in muscle anabolism

Furthermore, mycoprotein ingestion (121, 123, 134–137) increases muscle protein synthesis rate when taken as a whole food, an isolated source or in a blended form, particularly in young individuals. Mycoprotein (at a dose of 60–80 g) ingestion led to slower but more sustained hyperaminoacidemia and hyperinsulinemia when compared with 20 g protein-match milk (121). Similarly, mycoprotein ingestion (70 g) resulted in a less rapid but more sustained increase in serum insulin levels, peaking at 30 min after consumption when compared with milk protein (136). However, a large amount of mycoprotein ingestion coupled with its satiating properties (138, 139) may not be a pragmatic approach in compromised individuals (anorexic older adults, patients with sarcopenia and cachexia). In such situations, protein concentrate from mycoprotein, and BCAA-enriched mycoprotein may be a feasible option, but further investigation is warranted.

2.3 The role of insect-derived protein and bioactive peptides in preventive and clinical nutrition

Given that more than 2,100 edible insects are found worldwide, their nutritional composition is difficult to generalize (140). However, many edible insects contain high-quality protein (141), unsaturated fatty acids (linolenic and linoleic acid), micronutrients

TABLE 1 A summary of the purported beneficial effects of algae, fungi and insect-derived peptides.

Source	Species	Title of the article with references	Year of publication	Name of bioactive peptide/amino acid sequence	*In vivo/In vitro*	Beneficial effects of the peptide	Future research areas
Algae	*Spirulina platensis/ Arthrospira platensis*	Anti-obesity effects of *Spirulina platensis* protein hydrolysate by modulating brain-liver axis in high-fat diet fed mice (65)	2019	Spirulina platensis protein peptide hyrdolyste (SPPH)	*In vivo* animal (C57BL/6J mice)	Reduce body weight, serum glucose and total cholesterol	The molecular mechanism between Acadm and Acaca or Acsl1 warrants further study
		Purification and identification of anti-obesity peptides derived from *Spirulina platensis* (66)	2018	CANPHELPNK, NPVWKRK	*In vitro* using mouse 3T3-L1 preadipocytes and normal liver cells (L-O2)	Exhibit inhibitory effects on 3T3-L1preadipocyte proliferation, and reduce the accumulation of triglyceride	The detailed mechanism of action for the identified peptides needs to be explained
		Protein hydrolysate from *Spirulina platensis* prevents dexamethasone-induced muscle atrophy via Akt/Foxo3 signaling in C_2C_{12} myotubes (59)	2022	Spirulina protein hydrolysate (SPH)	C_2C_{12} cell line (CRL-1772)	Inhibits muscle atrophy mainly by activating the Akt/FoxO3a signaling pathway, increased myotube length and diameter in C_2C_{12} cells,	To translate the effect of SPH as a healthy functional food material for the prevention, treatment, and improvement of muscle atrophy, *in vivo* study using animal models is required
		Identification of anti-diabetes peptides from *Spirulina platensis* (87)	2019	GVPMPN, RNPFVFAPTLLTVAAR and LRSELAAWSR	*In vitro*	Inhibition of α-amylase, α-glucosidase and DPP-IV	*In vivo* studies are important
		Characterization and antitumor activity of protein hydrolysates from *Arthrospira platensis (Spirulina platensis)* using two-step hydrolysis (107)	2016	AGGASLLLLR, KFLVLCLR(KR),LCLR (LR), LAGHVGVR	*In vitro* and *in vivo* (using nude mice)	Dose dependent inhibitory effect against breast cancer cells (MCF-7), lung cancer cells (A549), gastric cancer cells(SGC-7901), colon cancer cells (HT-29), liver cancer cells(HepG2)	Further study is warranted to divulge why the identified peptides did not inhibit cancer growth in a time dependent manner
		In silico and *in vitro* assessment of bioactive peptides from *Arthrospira platensis* phycobiliproteins for DPP-IV inhibitory activity, ACE inhibitory activity, and antioxidant activity (79)	2022	Phycobiliprotein hydrolysates (PBPHs)	*In silico* and *in vitro*	ACE inhibitory activity, DPP-IV inhibitory activity, antioxidant activity	*In vivo* study is required
	Chlorella vulgaris	Antihypertensive effects, molecular docking study, and isothermal titration calorimetry assay of angiotensin I-converting enzyme inhibitory peptides from *Chlorella vulgaris* (80)	2018	Val-His-Trp (VHW), Thr-Thr-Trp (TTW)	*In silico* and *in vivo* (SHR). Molecular docking and Isothermal titration calorimetry (ITC) assay	VHW reduces SBP from 234 to 184 mmHg happened at 2 h. TTW reduces DBP from 180 to 140 mmHg at 2 h. Thus, VHW and TTW could be used to treat different hypertensive phenotypes or cooperate together.	Enrichment of the tryptophan content of the identified peptides is important

(Continued)

TABLE 1 (Continued)

Source	Species	Title of the article with references	Year of publication	Name of bioactive peptide/amino acid sequence	*In vivo*/*In vitro*	Beneficial effects of the peptide	Future research areas
		Anticancer and antioxidant activities of the peptide fraction from algae protein waste (103)	2010	VECYGPNRPQF	*In vitro*	The identified peptides effectively induced cell death and inhibited the growth of AGS cells after G1 phase. The antioxidant activity of the peptide fraction was about 26-fold stronger than that of Trolox.	*In vivo* study is warranted
	Chlorella pyrenodosa	Separation, antitumor activities, and encapsulation of polypeptide from *Chlorella pyrenoidosa* (104)	2013	*C. pyrenoidosa* antitumor polypeptide (CPAP)	*In vitro*	Anti-proliferative activity against human liver cancer HepG2 cells.	Detailed encapsulation mechanisms, and *in vivo* study is required. Amino acid sequence of the peptide was not determined
	Enteromorphia Prolifera	Preparation and Characterization of an Anticancer Peptide from Oriental Tonic Food *Enteromorpha prolifera* (106)	2022	HTDT-6-2-3-2	*In silico*, *in vitro* and molecular docking	Inhibitory activity against NCI-H460 human cancer cell lines	HTDT-6-2-3-2 may also be novel inhibitors for ACE and DPP4. Future experiments will be conducted to verify this assumption
Fungi	*Pholiota adipose kumm* (Yellow-cap fungus)	Production and characterization of antihypertensive angiotensin I-converting enzyme inhibitor from *Pholiota adipose* (127)	2006	GEGGP	*In vivo* (SHR)	ACE inhibitory activity (decrease SBP by 22 mmHg)	ACE inhibitory activity is weaker than captopril. Research may require to enhance the ACE inhibitory activity of the identified peptide
	Hypsizygus marmoreus	Characterization of an antihypertensive angiotensin I-converting enzyme inhibitory peptide from the edible mushroom *Hypsizygus marmoreus* (129)	2013	LSMGSASLSP	*In vivo* (SHR)	ACE inhibitory activity (decrease SBP by 26 mmHg)	Human study is required for translating in to the actual health benefits.
	Pleurotus cornucopiae	Characterisation of a new antihypertensive angiotensin I-converting enzyme inhibitory peptide from *Pleurotus cornucopiae* (128)	2011	RLPSEFDLSAFLRA, RLSGQTIEVTSEYLFRH	*In vivo* (SHR)	ACE inhibitory activity (decrease SBP by 50 mmHg)	Further studies are necessary to reduce the molecular weight of the identified peptide for application into the medicinal industry.

(Continued)

TABLE 1 (Continued)

Source	Species	Title of the article with references	Year of publication	Name of bioactive peptide/amino acid sequence	*In vivo*/*In vitro*	Beneficial effects of the peptide	Future research areas
	Tricholoma giganteum (Giant mushroom)	Isolation and characterization of a novel angiotensin I-converting enzyme inhibitory peptide derived from the edible mushroom *Tricholoma giganteum* (131)	2004	GEP	*In vivo* (SHR)	ACE inhibitory activity (decrease SBP by 36 mmHg)	Human study is required for translating in to the actual health benefits.
	Agaricus bisporus (button mushroom)	Novel angiotensin I-converting enzyme inhibitory peptides derived from edible mushroom *Agaricus bisporus* (J.E. Lange) Imbach identified by LC–MS/MS (130)	2014	AHEPVK, RIGLF, PSSNK	*In vitro*	ACE inhibitory activity	*In vivo* study is required
	Ganoderma Lucidum	Isolation and characterization of three antihypertension peptides from the mycelia of *Ganoderma lucidum* (Agaricomycetes) (132)	2019	QDVL, QDVL, QLDL	*In vitro*	ACE inhibitory activity	Future studies on the cellular mechanism by which the identified peptides inhibit hypertension should be conducted to confirm this finding
Insects	*Tenbrio Molitor* (Yellow mealworm)	Identification and *in silico* analysis of antithrombotic peptides from the enzymatic hydrolysates of *Tenebrio molitor* larvae (165)	2019	SLVDAIGMGP, AGFAGDDAPR	*In silico* and molecular docking	Antithrombotic effect	Before applying it to the clinic, it still needs to prove the antithrombotic effect *in vivo* through a large number of experiments.
	Tenbrio Molitor (Yellow mealworm), Cricket (*Gryllodes sigillatus*), Locust (*Schistocerca gregaria*)	Evaluation of ACE, α-glucosidase, and lipase inhibitory activities of peptides obtained by *in vitro* digestion of selected species of edible insects (162)	2020	KVEGDLK, YETGNGIK, AIGVGAIR, IIAPPER, FDPFPK	*In vitro*	Inhibition of ACE, pancreatic lipase and α-glucosidase	Mechanism of lipase inhibition by peptides is still poorly understood, requiring further study
	Silkworm(*Bombyx mori*)	Novel tripeptides with α-glucosidase inhibitory activity isolated from silk cocoon hydrolysate (163)	2011	E5K6	*In vitro*	α-glucosidase inhibitory activity	Further studies are needed on the side effect of the identified peptide using animals
		A novel angiotensin-I converting enzyme (ACE) inhibitory peptide from gastrointestinal protease hydrolysate of silkworm pupa (*Bombyx mori*) protein: biochemical characterization and molecular docking study (148)	2015	Silkworm pupa protein hydrolysate (SPPH)/Ala-Ser-Leu (ASL)	*In vitro*, molecular docking	Competitive ACE inhibitor	*In vivo* study is required

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(iron, zinc, calcium, potassium, magnesium, manganese, copper, vitamin E, vitamin K, vitamin B_2, and vitamin B_{12}) and fiber (142–145). Interestingly, iron and zinc found in crickets, grasshoppers and mealworms have been shown highly bioavailable compared to sirloin beef (143). Currently, common edible insect species are house cricket (*Acheta domesticus*), African palm weevil (*Rhynchophorus phoenicis*), yellow mealworm (*Tenebrio molitor*), mopane worm (*Gonimbrasia belina*), domesticated silkworm (*Bombyx mori*),and honeybee (*Apis mellifera*) (146). Edible insects are a sustainable source of protein for food and feed given their lower water and land consumption, high feed conversion efficiency, low greenhouse gas emissions compared to livestock, short life cycle, and rapid intrinsic growth rate (147, 148).

2.3.1 The role of insect-derived protein in muscle protein synthesis: insight for sarcopenia prevention

Studies showed that ingestion of lesser mealworm-derived protein (149), and cricket protein powder (150) were capable of stimulating MPS at rest and after exercise in young men. In particular, similar postprandial amino acid availability and MPS rates occurred after ingestion of 30 g lesser mealworm-derived protein to an equivalent amount of milk protein concentrate (149). In addition, no significant difference was observed in the mammalian target of rapamycin (mTORC1) signaling between cricket, pea, and whey protein despite a higher concentration of EAA and leucine occurring after ingestion of whey (150). Similarly, the EAA, BCAA, and leucine plasma levels peaked earlier in soy, whey and beef-derived protein than for cricket and lesser-mealworm (151, 152). The observed differences may be attributed to the slowly digested properties of lesser mealworm and cricket-derived compared to animal-derived proteins.

The high muscle protein anabolic potential of insect-derived proteins provides a strong initiative for integrating insects into the diet, especially in Western countries where acceptance of insect consumption is low. The high quality of insect-derived proteins coupled with their high amounts of micronutrients and antioxidants (153–155), will be of particular relevance in populations that consume less protein and suffer from anabolic resistance (156), such as the older and more clinically compromised populations.

2.3.2 The role of insect-derived bioactive peptides in preventing obesity, diabetes and hypertension

Although human studies are still lacking, peptides and bioactive compounds derived from edible insects could provide health benefits, such as anti-oxidant (157), anti-obesity (158), anti-diabetic (159) and anti-hypertensive properties (160). A study showed that yellow mealworm larvae powder administration in obese mice reduced body weight gain by decreasing lipid accumulation and triglyceride content in adipocytes (158), thus demonstrating the potential to induce weight loss. Moreover, an ethanol extract of the Korean horn beetle *Allomyrina dichotoma* injection into the brain tissue of obese mice reduced both endoplasmic reticulum (ER) stress and hormone-induced change in feeding behaviour (159). Thus, it could imply in preventing and treating obesity and T2DM since reduction of ER stress enhances insulin-producing beta cells (161).

Antioxidant activity in edible insect species was reported, including free radical-scavenging activity, and iron-chelating ability (157). Moreover, inhibition of ACE, pancreatic lipase and α-glucosidase have been observed in peptides derived from yellow mealworm(*Tenbrio Molitor*), silkworm (*Bombyx mori*), cricket (*Gryllodes sigillatus*) and locust (*Schistocerca gregaria*) (160, 162–164). Besides the ACE inhibitory activity, peptides derived from *Tenebrio molitor* larvae showed strong antithrombotic properties (165). However, the evidence mentioned above (157–160, 162–165) requires further human studies to translate into actual health benefits.

2.4 Food safety of edible insects

Apart from the nutritional, environmental and health benefits of edible insects, food safety issues need to be considered. This includes anti-nutrient content, allergenic potential, microbial safety and chemical contamination. Anti-nutrients, such as phytic acid, tannin, saponins, oxalate and cyanogenic glycosides have been determined in edible insects (145, 166, 167). More research on the anti-nutritional properties is necessary. Allergic reactions that could be triggered by insect consumption include nausea, vomiting, diarrhea, asthma, and skin reactions (168, 169). Commonly, tropomyosin and arginine kinase pan-allergens have been identified (168–170). Cross-reactivity and co-sensitisation between (insects and house dust mites) and (insects and crustaceans) occur because of these pan-allergens (168, 169). Therefore, clear labelling and communication of the allergenic potential of insects to the consumer is required since insect protein allergenicity is not removed by thermal treatments (168).

Concerning microbial safety, different microbiota have been found on raw edible insects, including lactic acid bacteria, Enterobacteriaceae, fungi, mesophilic aerobes, spore-forming bacteria, and foodborne pathogens (171), albeit no outbreaks associated with pathogens have been reported in the scientific literature. Thus, effective decontamination, and good hygiene practices during rearing, processing and storage are essential to minimize the microbial hazards of insect-containing food products (172).

Regarding chemical contamination of edible insects, low levels of contaminants (the level below the legal maximum amount), such as dioxin compounds, pesticide residue, arsenic, cadmium, copper, nickel, mercury, lead, and tin have been identified (173, 174). Insect species, rearing conditions, feed substrate including the packaging material of the substrate, and post-harvest processing were factors for the chemical contamination of edible insects (172, 175). Regular monitoring of the rearing environment, strong supplier auditing and certification process could reduce the risk of heavy metal contamination (176). Additionally, using naturally derived biopesticides from plants, micro-organisms or beneficial insects, such as neem oil, *bacillus thuringiensis*, and insect pheromones could decrease the deposition of residual pesticides (177). Future research should focus on determining the best processing conditions to create insect protein isolates with good functional characteristics, cost-effectiveness, and environmental sustainability that can be used in food formulation.

2.5 Challenges and strategies to consume edible insects

Despite a surfeit of health benefits, and the potential of edible insects to represent an environmentally sustainable nutrient source, willingness to consume insects as a food is low in Western countries (178, 179); albeit they aren't against advances and food innovations. Food disgust (the product goes beyond the internalized norm of what food is), lack of familiarity with insect consumption, neophobia (hesitance to consume unfamiliar food), lack of product information, curiosity or sensation seeking and food technology neophobia were the identified drivers for low acceptance of insect consumption (178–180). As a result, different strategies have been suggested to convince consumers, such as underscoring that insects are nutritious, harvesting properly on controlled farms, making insect products delicious (enhancing the culinary experience), familiarizing insect-based products, integrating them in unrecognizable forms in familiar products, marketing insect-based products by taste, using celebrities to promote the product, targeting specific groups (sensation seekers, adventurous consumers or children), information provision from a nutritional and environmental standpoint, devising market approaches (stylistic images, choosing supermarkets for retailing, and using promotional tools such as buy-one-get-one-free, and discounts) (176, 181).

3 Conclusion

In conclusion, proteins derived from algae, fungi, and edible insects are high-quality proteins as animal sources and demonstrate significant potential as a sustainable source of bioactive peptides, which are metabolically potent and have negligible adverse effects. They show promise to prevent and treat diseases associated with oxidative stress, obesity, diabetes, cancer, cardiovascular disease (especially hypertension), and neurodegenerative diseases. Given the abundance of algae, fungi and insect peptides performed *in vitro* or *in vivo* animals, further research, validation and clinical studies are needed to fully establish their safety, efficacy and practical application in preventive and clinical nutrition. Additionally, social and behavioral change communication strategies would be important to increase health awareness of nutritional benefits and promote consumer acceptance of alternative protein sources.

Author contributions

MY: Conceptualization, Methodology, Visualization, Writing – original draft, Writing – review & editing. MA: Conceptualization, Methodology, Visualization, Writing – original draft, Writing – review & editing. SC: Conceptualization, Methodology, Visualization, Writing – original draft, Writing – review & editing. MM: Conceptualization, Methodology, Visualization, Writing – original draft, Writing – review & editing.

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Conflict of interest

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Diet, nutrition, and climate: historical and contemporary connections

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This paper reviews the past global nutrition efforts, particularly those led by the Global Alliance for Improved Nutrition (GAIN), at the critical intersection of nutrition and climate change. Despite progress in tackling malnutrition and promoting sustainable food systems, significant challenges remain, especially in regions like Sub-Saharan Africa and South Asia, where micronutrient deficiencies persist. The paper underscores the urgent need to integrate nutrition into climate strategies and strengthen food system resilience. Initiatives like the Scaling Up Nutrition (SUN) movement, the Food Systems Dashboard, and GAIN's public and private sector partnerships at the local levels have contributed to transforming food systems. However, there is an urgent need for more robust policies that effectively align nutrition, climate, and equity goals. Looking ahead, we advocate for increased financial investment, improved policy frameworks, and innovations in technology and data monitoring to drive sustainable food system transformations. We further underscore the importance of addressing micronutrient deficiencies, promoting biodiversity, and developing healthier crops to support climate-smart agriculture. Achieving resilient, equitable, and sustainable food systems over the next years will depend on collaborative efforts across sectors and stakeholders.

KEYWORDS

nutrition, climate change, food systems, diets, sustainability, policy

1 Introduction

The narrative around nutrition has evolved significantly, shifting from a focus on infection and mortality to acknowledging its critical role in overall health and development. Early efforts targeted undernutrition, but the approach has since broadened to include overweight and obesity and related non-communicable diseases, as well as multisectoral interventions and food systems, recognizing their impact on both human health and the environment.

Today, the link between nutrition and climate change is central due to the profound impacts that food production and consumption have on the environment and vice versa. Food systems contribute significantly to environmental degradation through practices such as deforestation, greenhouse gas emissions, and excessive water use in agriculture. These processes drive biodiversity loss and exacerbate global warming, with food production, processing, and transportation being key contributors to these environmental pressures (1–3). However, food processing also plays an essential role in reducing food waste, which is critical for minimizing environmental impact across multiple indicators (4). At the same time, climate change poses substantial risks to food production. Increasingly frequent extreme weather events, shifting agricultural zones, and changing rainfall patterns threaten food security and nutrition, with direct impacts on food supply, quality and safety that can lead not only to food insecurity but also to dietary shifts toward more processed foods (5–8). This bidirectional relationship between food systems and climate change underscores the urgency of addressing climate change through sustainable food and nutrition practices.

A growing body of research and evidence, including reports by the United Nations and the Intergovernmental Panel on Climate Change, has emphasized the need for integrated approaches to mitigate climate change while improving nutrition. However, integrating nutritional goals with climate objectives remains a complex challenge. Particularly in regions like Sub-Saharan Africa and South Asia, where undernutrition and high rates of micronutrient deficiencies persist, rising influence of Western dietary patterns, including increased consumption of red meat, is driving obesity and non-communicable diseases. These shifts complicate efforts to promote sustainable and nutritious consumption patterns (9–12).

This perspective paper reflects on past efforts at the intersection of nutrition and climate, using the lens of work undertaken by the Global Alliance for Improved Nutrition (GAIN) during this period. It also explores future approaches needed to address ongoing challenges and highlights potentially impactful strategies moving forward.

2 Historic overview and current state

2.1 Review of past trends and key milestones

The 2008 food price crises, where rice prices rose by 300% (13) and wheat and maize doubled (14) exposed the vulnerability of food security to price volatility. This highlighted the need for resilient food systems to ensure global food security amidst fluctuating markets.

2.1.1 Nutrition and growth

Launched at the 2010 UN Millennium Development Goals Summit, the Scaling Up Nutrition (SUN) movement emphasizes the critical 1,000-day period from conception to a child's second birthday. Driven by the 2008 Lancet series on Maternal and Child Undernutrition (15), it promotes nutrition-specific and nutrition-sensitive interventions through country-led, multi-actor efforts involving governments, donors, civil society, businesses, and academia. This marked a shift from focusing solely on hunger and human rights to highlighting the economic impacts of malnutrition, including micronutrient deficiencies, wasting, stunting, obesity and the rising burden of non-communicable diseases (16, 17).

Since its inception, 66 countries have joined the SUN movement (18). While the SUN movement primarily focuses on LMICs, challenges like non-communicable diseases, poor diet quality, and the impact of diet on climate change are also critical in high-income countries, highlighting the global nature of nutrition challenges.

2.1.2 Mainstreaming nutrition

The Mainstreaming Nutrition Initiative (19) and the 2013 Nutrition for Growth Summit in London (20), shifted the focus from calorie adequacy to diverse, nutritious diets. At the summit, over 100 stakeholders pledged more than $4 billion for nutrition-specific projects and $19 billion for nutrition-sensitive initiatives (20). Nutrition's integration into broader development agendas was further supported by the UN Decade of Action on Nutrition (2016–2025), led by the World Health Organization and the Food and Agriculture Organization, and supported by the World Food Programme, the International Fund for Agricultural Development, and the United Nations Children's Fund (21).

During this period, organizations such as EAT (22) and the Consultative Group on International Agricultural Research (CGIAR) (23), emphasized nutrition-sensitive agriculture and sustainability. The first Global Nutrition Report in 2014 acted as an accountability mechanism, tracking progress against global nutrition targets (24). Notable initiatives during this period further included CGIAR's work on improving access to affordable, nutritious, and diverse diets and the EAT Stockholm Food Forum, which fostered collaboration between business, science, and politics to achieve sustainable food systems.

2.1.3 Sustainable development goals

The transition from the Millennium Development Goals (25) to the Sustainable Development Goals (SDGs) (26) in 2015 marked another pivotal shift, with a sharper focus on ending hunger and ensuring food and nutrition security. The SDGs called for a new food system paradigm, recognizing the importance to address all forms of malnutrition including underweight, micronutrient deficiencies as well as obesity, and underscoring the need for systems that support diverse, healthy diets. The Global Nutrition Report 2015 highlighted the intricate relationship between climate change and nutrition, and the pivotal role of businesses in addressing these challenges (27). By this time, 72 LMICs had reached the Millennium Development Goals target of halving the number of people suffering from hunger (28).

Based on one of the key recommendations from the nutrition community back in 2015 (29) the importance of measuring diet quality to connect agriculture and nutrition has been emphasized. As of October 2024, following provisional approval by the Inter-agency and Expert Group on SDG Indicators, indicators of diet quality (Minimum Dietary Diversity for non-pregnant women aged 15–49 years and for children aged 6–23 months) have been considered to be added to the SDG framework for the first time (30). This represents significant progress in the ability to measure and improve diet quality on a global scale, though they have yet to be fully approved (31).

2.1.4 Multiplying impact

By 2017, the global community acknowledged that hunger was once again on the rise. The Global Nutrition Summit in Milan emphasized the powerful multiplier effect of improving nutrition across all SDGs, indicating that addressing nutrition is crucial to achieving broader development goals (32). The High-Level Panel of Experts report introduced a conceptual framework for food systems for diets and nutrition, reinforcing the need for integrated approaches (33).

2.1.5 Integrating climate and diets

The 2019 United Nations Climate Action Summit and the United Nations High-Level Meeting on Universal Healthcare underscored the importance of integrating nutrition with climate action. The EAT-Lancet Commission contributed influential research on sustainable food systems, advocating for healthy diets that promote plant-based foods and reduce ultra-processed food consumption—bridging the gap between nutrition and environmental sustainability (34).

2.1.6 Emphasizing data, accountability, and food systems transformation

From 2020 to 2024, there has been a strong focus on detailed data and accountability to improve global nutrition and food systems. The

COVID-19 pandemic exposed the lack of resilience in food systems and highlighted diet quality as a key factor in COVID-19 co-morbidity, especially for individuals with non-communicable diseases. This underscored the need for robust food systems capable of withstanding crises and addressing both undernutrition and overnutrition.

The 2020 Global Nutrition Report underscored the importance of granular data to address nutrition inequalities effectively (35). Similarly, the Ceres2030 Report highlighted the need to refocus research on the needs of smallholder farmers, stressing the value of original data in shaping impactful interventions (36). In 2021, the United Nations Food Systems Summit, stressed multi-stakeholder approaches, policy coherence, and capacity building for systemic change (37). By 2024, these efforts culminated in the unveiling of a new economic model by the Food System Economics Commission. This model maps the impacts of two potential futures for the global food system, offering critical insights into the economic implications of different food system trajectories and guiding policy and investment decisions for a sustainable future (38).

2.1.7 GAIN's contributions to food systems transformation

In recent years, GAIN has played a key role in advancing global food system transformation through various initiatives. GAIN, in partnership with others, launched the Food Systems Dashboard, a tool that compares food system drivers, components, and outcomes across countries. The dashboard integrates data to identify challenges and strategies to improve nutrition, health, and environmental outcomes. As of 2024, it includes sub-national information for six countries, with two more forthcoming (39).

Building on the UN Food Systems Summit, GAIN introduced the Nourishing Food Pathways program, supporting food systems transformation in 10 countries to accelerate progress toward the Sustainable Development Goals, particularly SDG2 (40). GAIN also co-led the Food Systems Countdown Initiative, which launched baseline results to monitor food system transformation with data-driven insights (41). By June 2024, national data for 50 selected indicators became available through the dashboard to track food system progress. Through these initiatives, GAIN continues to drive progress toward more sustainable, equitable, and nutritious food systems globally, and provide exemplars for others to adopt or adapt.

2.2 A vision and opportunities for the future

For the future, achieving sustainable food systems will require an integrated approach that includes health, social protection, and water/sanitation systems. Addressing gender equity and recognizing the link between environmental sustainability and human health, particularly regarding climate and water, will be crucial for nutrition.

2.2.1 Global initiatives—integrating nutrition and climate

Global climate and nutrition strategies remain misaligned. The Initiative on Climate Action and Nutrition (I-CAN) found that only 1% of climate-related Official Development Assistance financing and 2% of Nationally Determined Contributions mention nutrition explicitly or have concrete plans to address nutrition. Additionally, 95% of Global Nutrition Report commitments and 83% of public food procurement nutrition-related policies do not consider climate or sustainability (42).

Donors, United Nations agencies (such as the World Food Programme, International Fund for Agricultural Development, Food and Agriculture Organization, Children's Fund, International Bank for Reconstruction and Development), and governments must integrate nutrition into their climate action plans and vice versa. I-CAN was launched at COP27 by the Egyptian presidency and is now implemented by GAIN alongside key UN partners, with the objective to bridge climate and nutrition strategies by providing baseline data, policy recommendations, and funding guidance, thus supporting countries in aligning their climate and nutrition goals (42). Other initiatives like Ceres2030's food system roadmap (36), the Food Systems Countdown Initiative (43), and the Food System Economics Commission (44) should be locally adapted, using disaggregated data to ensure progress on both fronts.

In addition to its leadership of I-CAN, GAIN is actively supporting the implementation and expansion of Ceres2030 under Hesat2030 (45), providing greater focus on nutrition and climate impacts when developing country roadmaps for effective public and private sector interventions, as well as the Food Systems Countdown Initiative, to monitor food system progress. GAIN's country dashboards further support this by offering sub-national evidence to inform tailored, effective food system transformations.

2.2.2 National policies and food systems thinking

National policies remain fragmented, failing to integrate agriculture, nutrition, health, and climate. This policy incoherence can lead to contradictions, and policy goals in one area can undermine progress in another, for instance, when efforts to promote food systems transformation neglect the impacts of climate change (46). Despite commitments to food systems transformation, evidence on countries' financing streams for these processes and active identification of policy incoherence remain limited (47).

Additionally, subsidies often do not support nutritious, climate-smart production, while rising food prices especially impact low-income households. While combining taxes on unhealthy foods with subsidies on healthy ones could be an effective approach (48, 49), there is a need to ensure that tax burdens do not disproportionately fall on low-income households (50). Additionally, shifting diets and supply chains to increase access to nutritious, low-environmental-impact foods is critical. Current research is focused on identifying and promoting culturally accepted, nutritionally valuable, and environmentally sustainable foods, with policy implications for dietary guidelines, agricultural incentives, public procurement, and social protection programs. It is also essential to consider the affordability of these foods, how their nutritional value may be influenced by women's or children's unique dietary needs, and how food consumption patterns vary across different regions and seasons.

GAIN supports national governments in defining their Food System Pathways and is actively developing a tool, recently piloted in Nigeria and now being deployed in nine additional countries, to help governments diagnose and improve the alignment of policies across different sectors (51). The Financial Flows to Food Systems tool, developed by the International Fund for Agricultural Development and the World Bank, provides data on food systems financing to inform policy decisions and promote transparency. GAIN is supporting its rollout in 11 countries (47). GAIN also fosters collaboration with the private sector through initiatives like the Nutrition Enterprise Development, which helps local entrepreneurs scale nutrition-focused businesses (52), and the Nutritious Foods Financing Facility, which provides financing to SMEs producing affordable, nutritious foods (53). Additionally, GAIN co-convenes the SUN Business Network, fostering private-sector commitments to reducing malnutrition through healthy food availability.

2.2.3 Trade, dietary and production diversification

Trade policies will play a crucial role in addressing food and nutrition security, economic growth, and sustainability goals like climate change. There is a need for a nuanced understanding of the complex interactions (54) between these areas and a stronger focus on integrating nutrition and environmental considerations into trade policies (55).

Research should explore how climate change will affect nutritious food production and trade flows, with a focus on developing healthier crops beyond staples like wheat, maize, and rice. Emphasis on fruits, vegetables, and sustainable protein sources is key for diversifying diets and improving nutrition, especially in LMICs. Understanding the behavioral and cultural challenges of dietary changes is also vital, as education and culturally appropriate strategies are needed to promote healthier, more sustainable diets (56, 57).

GAIN is driving change at the consumer level through initiatives like Consumer Demand Generation, which encourages the purchasing of healthier, sustainable foods through social marketing and retail promotion strategies. The Food Culture Alliance aims to address food preferences, a determinant of consumer demand, by leveraging food cultures strategies, ensuring that food system changes are both culturally relevant and widely acceptable (58).

2.2.4 Biodiversity

An analysis under the Initiative on Climate Action and Nutrition found that nutrition was generally not strongly integrated into 192 national biodiversity strategies (59). Biodiversity is essential for sustainable food systems, but diets lacking in diversity—especially plant biodiversity—continue to undermine both environmental sustainability and health outcomes. Recent research has highlighted the importance of adopting diets rich in plant biodiversity, such as the Mediterranean diet, which not only supports environmental sustainability but also enhances health (60).

Clear opportunities exist to find co-benefits through improved diversity in production and consumption, benefits to soil health (and, in turn, the nutritional content of crops), and food systems resilience, which helps to ensure sustained access to healthy diets even in the face of environmental and socio-economic challenges (59). Policy recommendations emphasizing the need to promote the integration of underutilized crops, support sustainable agricultural practices, and foster consumer awareness through education and clear food labeling are needed. This involves promoting the cultivation of crops that are well-suited to local conditions and more resilient to environmental stressors.

GAIN, as an active partner alongside the African Union, is involved in initiatives like the Vision for Adapted Crops and Soils, led by the U.S. Department of State. These initiatives aim to identify and promote public and private investments into the most nutritious and climate-resilient crops in Africa (61). Such strategies can help increase dietary diversity, improve nutritional outcomes, and contribute to the conservation of biodiversity, ultimately supporting more resilient and sustainable food systems globally.

2.2.5 Technology innovations

Technology and innovation will drive advancements in nutrient-enriched crops and biofortification, which are essential for improving food quality, especially for vulnerable populations, and increasing crop resilience to environmental stressors. However, scaling these innovations remains a challenge.

Breeding programs need to focus on healthy diets and resilient crops, ensuring new varieties reach both farmers and consumers to support sustainable, climate-smart agriculture. The development of alternative animal source foods is another key area, with potential benefits for both health and the environment (62). However, deeper understanding is needed regarding their nutrition, processing, environmental impact, affordability, and food safety. Many types of alternative proteins require significant processing, which can contribute to environmental pressures. Striking a balance is essential to ensure these innovations support sustainability without unintended negative impacts.

GAIN, in collaboration with the Food and Agriculture Organization and other partners, is conducting research to ensure alternatives to animal source foods positively contribute to global food systems (including through nutrition, environmental sustainability, food safety, and socioeconomic considerations). Addressing these challenges will be pivotal in shaping sustainable, resilient, and equitable food systems over the coming years.

2.2.6 Monitoring global diet quality

There has been a historical lack of mechanisms for monitoring diet quality globally, which is critical for developing effective nutrition policies and ensuring accountability in improving diets.

The future should focus on improving global diet quality monitoring and addressing diet disparities across different demographic groups. This will involve proposing new SDG diet quality indicators, such as Minimum Dietary Diversity for Women and Children, and using data to inform global and national policy interventions.

The Global Diet Quality Project (63), a collaboration between Gallup, Harvard University, and GAIN, has developed the first-ever mechanism for monitoring diet quality globally. Data collected from 85 countries representing 85% or the world's population allow for an in-depth understanding of how diet quality varies across different demographics, providing crucial insights for developing effective nutrition policies and proposing new SDG diet quality indicators, such as Minimum Dietary Diversity for Women and Children.

3 Discussion

Reflecting on past efforts, certain missteps must be avoided as we move forward.

Actionable Indicators: While focusing on long-term outcomes, like stunting has raised awareness of nutrition and accelerated investments, it has often overshadowed more actionable, short-term, indicators like diet quality, which are easier to modify and better suited for tracking progress in the medium term.

Crop Breeding: Another critical area of past oversight was in crop breeding programs, which prioritized high yields over nutrient density and sustainability. This focus on quantity over quality contributed to the persistence of micronutrient deficiencies, especially in vulnerable populations. Future breeding efforts must emphasize nutrient-rich (or nutrient enriched, i.e., biofortified) crops that not only sustain high yields but also support healthy diets. The past emphasis on high yields led to intensive monoculture production systems that created significant environmental degradation, including loss of biodiversity, soil depletion, and unsustainable natural resource use. Future crop breeding must balance the need for greater productivity, with the need for higher nutrient density and environmental sustainability.

Food Systems Transformation: Despite progress, challenges persist in transforming food systems. Regions like Sub-Saharan Africa and South Asia still face significant hurdles in achieving nutritional security and climate resilience. These challenges are often compounded by limited funding, inadequate access to technology, and political instability, which hamper the implementation of effective interventions. Additionally, addressing micronutrient deficiencies and integrating nutrient-dense foods into everyday diets, remain under-addressed. The persistence of these issues can be attributed to a combination of factors, including insufficient financial resources, technological limitations, and a lack of supportive policy frameworks. Equity is vital to be considered and discussed, as new dietary recommendations and food system transformations are proposed, existing inequalities must be exacerbated. For instance, while alternative animal source foods may offer environmental and health benefits, they could also have unintended consequences for low-income populations, such as reducing access to affordable protein sources, increasing reliance on highly processed foods that contribute to overweight and obesity, or disrupting traditional livelihoods. Addressing these concerns requires a careful balance between promoting sustainable practices and ensuring that vulnerable populations are not disproportionately affected.

To achieve a truly sustainable transformation of global food systems, several key elements must be addressed:

1. Increased and sustained financial investment is essential to support research, development, and the scaling of innovative practices. Financial flows to food systems transformation need to be analyzed, for example, using the Financial Flows to Food Systems tool, to foster mutual accountability across both public and private sectors. Incentivizing private sector investment in sustainable practices through tax benefits, grants, or matched funding can further align efforts with sustainability and equity goals.
2. Coherent and integrated policy frameworks that align nutrition, climate, and equity goals are crucial. Such policies should provide clear guidance and incentives for adopting sustainable practices and support the transition to more resilient food systems. Tools such as the policy coherency tool, can help ensure that policies on agriculture, health, and environment reinforce each other.
3. Technological advancements, particularly in areas such as data collection, crop breeding, and sustainable farming techniques, are necessary to meet the challenges posed by climate change and evolving dietary needs. These innovations must be accessible and adaptable to different regional contexts. Scaling technology adoption could be supported through regional innovation hubs and training programs. Collaborations with tech firms and regional stakeholders could further make these technologies more affordable and regionally relevant.
4. The availability and accessibility of comprehensive, disaggregated data is vital for monitoring progress, identifying gaps, and making evidence-based decisions. Platforms like the Food System Dashboard as well as national efforts on sub-national data and monitoring initiatives can provide the insights needed to track and guide food system transformations effectively.
5. The transformation of food systems requires collaboration across a broad spectrum of actors, including governments, international organizations, the private sector, civil society, and local communities. Dedicated platforms and alliances can encourage knowledge sharing, align efforts toward common goals, and foster transparency. Establishing task forces focused on specific challenges can further help balance competing priorities and ensure a coordinated approach to food systems transformation.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

KD: Conceptualization, Investigation, Project administration, Writing – original draft, Writing – review & editing. MT: Conceptualization, Project administration, Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Integrating food is medicine and regenerative agriculture for planetary health

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The urgent need to address both human and environmental health crises has brought attention to the role of food systems in driving climate change, biodiversity loss, and diet-related diseases. This paper explores the intersection of Food is Medicine (FIM) and regenerative agriculture (RA) as an emerging approach with the potential to help address the interconnected challenges of human and ecological health within healthcare and food systems. FIM programs, such as produce prescriptions and medically tailored meals, aim to improve health outcomes by increasing access to nutritious foods and promoting nutrition equity. RA, focusing on soil health, biodiversity, and reduced reliance on synthetic inputs, offers more sustainable agricultural practices that can align with FIM goals. This paper highlights key opportunities, recent policy developments, and evidence gaps, calling for concerted efforts to clearly define RA practices and foster collaboration between community, healthcare, agriculture, and policy stakeholders. Strengthening these interconnections could lead to more resilient food systems and improved health outcomes at both individual and population levels.

KEYWORDS

food is medicine, regenerative agriculture, sustainable food system, planetary health, nutrition intervention, produce prescription program, medically tailored meals

Introduction

Planetary health describes the inextricable link between the biophysical, sociopolitical, and economic well-being of human societies and the earth's natural systems (1). Advancing planetary health is challenging due to profound shifts in agricultural practices, global supply chains, meeting the needs of growing populations and dietary patterns over recent decades (2). Currently, food systems are responsible for over 30% of global greenhouse gas emissions, 50% of ocean eutrophication, 70% of freshwater use, 90% of tropical deforestation, and unprecedented rates of topsoil and biodiversity loss (2, 3). Simultaneously, many food systems contribute to nutrient-poor and excessively processed dietary patterns, contributing to both undernutrition and diet-related chronic diseases (2).

The extensive impact of food systems on planetary health highlights the urgent need to transform how food is produced, distributed, and consumed. Achieving sustainable food systems will require multisectoral collaboration across food supply chains. For instance, food producers must be supported in adopting agricultural practices that improve climate and ecosystem outcomes. Equally, consumers need equitable access to nutritious foods that support well-being, disease prevention, and treatment.

In this paper, we explore the growing connection between Food is Medicine (FIM) and regenerative agriculture (RA), two movements reshaping food systems through complementary, multilevel actions across the food supply chain. We discuss the role of produce prescription, medically tailored grocery (MTG), and medically tailored meal (MTM) programs, which provide patients with fresh produce and other healthy foods or meals through prescriptions issued by healthcare providers and organizations. While our primary focus is on regenerative agriculture, we also examine organic agriculture, highlighting key similarities and differences between the two. By examining current definitions and showcasing real-world examples of FIM and RA integration, we outline the potential co-benefits of aligning these approaches. We also identify uncertainties that are limiting progress and opportunities to facilitate this research, implementation, and partnerships to address these challenges. Engagement from policymakers, healthcare practitioners, farmers, community organizations, patients, and researchers will be crucial in advancing the integration of FIM and RA to help promote a healthier planet and population.

Food is medicine overview

Food is Medicine (FIM) is a healthcare strategy aimed at improving health outcomes and promoting health equity by incorporating nutritious food into disease prevention, management, and treatment (4, 5). The initiatives within FIM prioritize the inclusion of nutrient-rich foods to support healthier dietary intake and habits (6). FIM encompasses a range of interventions with varying levels of intensity, tailored to the complexity and needs of patients, from more intensive therapies like MTMs designed for patients with complex medical conditions and high healthcare usage to population-level policies and programs aimed at reaching general populations (4). Evidence supports the benefits of Food is Medicine interventions in improving food security, diet quality, health outcomes, financial strain, and mental health (4, 6). In this present review, we focus on FIM programs integrated into healthcare settings like medically tailored produce, groceries, and meals, as opposed to more population-level healthy food programs and policies.

Organic and regenerative agriculture

Organic agriculture

The U.S. Department of Agriculture's National Organic Program defines organic agriculture as "the application of a set of cultural, biological, and mechanical practices that support the cycling of on farm resources, promote ecological balance, and conserve biodiversity (7)." To be considered organically grown, agricultural producers need to comply with a uniform set of standards in their production practices. These standards prohibit the use of synthetic fertilizers, pesticides, and genetically modified products (8). While not required, many organic farmers implement sustainable production practices to naturally improve the nutrient content of soil and to manage pests. These practices include the use of manure, reduced tillage, as well as crop rotation and diversification. In the United States, producers who market their produce as organic must undergo USDA organic certification, which can be time and cost-prohibitive for small or limited-resource operations (9–12). From an environmental perspective, organic systems often have lower yields than conventional, with a marginal positive contribution to reduced greenhouse gas emissions (13). Globally, on average, organic systems use less energy and have positive impacts on ecosystems by improving or preserving biodiversity, soil health, and stability, as well as water quality (13, 14). Limited evidence suggests that some products produced using organic practices have a higher density of individual nutrients (e.g., vitamin C and polyphenol levels) than their conventional counterparts, as well as lower pesticide residues (15). More research is needed to understand if consuming organic food has increased benefits to human health.

Regenerative agriculture

The concept of RA gained prominence in the 1970s and has been championed by several groups including the Rodale Institute, a pioneering organization in sustainable farming practices. RA focuses on building and improving soil health, utilizing grazing livestock, eliminating synthetic inputs, and enhancing biodiversity, all with goals of creating economically and biologically stable agricultural systems (16, 17). As defined by Robert Rodale, RA aims to increase land and soil productivity while minimizing environmental impacts and reducing reliance on non-renewable resources by emphasizing the interconnectedness of all elements within a farming system, including the farmer (16). It is distinct from organic farming in that it does not necessarily employ organic practices—although there is often the assumption that it does. While RA and local food systems may sometimes overlap, they are not inherently linked. For example, one could support local farms without RA practices, or purchase RA products from non-local regions. While the interest in RA has gained recent attention, the practices that characterize regenerative farming today have been used within Indigenous systems for millennia (18). Practices that are foundational to RA including, but not limited to tillage reduction, crop rotation, intercropping, rotational grazing, cover cropping, and agroforestry, all emerged in pre-colonial Indigenous communities (18).

Despite these foundational principles, the definition and use of the term RA remain fluid, varying based on outcomes, processes, or a combination of the two (19). This variability may be attributed to geography and contextual factors, requiring place-based specificity (17). In the absence of a single accepted definition, variability can also be attributed to marketing efforts by heterogeneous producers to declare their practices as "regenerative." In one review, the most mentioned RA practices emphasized minimal external inputs, such as synthetic fertilizers and pesticides, and the utility of on-farm inputs like compost and manure from grazing animals (19). The most frequently cited outcome of RA was improved soil health, followed by enhanced biodiversity, and better water retention. In terms of human health, limited evidence suggests crops grown with regenerative agricultural practices that combined no-till, cover crops, and crop rotations may also have higher nutrient densities, including increased levels of vitamins, minerals, and beneficial phytochemicals (20). Thus, enthusiasm is growing about the potential of RA to build resilient agricultural systems that can adapt to climate change, reduce environmental impacts, and ensure continued production of nutritious foods (21).

At the same time, the promise and hope may be outpacing the evidence (22). For example, evidence that RA can meaningfully contribute to carbon soil sequestration is mixed (23). Additional concerns surrounding soil carbon measurements include accurately measuring natural carbon flux throughout the agricultural system to quantify net carbon emissions from agricultural production strategies (24). Some agricultural producers are combining regenerative and organic practices on their farms and may seek certification through the Regenerative Organic Alliance to become Regenerative Organic Certified (25). While recognizing adherence to these practices can be important, ensuring that standardized regenerative certification is accessible, particularly for marginalized, diversified, and/or limited-resource producers, is also critical.

Regen10, a collaborative global initiative working to support an equitable and regenerative food systems transition, is developing a farmer-centric, outcomes-based framework focused on environmental, economic, and socio-cultural outcomes at both farm and landscape levels (26). Regen10's approach includes dialogue with stakeholders, on-the-ground trials, and consultations to incorporate the needs of farmers, landscape stewards, and Indigenous communities. This framework aims to enable the collection of primary data, offering insights into how different agricultural practices impact diverse outcomes. Introduced at COP28, the "zero draft" framework will undergo testing throughout 2024 to refine its indicators and metrics, with the goal of aligning regenerative practices with broader global objectives such as the Paris Agreement and the UN Sustainable Development Goals. This framework could help fill key evidence gaps in regenerative agriculture.

Interlinking food is medicine with regenerative agriculture

Food procurement within FIM programs represents an opportunity to advance planetary health by sourcing whole foods (produce prescriptions and medically tailored groceries) or ingredients (MTM) produced using sustainable agricultural practices, such as those used in certified organic or regenerative systems. Certified organic products and ingredients are widely available at a variety of outlets from large supercenters to farmers markets (27). Regeneratively produced products are more difficult to define and source given the absence of any federal or other widely accepted certification system. Based on our interactions with FIM programs, most programs who are sourcing regenerative products are doing so through local and regional food systems, e.g., by partnering directly with local farms. In so doing, these and other FIM programs who prioritize local sourcing are aligned with the USDA's focus on more resilient local and regional food systems and access to healthy and nutritious food in all communities (28). Such programs demonstrate how federal funding can foster collaboration between healthcare and agriculture, which can help successfully advance FIM programs (6). The 2018 Farm Bill allocated $250 million for fruit and vegetable financial incentives, with $25 million specifically earmarked for produce prescription programs through the Gus Schumacher Nutrition Incentive (GusNip) program to improve dietary health by increasing fruit and vegetable intake, reducing food insecurity, and minimizing healthcare utilization and related costs (29). Since 2019, GusNip has provided over $270 million in funding to 197 projects (29). An additional $48 million of funding from the USDA American Rescue Plan Act further supported these initiatives in 2022 (28, 30).

As FIM programs gain momentum nationally, there is growing interest in how their sourcing strategies could also yield benefits for planetary health. This shift in focus is reflected in recent policy and analytical frameworks, such as the U.S. Department of Health and Human Services (HHS) framework of FIM indicators for potential use by healthcare systems and FIM providers. One of the four domains focuses on Food Production and Sourcing Effect, with indicators that include increased sourcing of regional food for FIM, strengthened local food economies, increased support for regional food producers, and local food systems transformation and expansion (31). In September 2024, Rep. Barbara Lee introduced a bill in Congress to support the establishment, implementation, and expansion of Food as Medicine (FIM) programs (32). The Food as Medicine Waiver Grant Program would fund proposals that aim to reduce nutrition-related chronic conditions, address food insecurity, and improve health outcomes through medically supportive food interventions, giving priority to organizations or entities that provide locally or regionally sourced foods that are grown or working to transition to a covered method of production, defined as regeneratively produced, organically produced or both. The bill further defines regeneratively produced as "an integrated approach to farming and ranching rooted in the principles of soil health leading to improved target outcomes" and provides specific examples such as building soil health and restoring and maintaining water resources. Additionally, this bill would give funding priority to proposals that provide technical assistance and infrastructure support to producers using these covered methods (32). Given the urgent need for all systems, including healthcare, to address climate change and planetary health, the inclusion of sustainable practices in FIM programs is relevant and timely. This emphasis on sustainable sourcing in FIM programs has the potential to not only support community health outcomes but also mitigate the environmental impacts of food production through the agricultural practices employed (33).

Public awareness and engagement in FIM and RA

As policy efforts seek to advance sustainable food sourcing in FIM programs, the role of consumer and patient involvement becomes increasingly important. While comprehensive data on patient and consumer awareness of FIM and RA practices are limited, addressing potential uncertainty and building strong community engagement is relevant to the success and sustainability of these initiatives. Public interest and buy-in related to food sourcing and production practices could act as drivers for producer implementation and policy changes. Academic–community partnerships, such as Community Action Boards (CABs) and Food Policy Councils (FPCs), at local, state, and regional levels, can help identify potential needs and inform strategies for effective community awareness campaigns and policy engagement (34, 35). Additionally, healthcare systems not only provide patient care but also act as training grounds, which could play a key role in educating patients and setting up future professionals for careers that support FIM and sustainable agricultural practices. At the same time, while consumer awareness may help drive demand and public support for FIM, it may not be critical for FIM and RA effectiveness. Many healthcare therapies are successfully implemented based on their effectiveness rather than direct public demand.

Incorporating local food systems and RA into FIM

Several real-world examples highlight both the progress made and the gaps that need to be addressed in merging FIM with specific sourcing criterion (Figure 1).

Recipe4Health

Recipe4Health (R4H), is an innovative FIM program in Alameda County, California that addresses both nutrition insecurity and economic barriers to food access, and focuses on environmentally sustainable, local procurement practices that aim to advance equity (36). Currently, R4H serves eligible participants who are food insecure and/or have cardiometabolic risk factors such as obesity, type 2 diabetes, or hypertension. Recipe4Health sources produce from Dig Deep Farms, a regenerative, organic farm led by local, Black, Indigenous, and People of Color (BIPOC) farmers who employ formerly incarcerated individuals. Produce boxes are delivered weekly for 16-weeks and contain predominantly vegetables and some fruits as part of the Food Farmacy. Thus far, R4H participants have significantly improved their fruit and vegetable consumption, rates of food insecurity have improved, physical activity levels have increased, and there have been improvements in chronic disease biomarkers such as HbA1c and non-HDL cholesterol when compared to a propensity matched control group over the course of 12 months (37). There is ongoing research to assess the environmental impacts of the R4H program.

Foodshed

Foodshed is a farmer-owned and operated cooperative in San Diego, CA that aims to address food insecurity, support local small-scale farmers, and build climate resilience, with a focus on RA practices since 2018 (38). Recognizing the challenges small RA farmers faced in scaling up and maintaining economic viability, Foodshed was created to pool resources and reduce risk across multiple farms, helping farmers access larger markets and distribute their produce efficiently. Through a collaborative crop planning model, they work closely with a core group of farmers to ensure a continuous supply of varied produce that meets market needs. The cooperative purchases fresh produce from 60 small-scale farmers prioritizing BIPOC-owned farms and those that employ RA practices (38). Foodshed's ability to support RA and scale its operations was significantly boosted by federal funding from the American Rescue Plan Act, alongside a $5 million grant from the USDA's Partnership for Climate Smart Commodities that enabled the cooperative to offer financial incentives for farmers to implement RA practices while also paying them a premium to supply food to historically underserved communities. Foodshed currently supplies the San Diego Foodbank with local produce on a weekly basis and is building toward expanding into FIM to support produce prescription programs in healthcare. This example highlights the potential value of a cooperative model for linking small-scale farmers with larger organizations to access and support new markets, and the important role of government grants for growth and scaling.

Community servings

Community Servings is a large non-profit organization based in Jamaica Plain, Massachusetts, that provides medically tailored meals and nutrition services to critically and chronically ill individuals and their families (39). Community Servings serves nearly 4,000 clients annually, delivering over 875,000 made-from-scratch meals per year (40). Community Servings local food program is a critical part of their mission and one of the ways they contribute to building a local, sustainable, community driven food economy. Through partnerships with local farms, purveyors, and food rescue organizations, they receive over 50,000 pounds of donated produce annually, including high-quality "seconds" (imperfect produce) that might otherwise go to waste (41). By sourcing locally and implementing efficient inventory management, Community Servings not only supports local farmers but also ensures that nutritious, minimally processed foods reach those in need, reducing both waste and environmental impact (42). While currently Community Servings does not include any formal RA criteria in their sourcing, they do take farming practices into account and prioritize local farms to help support a resilient, sustainable regional food system.

Delta GREENS

A study is underway in the Mississippi Delta to test whether a multi-level, community-engaged intervention designed to build a sustainable food economy through Food is Medicine (FIM) programming can improve minority health outcomes and reduce health disparities (43). The Delta GREENS FIM Project is a collaboration between Tougaloo College, the Ruben V. Anderson Center for Justice, Delta Health Center, Center for Science in the Public Interest (CSPI), and Tufts University. The project directly engages with local farmers to grow fresh produce for FIM prescription boxes, emphasizing the importance of clear communication, strong community partnerships, and ongoing support to achieve its goals.

The project delivers fresh, locally grown produce to underserved populations, offering valuable insights into the complex dynamics of Food is Medicine (FIM) programs, particularly in rural settings. It addresses key challenges such as selecting crops that meet both nutritional needs and local farming capabilities and overcoming logistical barriers like transportation and storage. This study highlights essential elements for sustaining FIM initiatives, especially for marginalized producers, while underscoring the broader structural supports required to create sustainable, community-driven food systems that advance both health equity and regional food security. Though Regenerative Agriculture (RA) is not formally integrated, the project's focus on local sourcing and community-based food systems aligns with RA principles by promoting sustainability, reducing dependency on external suppliers, and fostering resilience in the regional food economy.

FIM projects that engage with local food systems may help strengthen the connection between food production and consumption. By sourcing from local producers, these programs may contribute to building more resilient regional food systems and have the potential to increase the availability of culturally relevant foods tailored to local markets (6).

Future directions

While the integration of FIM and RA has potential for the promotion of planetary health, key uncertainties remain to be explored (Figure 1).

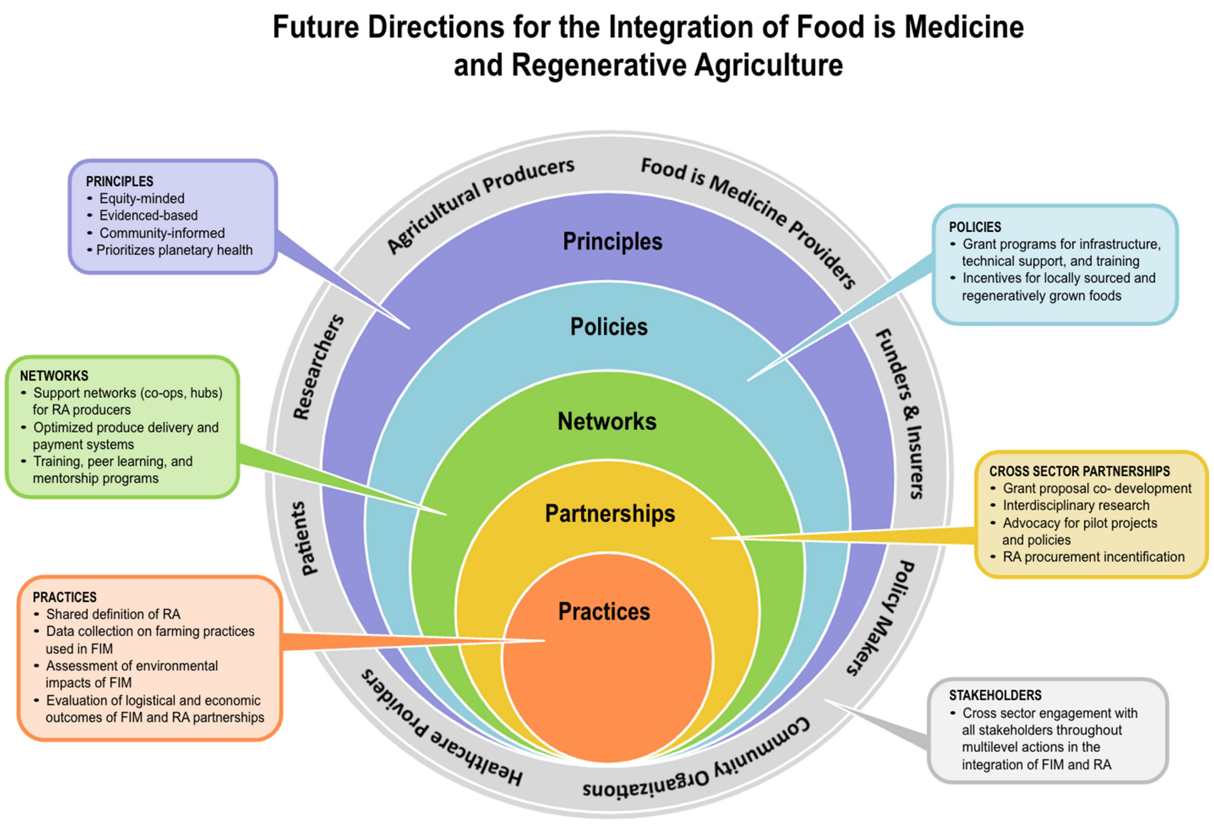

FIGURE 1
Future directions for the integration of food is medicine and regenerative agriculture.

Practices: defining RA

The lack of a widely accepted and measurable definition of RA among farmers, practitioners, and researchers can hinder fruitful collaboration and policy efforts to promote widespread adoption of RA practices, including within FIM procuring pathways. While a Congressional bill has been introduced which includes a more standardized definition of RA, it is not yet finalized, leaving uncertainty around the standardization, adoption, and implementation of RA practices. In the context of FIM programs, establishing a definition for RA that accounts for regional variations in feasibility and context is essential. Efforts like Regen10's farmer-centric, outcomes-based framework, which integrates environmental, economic, and socio-cultural dimensions, could provide valuable insights for shaping standardized yet adaptable definitions of RA. Any final definition should also consider previously silenced Indigenous epistemologies around the world and be rooted in values of reciprocity, respect, collective well-being, knowledge co-creation, and (re)localization (18). While flexibility and regional variations are important for farmers' accessibility, some level of standardization is needed to align stakeholder efforts and foster broader policy support for RA (19, 33). Collecting data on farming practices, assessing environmental impacts, and evaluating logistical and economic outcomes are critical steps in supporting the scalability and standardization of RA. These efforts ensure that RA aligns with regional contexts and helps build evidence for its broader adoption within FIM programs.

Cross-sector partnerships

Cross-sector partnerships are crucial to the success of FIM programs that prioritize RA (44, 45). In addition to healthcare systems, academic institutions, and payers, government agencies, foundations, NGOs, and community-based organizations also play key roles. Together, these entities can drive the shift toward sustainable, health-focused interventions that improve patient outcomes and build the necessary support for environmentally responsible food sourcing.

Healthcare systems can establish long-term forward contracts with RA producers for FIM programs to ensure a reliable supply. Additionally, healthcare systems can align other procurement policies with value-based purchasing models that incentivize the sourcing of RA products, thus accelerating demand. Academic scientists should conduct interdisciplinary research that evaluates the potential dual benefits of RA-produced foods on patient health outcomes and environmental sustainability. Furthermore, by collaborating with farmers and community partners, academic researchers can co-develop grant proposals that study both health needs and ecological goals, helping to ensure that research outcomes translate into practical solutions that benefit the communities involved. Payers can further advance this field by financially supporting FIM programs that source from RA farms, funding pilot studies on their effectiveness, and advocating for policy reforms to consider RA foods in Medicaid and Medicare reimbursement frameworks.

Networks and education

Given the general small scale of RA farms at this time, building a cooperative network or food hub model can be crucial for small RA farms to support FIM programs and maintain a consistent supply of produce, especially when faced with challenges like crop failures. As highlighted in the Foodshed case study, cooperative models can allow for resource sharing and provide mutual support among farms, ensuring continuity in food production. However, these networks must also be paired with efficient distribution and payment systems to ensure timely and sustainable delivery of produce to patients in healthcare systems.

Many producers aiming to transition to RA practices also need access to training and resources to implement these strategies effectively. Programs like the USDA's National Organic Initiative through the Environmental Quality Incentives Program (EQIP) provides assistance to producers transitioning to organic farming by helping them develop region-specific approaches for implementing approved practices (46). A similar program tailored for RA could help overcome the technical assistance barriers and lapse in production and revenue, producers may face when transitioning. The proposed Farmer to Farmer Education Act, part of the 2023 Farm Bill, aims to build networks that connect farmers with mentors and group learning experiences, supporting their efforts to adopt consistent, science-based, and site-specific conservation practices for long-term success (47). Additional resources are needed as farmers transition to RA practices.

Policy

Policy can play a crucial role in fostering and building both the infrastructure and the evidence base for interlinkages between FIM and RA. Existing USDA grant programs, such as the Local Food Promotion Program (LFPP) and the Regional Food Business Centers initiative, offer potential avenues for expanding support to FIM and RA projects. These programs could be tailored to include specific funding for infrastructure that supports FIM initiatives, including investments in cold storage, transportation, and aggregation hubs. Such enhancements would enable small and mid-sized farms using RA practices to distribute their products more efficiently to healthcare organizations. Additionally, these grants could provide technical assistance to help farmers navigate healthcare partnerships and meet regulatory requirements, further strengthening the connection between FIM and RA.

The Centers for Medicare and Medicaid Services (CMS) could also help drive the adoption of locally sourced and sustainably produced food in FIM programs by incorporating specific metrics and health outcome goals into Medicare and Medicaid reimbursement requirements to incentivize healthcare providers to source regeneratively grown food. This would not only support patient outcomes but also support farmers using or transitioning to regenerative practices by providing a market for their products. Finally, USDA and NIH could partner on research to further explore the food and health benefits of regeneratively grown food. A collaborative research agenda could focus on long-term studies that assess the impacts of RA-sourced food on chronic diseases, nutrient density, and overall patient well-being and satisfaction. Such research would provide the evidence needed to solidify the role of RA within FIM programs, making it easier for policymakers, healthcare providers, and farmers to work together to build a more sustainable and equitable food system.

Encouraging the adoption of RA practices through financial incentives, ecological training, and technical support within government-funded programs can accelerate their widespread use while promoting both health and environmental stewardship (6, 48, 49). This approach also levels the playing field, particularly for small or mission-driven organizations, such as non-profits, and novel healthcare programs prioritizing planetary health, such as FIM, that might face competitive disadvantages due to limitations in infrastructure, scale, or funding. Federal policies promoting RA will require a standardized definition and metrics of RA practices.

Principles

The intersection of FIM and RA requires a focus on planetary health, placing environmental sustainability as central to healthcare and food sourcing strategies. Approaches should emphasize equity, making nutritious, sustainably grown food accessible to vulnerable and underserved communities. Policies and practices must be evidence-based, supported by research that measures both health and environmental outcomes. Additionally, community engagement is critical, ensuring that interventions are responsive to local conditions and grounded in the values and priorities of the communities they serve.

Conclusion

To protect both human and environmental health, we must reorient our food systems to be nourishing, equitable, and sustainable. The shift can be supported locally, with consumers, communities, and institutions driving sustainable practices. Local actions can model broader, systemic change needed to meet global health and sustainability targets. However, the adoption of healthy diets from sustainable food systems will require more than individual actions—it will call for a collective restructuring of how we fund, produce, distribute, and consume food, with an emphasis on reducing environmental impact while ensuring food equity for all (50). As one potential solution, an intersection between FIM and RA could help advance these goals. Achieving this vision will require new research, cross-sector partnerships, networks, and policies that prioritize the intersections and uncertainties that interlink our food with human and planetary health.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

MR: Conceptualization, Writing – original draft, Writing – review & editing. OW: Writing – review & editing. KB: Writing – review & editing. NB: Writing – review & editing. CE: Writing – review & editing, Conceptualization. DM: Writing – review & editing, Conceptualization.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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The protein transition: what determines the animal-to-plant (A:P) protein ratios in global diets

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Background: Several high-income countries have announced plans to reduce the animal-to-plant (A:P) protein ratios in their population diets. Their current A:P ratio is around 65:35, with two thirds of the protein coming from animal sources, meat, eggs, and dairy. Efforts to reduce the dietary A:P protein ratio to 50:50, 40:60, or below are sometimes referred to as a "healthy protein transition."

Methods: Analyses of Food and Agriculture Organization (FAO) and World Bank data were used to show that an opposing and far more important protein transition is taking place globally.

Results: In most low- and middle-income countries (LMIC), the dietary A:P protein ratio was closely associated with, if not determined, by gross national incomes (GNI). As incomes rise, LMIC populations adopt more varied and more nutrient-rich diets with more animal proteins and especially meat. This protein transition, manifested by a strong observed relation between rising incomes and higher A:P protein ratios, follows a well-known principle of economics known as Bennett's Law.

Conclusion: Consumer education and regulatory and policy measures aimed at reducing dietary A:P protein ratios worldwide may not uncouple the fundamental relation between powerful economic forces and global diet structures.

KEYWORDS

protein transition, animal:plant protein ratios, FAO Food balance sheets, World Bank income classification, Bennett's law, animal-based proteins, plant-based proteins, low and middle income countries (LMIC)

1 Introduction

An important protein transition is currently occurring across lower-and middle-income countries (LMIC), mostly in the global south (1–3). Viewed as a key component of the broader and well-defined nutrition transition (4), the term protein transition refers to the replacement of traditional proteins from staple grains, pulses, and root crops with more animal-source foods and especially meat (5). This protein transition is largely driven by economic development and rising incomes, though the selection of specific animal protein: beef, pork, chicken, or dairy can vary across geographic regions, depending on tradition and cultures (1, 5). The LMIC trend toward *more* animal protein has been actively promoted by multiple actors (6, 7), including international agencies aiming to improve LMIC diet quality and population health.

Efforts by some high-income countries (HIC) to promote diets with *less* animal protein have been referred to as a "healthy protein transition" (8). Built around consumer education, technological advances, and policy measures (2), such efforts aim to replace meat and dairy with more plant-based options. The "healthy protein transition" has been vigorously promoted by researchers (2), foundations (9, 10) and by national and local government (11–13), aiming to stem climate change and also improve HIC diet quality and population health.

Mean protein consumption in the highest-income countries, including the United States, is greatly above the recommended value of 50 g/person/day (14–16). The mean dietary A:P protein ratio is around 65:35, with two thirds of the protein coming from meat, eggs and dairy. The Dietary Guidelines for Americans (DGA) are poised to reduce total protein, reduce amounts of meat, poultry and eggs, and increase the amounts of beans, peas and lentils in the USDA Healthy US Style Dietary Pattern (17, 18). While the Dietary Guidelines Advisory Committee report strongly favored plant-based diets (18), no specific targets for reducing dietary A:P protein ratios have yet been established.

By contrast, such targets are being promoted in the European Union. The EU protein strategy for human nutrition is built around plant-based proteins (11). Focusing on the need to reduce the A:P protein ratio in the French diet, the French National Institute for Agronomic Research and the Environment (INRAE) has suggested an A:P protein ratio of 50:50. At this time, the typical French diet derives up to 68% of protein from animal source foods (19). The Health Council of the Netherlands has proposed an even lower A:P ratio of 40:60 for consideration by the Dutch government (8, 20). In the current Dutch diet, the ratio is reversed (8). The Flemish Green Deal Protein Shift aims to shift the A:P protein ratio to 40:60 by year 2030 (21). Efforts to promote plant-based eating are also under way in Germany, Belgium, Sweden, and the United Kingdom (22–24). These efforts are driven by concerns about nutrition and health, the impact of agri-systems on the environment, and concerns with animal welfare (25–27). Plant-based diets are reputed to be associated with improved nutrition, greater affordability, and lower environmental footprint (28).

Local initiatives are also prominent. Twenty-five city governments globally have supported the 2021 Plant-Based Treaty in order to stem the impact of climate change, with Amsterdam becoming the first EU plant-based capital (29). The Plant Based Food Alliance in the UK has asked the current Labor government and other policymakers to help promote plant-based food consumption to achieve healthier and more sustainable diets (30). Dietary guidelines for the Netherlands, Germany and the United Kingdom refer to the need to limit the impact of existing dietary patterns on the environment. The European Green Deal has prioritized the production, provision, and consumption of alternative sources of proteins and has promoted dietary shifts toward sustainable plant forward diets (12). The Nordic Nutrition Recommendations feature a predominantly plant-based diet that is high in vegetables, fruits, berries, pulses, potatoes and whole grains (31). Denmark, Sweden and Germany were at one point considering a meat tax (32). Several companies have invested in alternative protein technologies to produce plant-based alternatives to meat, milk and dairy products (33).

On the global scale, the influential EAT-Lancet Planetary Health Diet has proposed an A:P protein ratio of approximately 30:70, with most of the dietary protein coming from grains, root crops, pulses, and from nuts and seeds (34). Beef and pork consumption in the Planetary Health Diet was restricted to only 7 g each per person per day, with higher amounts recommended for chicken and fish. Not sensitive to local traditions and cultures, the Planetary Health Diet has come under criticism for being inadequate in priority micronutrients (35) and unaffordable for the most part by the global poor (36).

The present objective was to assess the strength of the relation between country-level A:P protein ratios and gross national incomes (GNI). The main question was whether there were any countries that managed to combine high incomes with largely plant-based diets. The present approach was to use historical food balance sheets from Food and Agriculture Organization of the United Nations (FAO) (37) merged with gross national incomes (GNI) from the World Bank (38). Finding existing precedents might inform current efforts at reducing the proportion of animal proteins in the global diet.

One concern was that efforts by HIC actors to impose plant-based diets on a global scale may be in vain, since they run counter to the laws of economics (3, 4). Economic forces and diet structures appear to be inextricably linked, a phenomenon that gives rise to the well-established nutrition transition (3). As incomes rise, people eat less energy-dense root crops, legumes, and cereals and diversify their diets to include more animal-sourced foods and especially meat (3). The proportion of protein energy from root crops, legumes, and cereals declines whereas the proportion of protein energy from meats, eggs, and dairy increases. That fundamental observation is known as Bennett's Law. Effectively, Bennett's Law predicts that plant-based proteins will be replaced by animal proteins as an inevitable consequence of economic growth (3). It is a matter of record that the more affluent economies and wealthier consumers have more varied and higher-quality diets and seek out calories that are more expensive and more nutrient-rich (4).

2 Methods

FAOSTAT (37) food balance sheets for selected commodities (including animal and plant source foods) are used to calculate amounts of total protein, animal protein, and plant protein (in kg/capita/y) that are available for human consumption by country. The data are corrected for export and other food uses and apply to formal retail markets only. Informal markets are not included. FAO food balance sheets are supposed to be corrected for food waste and loss, including post-harvest losses, processing losses, distribution losses, and household and retail losses. The FAO uses global averages or specific country data to estimate waste and loss; however, accurate data can be lacking. The present analysis used FAOSTAT historical series estimates for energy from plant and animal proteins in calories/capita/day for the years 1961–2020 (37, 38). Despite their limitations, FAOSTAT data are routinely used as proxies for food consumption at country level. For example, diet modeling of the EAT Lancet Planetary Health Diet (39) relied on the FAO food balance sheets.

The World Bank classifies economies into four income groups: low, lower-middle, upper-middle, and high income. The approximate gross national income (GNI) categories, expressed in US dollars per capita are: low income (GNI < $1000), lower middle income ($1,000–$4,000), upper middle income ($4,000 to $13,000) and high income (>$13,000). The present analyses used historical GNI series for the years 2000–2020 (38). The World Bank incomes data are highly skewed and are conventionally presented following a log transformation. Historical data series spanning several decades are publicly available and can be downloaded from the FAO and World Bank websites, respectively. Multiple prior analyses confirming Bennett's Law have used the same FAOSTAT food balance sheets, often joined with incomes from the World Bank (3).

3 Results

Figure 1A shows the relation between animal protein in g/capita/day and vegetal protein also in g/capita/day that are available for human consumption by country. The data are from FAOSTAT historical series for 1961. Countries are color coded by geographic region and the size of the circle reflects population size by country. The dietary A:P protein ratios are indicated by black lines.

In 1961, the US was well above the dietary A:P protein ratio of 60:40. High income countries in Western Europe, France, Germany, and the UK had A:P protein ratios of between 50:50 and 60:40. In Eastern Europe, Poland and the USSR were well below the A:P protein

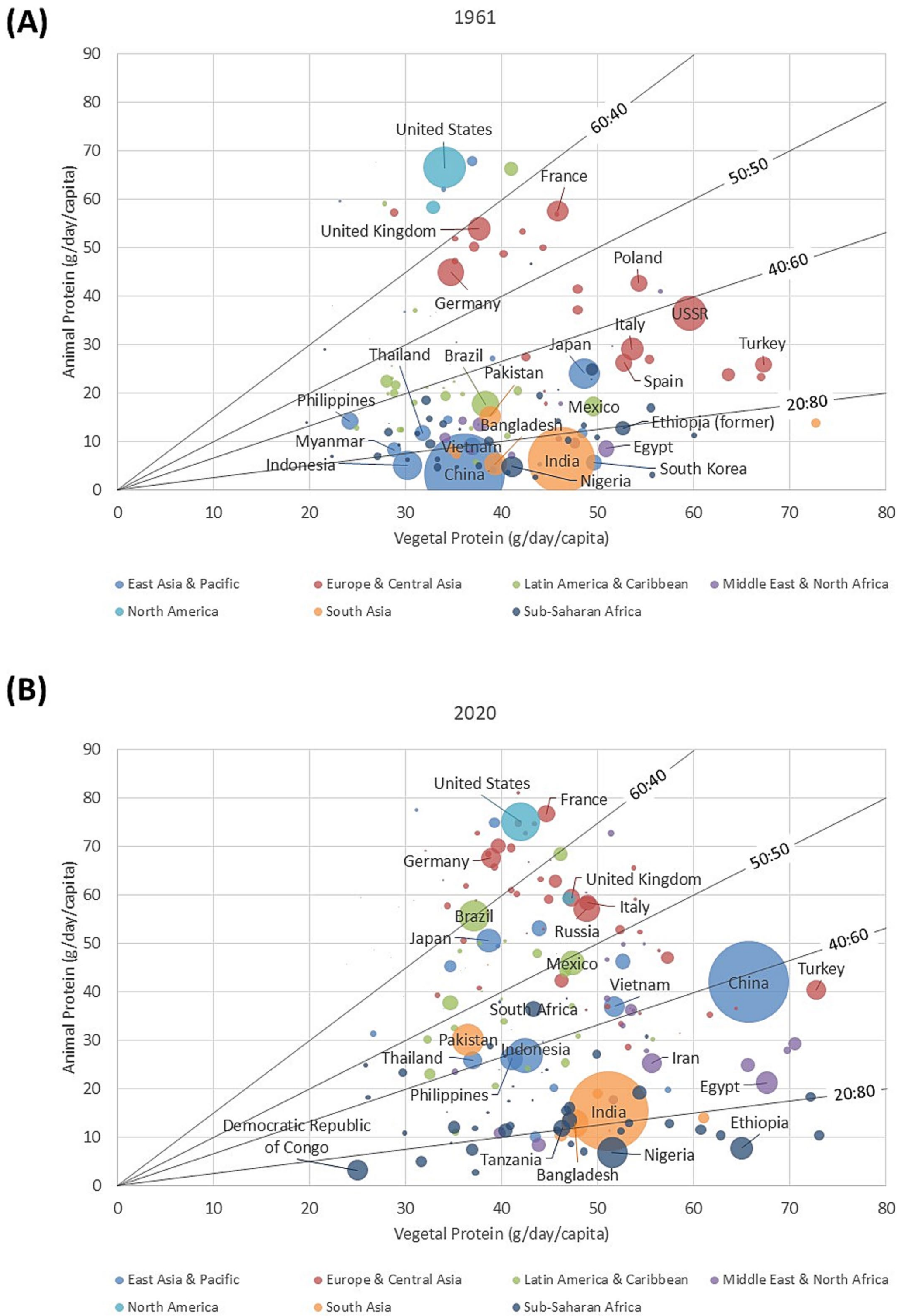

FIGURE 1
Animal protein (in g/day/capita) plotted against vegetal protein (in g/day/capita) from FAOSTAT by country in 1961 **(A)** and 2020 **(B)**. Countries are color coded by geographic region. The size of the circle reflects the country's population size. Dietary A:P protein ratios are indicated.

ratio of 50:50. The two largest countries in Asia, India and China were below A:P ratio of 20:80 with relatively little animal protein in the diet. Countries in Africa had dietary A:P protein ratios that were even lower.

Between 1961 and 2020, total protein availability and the dietary A:P protein ratios increased substantially for most countries as shown in Figure 1B. The US, France, Germany and the Netherlands now all had dietary A:P protein ratios above 60:40. Reaching A:P protein ratio of 60:40 in the Americas was Brazil, with Mexico now close to the 50:50 line. In Asia, there was now a clear separation between China and India that could be cultural but could also be linked to sharp differences in the speed of economic growth during the intervening 60 years. China was now close to A:P protein ratio of 40:60, whereas India was still around the 20:80 line. Remaining below A:P protein ratio of 20:80 were some of the lower income countries in Africa, Ethiopia, Nigeria, and the Democratic Republic of the Congo.

Figure 2A shows adjusted net national income per capita for 164 countries plotted on log scale against percent animal protein from FAOSTAT. The data are for year 2000. Country populations are indicated by size of the circle and the color coding reflects the World Bank income categories. The direct and strong relation between higher GNI and higher percent of animal protein (as percent of total protein) is very clear. Spearman correlation coefficient was 0.81. The reduced 40:60 A:P protein ratio that was proposed in the Netherlands is currently more characteristic of the Philippines, Thailand, and South Korea.

Figure 2B shows percent animal protein plotted against adjusted net GNI per capita for the year 2010. The strong relation between higher GNI and higher percent of animal protein (as percent of total protein) was unaltered. Spearman correlation coefficient was 0.81. Close to reaching the dietary A:P protein ratio of 40:60 were the rapidly developing Asian economies of China and Vietnam, in accordance with rising incomes. Remaining at around 20:80 A:P protein ratios were India and Bangladesh. Interestingly, in the Netherlands and in France there was evidence for a drop in percent animal protein between 2000 and 2010.

Figure 3 shows percent animal protein plotted against adjusted net national income per capita for the year 2020. Spearman correlation coefficient was 0.84. As shown before, China had A:P protein ratio of approximately 40:60, whereas India remained at around the 20:80 A:P protein ratio. Remaining below A:P protein ratio of 20:80 were lower income countries, mostly in Africa, with GNI values of below 1,000 USD per capita per year.

The dietary A:P protein ratios do not increase indefinitely with rising incomes and some slowing down is observed around 60% animal protein. No further increase was observed past GNI of 40,000 USD. At the highest country income levels, dietary A:P ratios were stable and higher incomes were no longer associated with higher dietary A:P ratios.

Figure 3 also shows likely pathways for reducing dietary A:P protein ratios by selected countries. For example, the Netherlands would most likely prefer to reduce the dietary A:P protein ratios at the population level without sacrificing incomes. That would be indicated by a vertical blue line in Figure 3. However, there are no existing precedents in the FAO data. Countries with the desired A;P protein ratio, as recommended by the Netherlands Health Council, are Thailand, China and Indonesia. Similarly, there are no historical or existing precedents for a country-level plant based diet for a country with incomes comparable to the US. Vertical lines going down to A:P ratios of 30:70 (EAT Lancet) or below show empty space and no precedents. Countries with dietary A:P ratios in that range are uniformly of much lower incomes, for example Iran and Bangladesh., as indicated by horizonal lines. Further down, dietary A:P protein ratios of 20:80 were characteristic of lower-income countries in Africa with least amounts of animal protein noted for Nigeria, Ethiopia and Democratic Republic of Congo.

Historical data permit analyses of time trends. Analyses of data for the period 2000–2020 confirm that rising incomes by country are associated with higher availability of animal protein, Figure 4 shows time trends for increases in percent animal protein for China, Indonesia, Thailand, Vietnam, and South Korea over the 20 year period. The growth was more pronounced for countries undergoing more rapid economic development, notably VietNam, China and South Korea. There was less economic growth for lower income Laos and Cambodia and the availability of animal protein did not rise.

It is interesting to note that the World Bank data point to little change in GNI values for France, the Netherlands and the US between 2000 and 2020. The corresponding FAOSTAT data for the same period point to no increase or even a decline in percent of animal protein available for human consumption.

4 Discussion

The present analysis, joining historical data series from the FAO and the World Bank, confirms the existence of a strong positive relation between GNI and the strong positive relation between GNI and the dietary A:P protein ratios. That relation between incomes and A:P protein ratios was little changed from 1961 to 2020 and held for each time point examined. Rising country-level GNI were associated with more total protein and with higher dietary A:P protein ratios. These observations confirm prior analyses (3, 40) and show the continued validity of Bennett's Law.

According to most economic projections, and assuming rising incomes, the global demand for animal protein is likely to increase in the coming decades (41). Based on the sheer sizes of their populations, this increase will be driven by rising demand from the LMIC. About 85% of the global population live in lower-and middle-income countries. Only about 15% live in high-income countries, as defined by the World Bank. Even fewer live in those high-income countries that are currently promoting plant-forward diets on a global scale.

The LMIC protein transition is supported by local and regional governments. Traditional plant-based diets of starchy staples built around cassava, rice, and maize have been associated with inadequate intakes of priority micronutrients iron, zinc, calcium, vitamin A (retinol), vitamin B12, and vitamin D (42). Plant-based proteins can lack lysine and have been associated with amino acid imbalance. Some of these deficiencies can be remedied by the addition of small amounts of animal-source foods to the diet (42, 43). Such foods provide bioavailable iron, zinc, calcium, vitamins A (retinol), B12, and other B vitamins in addition to high-quality protein (44). Incorporating *more* meat in the diet is one way to address micronutrient inadequacies, still prevalent across the LMIC. It is worth noting that local production of animal foods, livestock and dairy, has been increasing in Africa and Asia, with support from international

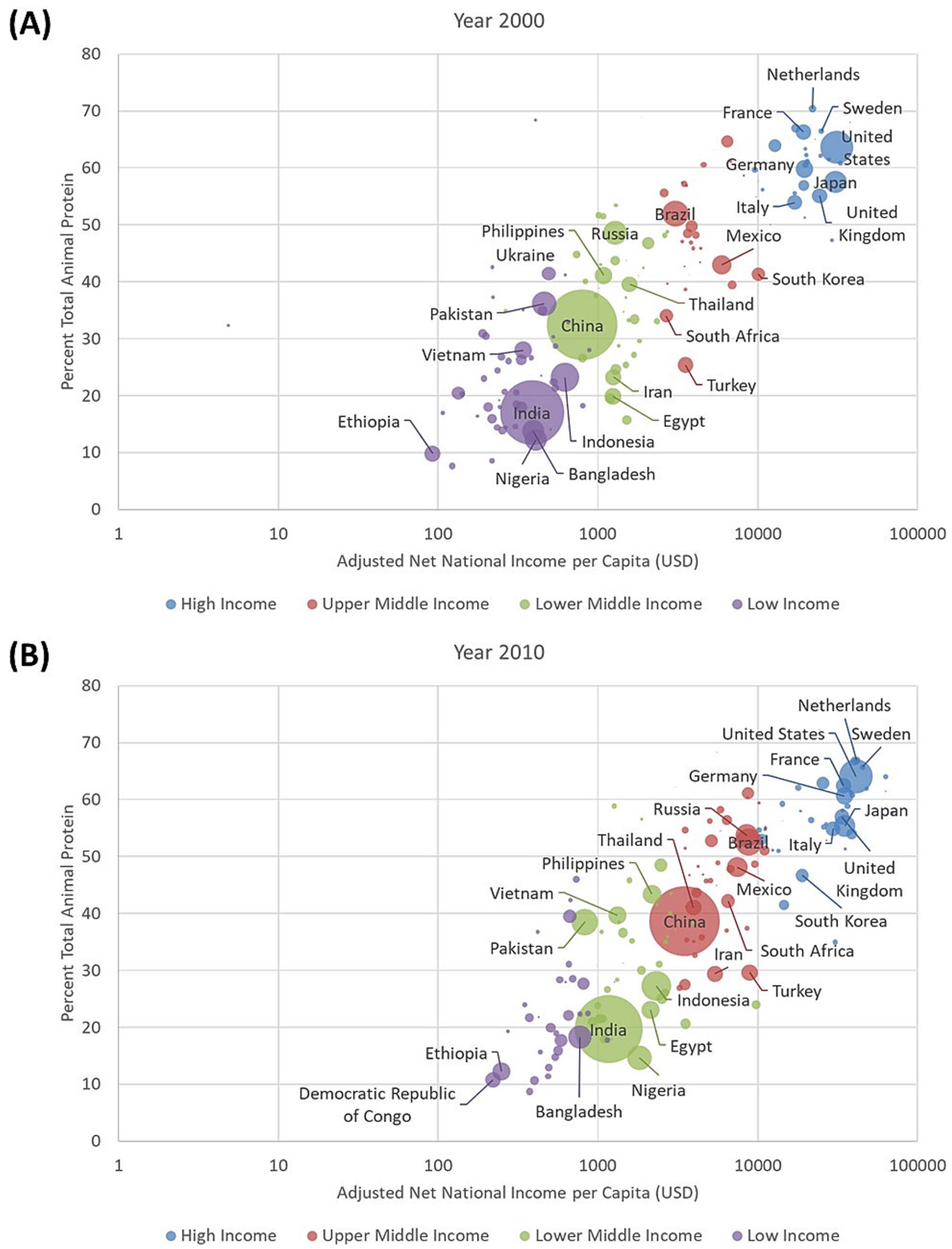

FIGURE 2
Adjusted net national income per capita in USD (on log-scale) plotted against the percentage of animal protein in the diet by country for year 2000 **(A)** and 2010 **(B)**. Countries are color coded by World Bank incomes categories. The size of circle reflects the country's population size. Dietary A:P protein ration of 40:60 is indicated.

agencies, notably FAO (6). Interestingly, the rising global demand for meat favors chicken and pork, rather than the more costly beef (3, 40).

It is important to note that the protein transition does not occur in all countries at the same time or at the same speed (1). Further, social as well as economic factors are involved (1, 5, 25). For example, in South Korea, rapid economic development was associated with a sharply higher meat consumption, notably pork. Farther down the economic scale, India has stayed with the dietary A:P protein ratio of about 20:80, most likely due to local religion and culture and despite significant economic growth. Major differences in protein consumption patterns have also been observed between Indonesia and Malaysia (5), countries that share the same geographic region but are very distinct in terms of economies, populations, traditions, and cultures.

Further analyses of FAO data indicate that some highest income countries may have reached peak meat consumption (3, 45). We confirm prior observations (based on the same FAO and WB data) that the dietary A:P protein ratio fails to increase further above GNI

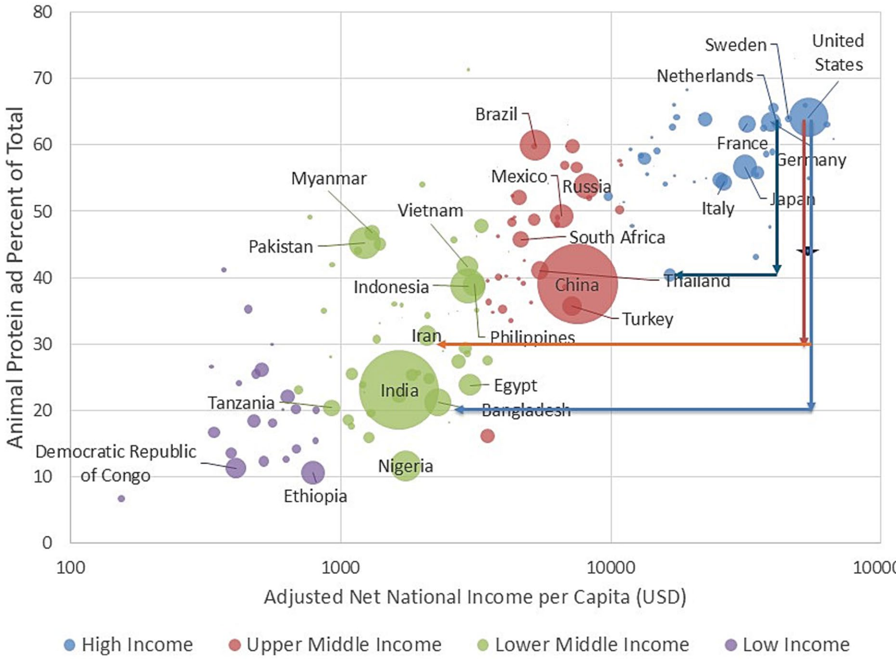

FIGURE 3
Adjusted net national income per capita in USD (on log-scale) plotted against animal protein as percent of total protein by country for 2020. Countries are color coded by World Bank incomes categories. The size of the circle reflects the country's population size. Vertical arrows represent a change in A:P ratios at constant incomes. Horizontal arrows point to countries with specific dietary A:P protein ratios.

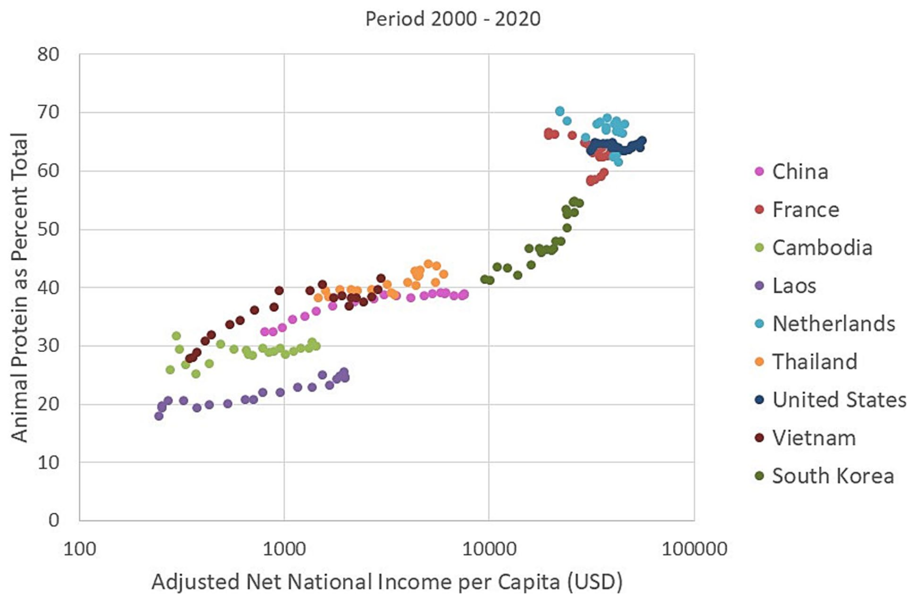

FIGURE 4
Temporal trends in percent animal protein (as percent total protein) from historical FAOSTAT data plotted against adjusted net national income per capita in United States dollars (USD) from The World Bank. The data for selected countries are for years 2000–2020.

of approximately $40,000. For some countries (notably France and the Netherlands) there were suggestions of a decline. Indeed, data from the French Ministry of Agriculture show that per capita meat consumption fell by 5.8% from 2003 to 2023, reaching 83.5 kg (46). Beef was replaced by lower-cost chicken.

Descriptions of the "healthy protein transition" in high-income countries rarely mention the influence of economics on consumer behavior (47, 48). Based on scoping literature reviews, the three main pathways to reducing dietary A:P protein ratios have been identified as consumer education and behavior change, technological advances in the manufacture of alternative proteins, and associated government-led policy, taxation, and regulatory measures (2). All of these seem to require top-down government interventions and can be viewed as more or less coercive (2). There is recognition that a comprehensive, if not compulsory, restructuring of food systems will be needed as well. For example, the Netherlands Organization for Scientific Research (NWO) recognizes that speeding the transition to plant-based proteins (20) will require major shifts in crop and animal production systems (24). Publicized EU policy measures have stressed the need to transition agri-food systems from "an animal-dominated regime to an alternative protein regime," which, according to some sources, could potentially mean the end of livestock farming in the EU (49). Other research studies, with varying degrees of emphasis, propose to disrupt existing EU food systems, stop the "meatification" of global diets, and end the influence of "Big Meat" (50).

The attempts at coercion and/or disruption have met with mixed success. The consumption of meat and dairy is so deeply rooted in European culture that replacing them with manufactured plant-based alternatives will not be easy (51). Proposed legislative measures to buy out and shut down livestock farms in the Netherlands had political repercussions (49, 52). In November 2023, the Party for Freedom won the general election, leading to a shift in policy direction. Attempts by the Mayor of Paris to institute vegan Paris Olympics met with general derision (53). When it comes to technological advances, ultra-processed plant-based meat alternatives have not met with the expected commercial success. Several nations are proposing measures to limit the use of meat and dairy terms to describe manufactured plant-based alternatives (54). However, there is potential for more plant protein from more traditional sources, namely pulses, legumes, nuts and seeds.

It is concerning that the growing literature on the sustainability benefits of plant-based diets is generated *exclusively* in high-income countries. Consumers in, e.g., Nigeria, living on $1 per day, may not have the same concerns with the environment as consumers in Sweden. Similarly, the health benefits of plant-based diets seem to apply to high income countries only (2). The fact that an opposing protein transition is taking place globally was barely mentioned in a scoping review (2). That might explain the current belief across some EU countries that the fundamental relation between economic forces and diet structures can be uncoupled at will.

Two fundamental questions need to be asked. First, should low-income countries abandon their aspirations to a healthier, more varied, and more nutrient-rich diet? Rich-country researchers are already thinking of ways to encourage LMIC populations to maintain their traditional "healthy" eating patterns (25). In particular, the traditional Latin American, Asian, and African "heritage" diets, previously associated with malnutrition, are now being touted as cultural models of healthy eating (55).

Viewed in this context, efforts by rich country actors to reduce dietary A:P protein ratios on a global scale, as exemplified by the EAT-Lancet Planetary Health Diet (34) appear to run counter to the laws of economics, namely Bennett's Law. The present analysis of global diet structures suggests that efforts to impose a single planetary health diet will most likely fail, as perhaps they should.

Second, there is little precedent for high-income countries to follow a largely plant-based diet on a population basis. Such diets do exist as demonstrated by FAO data. It is the feasibility of their adoption by high income countries that is unclear. In other words, will the population of France willingly adopt a diet with a 50:50 A:P ratio that is more characteristic of Mexico? Will the Netherlands, in a reversal of its colonial past, adopt a diet with a 40:60 A:P ratio that is more characteristic of today's Indonesia? Will the higher-income countries voluntarily adopt the EAT-Lancet Planetary Health Diet with and A:P ratio of 30:70? The present concern is that, barring some economic calamity, they will not.

As food prices increase or incomes drop, HIC consumers have been observed to trade down to cheaper types of meat, buy less meat, or adopt flexitarian diets with more grains, pulses and beans (3). Studies have linked recent adverse economic events to a lower consumption of animal proteins. For example, the consumption of meat and fish decreased during the great recession of 2008, with meat replaced by more eggs and plant based proteins (56–59). Faced with lower incomes, consumers ate less meat and more proteins from pulses and grains (3). In another study of purchase preferences in Finland, plant-based proteins were associated with lowest household incomes (60). In other words, the ostensible desire for more plant proteins may have been driven by the failing purchasing power and by rising prices for meat, poultry, and fish.

5 Conclusion

The present analyses points to a consistent and strong relation between rising incomes and more animal protein available for human consumption. Other than for a handful of the richest countries, this relation is predicted by Bennett's Law. That falling incomes are associated with less animal protein can be viewed as a corollary to Bennett's Law. In other words, stagnating wages and lower incomes, rather than consumer education, may drive consumers inexorably toward more plant-based foods. It is tempting to interpret some of the current efforts at reducing the dietary A:P protein ratios in the European Union, ostensibly driven by concerns with health and the environment, as mere manifestations of the fading economic power of Western societies.

Data availability statement

Publicly available datasets were analyzed in this study. This data can be found at: FAOSTAT data repository of the Food and Agriculture Organization of the United Nations, https://www.fao.org/faostat/en/#home. World Bank data repository on adjusted net national incomes per capita, https://data.worldbank.org/indicator/NY.ADJ.NNTY.PC.CD.

Author contributions

AD: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Supervision, Writing – original draft, Writing – review & editing. KH: Data curation, Formal analysis, Investigation, Methodology, Visualization, Writing – review & editing.

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Conflict of interest

AD is the original developer of the Naturally Nutrient Rich (NNR) and the Nutrient Rich Food (NRF) nutrient profiling models and is or has been a member of scientific advisory panels for BEL, Lesaffre, Nestlé, FrieslandCampina, National Pork Board, and Carbohydrate Quality Panel supported by Potatoes USA. AD has worked with Ajinomoto, Ayanabio, FoodMinds, KraftHeinz, Meiji, MS-Nutrition, Nutrition Impact LLC, Nutrition Institute, PepsiCo, Samsung, and Soremantec on quantitative ways to assess nutrient density of foods.

The remaining author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

The author(s) declared that they were an editorial board member of Frontiers, at the time of submission. This had no impact on the peer review process and the final decision.

Generative AI statement

The authors declare that no Gen AI was used in the creation of this manuscript.

Publisher's note

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Ecological impact and metabolic food waste of overweight and obese adults in Northern European and Mediterranean countries

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Introduction: Overeating is one of the main drivers of obesity due to the accumulation of excess body fat (EBF). This issue not only impacts human health but also depletes the planet's environmental resources through the production of excess food. Thus, the Metabolic Food Waste (MFW) index was developed to measure the food wasted due to EBF accumulation, associated greenhouse gas (GHG) emissions, and the water and land resources used in its production.

Methods: The present study aims to evaluate and compare the MFW and ecological footprints of some Mediterranean countries (MC) and North European countries (NEC). The MFW for six Mediterranean and North European countries (NEC) was calculated using the following: (i) EBF: This is defined as the difference between ideal and actual body weight in overweight and obese adults, with data sourced from the FAOSTAT and WHO databases; (ii) Food waste: This includes the food wasted due to EBF accumulation and energy intake from major food categories. Data for food waste were obtained from the FAO Food Balance Sheets; and (iii) Environmental Impact: This encompasses GHG emissions, water consumption, and land use associated with EBF by different foods. Data were obtained from the WWF Virtual Shopping Cart and the Barilla Centre for Food and Nutrition. Data were analyzed for the total population and standardized per 100,000 citizens.

Results: The results showed that NEC had the highest rates of obesity, while MC recorded slightly higher rates of individuals classified as overweight. Overall, higher EBF values for 100,000 citizens, including both obese and overweight individuals, were found in NEC compared to MC, with smaller population countries predominantly contributing to these trends. Data on MFW and ecological footprints showed that, regardless of the country, the impact of obesity is two to three times greater than that of being overweight. The highest values of MFW and ecological footprints were found in MC, both in the total and among overweight/obese populations.

Discussion: The present study highlights the harmful role of the overeating as on human health as on the resource exploitations of the Earth. In particular, both MC and NEC showed similar alarming data about overeating and, consequently, negative impact on EBF and ecological footprints, suggesting that residence in countries close or far from Mediterranean basin is not a proxy of adherence to healthy dietary patterns. For this reason, informative campaigns should be developed to improve the knowledge on conscious dietary choices for human and planet healthiness.

KEYWORDS

food sustainability, metabolic food waste, ecological nutrition, obesity, ecological footprints

1 Introduction

The World Health Organization (WHO) reported that in 2022, 2.5 billion adults (43% of the global population) were overweight, and among them, 890 million (16% of the global population) were living with obesity (1). Overweight and obesity among adults have also reached epidemic proportions in Europe, where 59% of adults are overweight, with 23% of them classified as obese (1). The WHO defines "overweight" and "obesity" as "*abnormal or excessive fat accumulation that may impair health*" (1). One of the primary causes of this pathological accumulation of body fat is the imbalance between energy intake and expenditure, where excess macronutrients from food are converted into body fat storage. In other words, overconsumption of food directly impacts human health by contributing to body fat accumulation. In 2015, a high body mass index (BMI) contributed to 7% of deaths from all-cause mortality, with cardiovascular diseases, diabetes, and cancer being the main co-morbidities (2), reinforcing the view of overweight and obesity as multifactorial illnesses and risk factors for various other conditions. However, not only is human health affected, but the planet is also affected by the phenomenon of overeating, particularly in terms of the environmental resources wasted in producing excess food. The ecological footprints and resources consumed by each individual's food and meal choices also affect planetary health. This is particularly relevant when considering food sources, such as plant-based versus animal-based foods, which have different impacts on the health of the planet (3). Additionally, an imbalanced intake of these food types in dietary patterns may negatively affect human health (4).

Robust data from life cycle assessments demonstrate that animal-based products have a greater environmental impact than their plant-based counterparts throughout the entire chain from producer to consumer (3). Considering these aspects, in 2019, the Eat-Lancet Commission developed an example of a "planetary" healthy diet, emphasizing substantial consumption of cereals, fruits, vegetables, legumes, and vegetable oils, along with a reduced intake of animal-based products, such as red and processed meats, which negatively affect both health and the planet (5). However, while numerous markers describe the health and disease status of individuals associated with their overall diet, the health of the planet is still represented by only a few indicators, including the so-called "footprints" (6, 7).

We recently developed a novel index to calculate the ecological impact of overeating – particularly in terms of overweight and obesity conditions, called metabolic food waste (MFW) (8), highlighting the unsustainability of excess body fat. In this study, MFW is identified as the kg of food that corresponds to the quantity leading to excess body fat (EBF) and its environmental impact expressed as carbon [$MFW_{(kgCO2\ eq)}$], water [$MFW_{(L)}$], and land footprint [$MFW_{(m2)}$] (8) of 60 overweight and obese Italian individuals. It was then empirically applied to the Italian population with a body mass index (BMI) over 25 kg/m^2. Another study evaluated MFW in seven FAO regions by comparing the dietary habits of different overweight and obese individuals worldwide and their environmental impacts (9). Our results showed that Europe was responsible for the largest volume of MFW (39.2 million tons), highlighting the importance of understanding the contributions of different EU countries to MFW's impact on planetary health (9). However, this analysis considered only the entire European continent (and others) rather than individual countries or groups of countries with similar dietary habits, nor did it assess the impact of each overweight or obese individual. Therefore, the present research concentrates on the European peninsula by retrieving data from six Mediterranean countries (MCs), which are expected to follow the sustainable Mediterranean diet, and six Northern European countries (NECs), which do not follow this diet, aiming to assess and compare MFW between the two areas. Moreover, the relative contribution of MFW for the main food commodities will be evaluated while also considering the individual contribution of each overweight or obese adult.

2 Materials and methods

The following steps were taken to estimate the MFW for each of the 12 selected countries from two geographic regions: (a) Italy, Spain, France, Portugal, Greece, and Croatia as MC, and (b) Denmark, Iceland, Ireland, Norway, Sweden, and the United Kingdom as NEC.

The most recent data on the total adult population (10), along with the prevalence of overweight and obesity (11) at the national level, has been used to assess the number of individuals classified as overweight or obese based on their BMI categories.

The value of the EBF, expressed in kilograms, was calculated as the difference between the ideal and actual body weight, derived using the BMI inverse function, as described elsewhere (9). Average body weights at the national level were then multiplied by the energy content of 1 kg of body fat (32.2 MJ) to determine the energy from EBF.

Energy from EBF was then associated with kilocalories from food as determined using the Food Balance Sheets (FBS) (10) in FAOSTAT, covering the time period 2010–2019. Food waste was calculated based on the total domestic supply from FBS food items, grouped into nine main groups: dairy products/milk/eggs, starchy roots, alcoholic beverages, cereals, meat/offals, sugar and sweeteners, fish/seafood, added fats, and pulses. Specifically, the percentage energy contribution of each food category was multiplied by the total amount of energy from EBF to determine the energy contribution of each food item contributing to EBF accumulation. This value was then translated into the amount of food wasted due to overweight/obesity, expressed as MFW ($_{\text{tons of food}}$).

TABLE 1 Demographic analysis and EBF levels in Mediterranean and Northern European populations.

Country	Total population (N)[1]			Overweight and obesity rates (%)[2]		Excess body fat (kg/100,000 citizens)	
	Males	Females	Total	24.9 > BMI > 29.9 kg/m^2	BMI > 30 kg/m^2	24.9 > BMI > 29.9 kg/m^2	BMI > 30 kg/m^2
Italy	29,456,255	31,206,813	60,663,068	38.4%	19.8%	2.71×10^{06}	1.02×10^{07}
Spain	22,887,826	23,746,305	46,634,131	37.7%	23.7%	4.16×10^{06}	1.05×10^{07}
France	31,328,637	33,338,953	64,667,590	37.8%	21.5%	3.33×10^{06}	1.03×10^{07}
Portugal	4,885,027	5,440,513	10,325,540	36.5%	20.8%	3.20×10^{06}	9.87×10^{06}
Greece	5,210,972	5,404,211	10,615,183	37.3%	24.8%	4.55×10^{06}	1.03×10^{07}
Croatia	2,024,136	2,184,475	4,208,611	35.0%	24.3%	4.85×10^{06}	1.01×10^{07}
Mediterranean countries	**95,792,853**	**101,321,270**	**197,114,123**	**37.8%**	**21.7%**	$\mathbf{2.28 \times 10^{07}}$	$\mathbf{6.12 \times 10^{07}}$
Denmark	2,840,401	2,870,945	5,711,346	35.8%	19.6%	3.53×10^{06}	1.17×10^{07}
Iceland	166,644	165,565	332,209	37.2%	21.8%	3.91×10^{06}	1.14×10^{07}
Ireland	2,324,524	2,371,266	4,695,790	35.3%	25.3%	5.06×10^{06}	9.85×10^{06}
Norway	2,646,258	2,604,692	5,250,950	35.2%	23.1%	4.32×10^{06}	1.00×10^{07}
Sweden	4,918,962	4,917,041	9,836,003	35.8%	20.6%	3.50×10^{06}	1.05×10^{07}
United Kingdom	32,695,427	33,602,517	66,297,944	35.9%	27.8%	5.68×10^{06}	9.50×10^{06}
North Europe countries	**45,592,216**	**46,532,026**	**92,124,242**	**35.7%**	**23.7%**	$\mathbf{2.60 \times 10^{07}}$	$\mathbf{6.31 \times 10^{07}}$

[1]FAO Statistic Division FAOSTAT (10). "Food Balance Sheets" 2019. https://www.fao.org/faostat/en/#data/FBS.
[2]World Health Organization (WHO) (11). "Global Database on Body Mass Index: BMI Classification" 2016.
Bold values, for each column, corresponds to the sum of the values of each single country belonging to Mediterranean or Nothern European countries.

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To determine the total environmental impact of MGW, the following indicators were considered: (a) GHG emissions, measured as carbon footprint ($MFW_{(kgCO2eq)}$), (b) biologically productive land use, measured as land footprint ($MFW_{(m2\ land)}$), and (c) water consumption, measured as water footprint ($MFW_{(L\ water)}$). Data were mainly obtained from the WWF Virtual Shopping Cart (12), with missing data taken from the Barilla Centre for Food and Nutrition (13).

Ethical review and approval were not required for the study involving human participants in accordance with local legislation and institutional guidelines.

Written informed consent from participants was not required to participate in this study in accordance with national legislation and institutional guidelines.

3 Results

The descriptive analysis of demographic data, anthropometrics, and EBF for MC and NMC is presented in Table 1. The percentage of overweight citizens in MC is, on average, slightly higher than in NMC, with Italy reporting over 38.4% of the total population in this category. In contrast, NEC exhibited higher obesity rates, with the United Kingdom showing 27.8% of the total population classified as obese.

To standardize EBF calculations, data were normalized per 100,000 citizens to account for differences in total population size across countries. In MC, EBF per 100,000 citizens ranged between 2.71×10^{06} kg and 4.85×10^{06} kg for overweight individuals and 1.02×10^{07} kg and 1.05×10^{07} kg for obese individuals, with Italy showing the lowest values in both categories. Similarly, in NMC, Denmark had the lowest EBF for overweight individuals and the highest EBF for obese individuals (3.53×10^{06} kg and 1.17×10^{07} kg, respectively). Then, the United Kingdom had the highest EBF for overweight individuals (5.68×10^{06} kg) and the lowest EBF for obese individuals (9.50×10^{06} kg) (Table 1).

In Table 2, the ecological impact of the European countries considered is reported in terms of MFW (kg of food) as well as CO_2, water, and land footprints. Overall, the values of MFW and all the other parameters of the ecological impact of MC are twofold higher than those of NEC in the total population. Among the countries, France, Spain, and Italy were responsible for the highest values of MFW (>3.0×10^{03} tons), water (~1.0×10^{13} L), and CO_2 (~1.0×10^{10} kg/CO_2 eq) in MC. In contrast, the UK showed the highest values of MFW (4.9×10^{03} tons), water (1.4×10^{13} L), CO_2 (1.2×10^{10} kg/CO_2 eq), and land (7.4×10^{10} m^2) among NC, followed by the Scandinavian countries. However, the countries show wide differences in total population, and normalizing the data per citizen may be appropriate. In Figure 1, the ecological impact of the European countries considered is represented geographically in terms of metabolic food waste, as well as CO_2, water, and land footprints per 100,000 citizens. The results were quite similar when comparing MC and NEC. Specifically, MFW was 3.71×10^{1} *vs.* 3.89×10^{1} tons of food waste, respectively. However, it emerged that even small countries are significant contributors to the ecological impact of EBF. In fact, not only Spain but also Croatia and Greece exhibited the highest amounts of MFW (7.00 and 6.82 tons of food waste) and CO_2 (2.01×10^{10} and

TABLE 2 Metabolic food waste expressed as amounts of wasted food (tons) and GHG emissions (kg CO_2eq), as well as water (L) and land (m^2) corresponding to EBF in Mediterranean and Northern European countries.

	Total				Overweight (24.9 < BMI < 30 kg/m^2)				Obese (BMI > 30 kg/m^2)			
Country	MFW (tons)	CO_2 (kg)	Water (L)	ECO (m^2)	MFW (tons)	CO_2 (kg)	Water (L)	ECO (m^2)	MFW (tons)	GHG (kg)	Water (L)	ECO (m^2)
Italy	3.2×10^{03}	8.5×10^{09}	9.7×10^{12}	5.3×10^{10}	6.3×10^{02}	1.7×10^{09}	1.9×10^{12}	1.1×10^{10}	1.2×10^{03}	3.3×10^{09}	3.7×10^{12}	2.0×10^{10}
Spain	3.1×10^{03}	9.1×10^{09}	1.0×10^{13}	5.5×10^{10}	7.3×10^{02}	2.1×10^{09}	2.4×10^{12}	1.3×10^{10}	1.2×10^{03}	3.4×10^{09}	3.8×10^{12}	2.1×10^{10}
France	3.8×10^{03}	1.1×10^{10}	1.2×10^{13}	6.4×10^{10}	8.1×10^{02}	2.3×10^{09}	2.5×10^{12}	1.4×10^{10}	1.4×10^{03}	4.1×10^{09}	4.4×10^{12}	2.4×10^{10}
Portugal	5.8×10^{02}	1.7×10^{09}	1.7×10^{12}	9.7×10^{09}	1.2×10^{02}	3.5×10^{08}	3.6×10^{11}	2.0×10^{09}	2.1×10^{02}	6.1×10^{08}	6.4×10^{11}	3.5×10^{09}
Greece	7.3×10^{02}	1.8×10^{09}	2.1×10^{12}	1.1×10^{10}	1.8×10^{02}	4.4×10^{08}	5.3×10^{11}	2.8×10^{09}	2.7×10^{02}	6.6×10^{08}	8.0×10^{11}	4.2×10^{09}
Croatia	2.9×10^{02}	7.1×10^{08}	8.0×10^{11}	4.2×10^{09}	7.2×10^{01}	1.7×10^{08}	2.0×10^{11}	1.0×10^{09}	1.0×10^{02}	2.5×10^{08}	2.8×10^{11}	1.5×10^{09}
Mediterranean countries	**1.2×10^{7}**	**3.3×10^{10}**	**3.6×10^{13}**	**2.0×10^{11}**	**2.5×10^{03}**	**7.1×10^{09}**	**7.9×10^{12}**	**4.3×10^{10}**	**4.4×10^{03}**	**1.2×10^{10}**	**1.4×10^{13}**	**7.4×10^{10}**
Denmark	3.7×10^{02}	9.9×10^{08}	1.0×10^{12}	5.8×10^{09}	7.2×10^{01}	1.9×10^{08}	2.0×10^{11}	1.1×10^{09}	1.3×10^{02}	3.6×10^{08}	3.7×10^{11}	2.1×10^{09}
Iceland	2.2×10^{1}	6.5×10^{07}	6.2×10^{10}	3.7×10^{08}	4.8×10^{01}	1.4×10^{07}	1.4×10^{10}	8.0×10^{07}	8.2	2.4×10^{07}	2.3×10^{10}	1.4×10^{08}
Ireland	3.3×10^{02}	7.7×10^{08}	8.6×10^{12}	4.8×10^{09}	8.4×10^{01}	1.9×10^{08}	2.2×10^{11}	1.2×10^{09}	1.2×10^{02}	2.7×10^{08}	3.0×10^{11}	1.7×10^{09}
Norway	3.5×10^{02}	8.2×10^{08}	8.9×10^{12}	5.3×10^{09}	8.0×10^{01}	1.9×10^{08}	2.1×10^{11}	1.2×10^{09}	1.2×10^{02}	2.9×10^{08}	3.1×10^{11}	1.9×10^{09}
Sweden	6.0×10^{02}	1.6×10^{09}	1.7×10^{12}	1.0×10^{10}	1.2×10^{02}	3.4×10^{08}	3.5×10^{11}	2.1×10^{09}	2.1×10^{02}	5.9×10^{08}	6.1×10^{11}	3.6×10^{09}
UK	4.9×10^{03}	1.2×10^{10}	1.4×10^{13}	7.4×10^{10}	1.4×10^{03}	3.3×10^{09}	3.8×10^{12}	2.1×10^{10}	1.7×10^{03}	4.2×10^{09}	4.9×10^{12}	2.7×10^{10}
Northern European countries	**6.5×10^{06}**	**1.6×10^{10}**	**1.8×10^{13}**	**1.0×10^{11}**	**1.7×10^{03}**	**4.2×10^{09}**	**4.8×10^{12}**	**2.6×10^{10}**	**2.3×10^{03}**	**5.7×10^{09}**	**6.5×10^{12}**	**3.6×10^{10}**

Data are shown for the total population, including overweight and obese individuals. BMI (Body Mass Index); MFW (Metabolic Food Waste, expressed in kg of food per x kg of EBF); Water (Water Footprint, expressed in liters); CO^2 (GHG emissions, expressed in kg of CO_2); ECO (Ecological Footprint, expressed in m^2).
Bold values, for each column, corresponds to the sum of the values of each single country belonging to Mediterranean or Nothern European countries.

1.91×10^{10} kg CO_2 eq) and water (1.69×10^7 and 1.67×10^7 L) impacts. Similarly, among the NEC, apart from the UK, Ireland, and Iceland displayed the highest amounts of MFW (7.03 and 6.47 tons of food waste) and CO_2 (1.83×10^{10} and 1.84×10^{10} kg CO_2 eq) impacts.

When considering only the whole overweight and obese populations, data confirmed a greater impact of total MCs compared to NECs, with nearly double values for obese individuals (Table 1). The countries most affected by MCs are identified as France, Italy, and Spain, while no significant differences are evident among NECs. To standardize the data for individual cases in each country, we presented the MFW (expressed in kg instead of tons for increased clarity) and the ecological footprints per overweight and obese individual for each country considered in Table 3. Overall, average values indicate a greater impact of MCs compared to NECs. However, similar results were found when comparing MCs and NEC among obese individuals (Table 3). Within MCs, overweight individuals showed some variabilities depending on the country: Greek and Croatian overweight individuals exhibit nearly double MFW values and ecological footprints compared to their Italian counterparts. Similarly, within NECs, Ireland and the UK show higher MFW and ecological footprint values than other countries. No substantial differences are noted within the northern and MC categories (Table 3). Figure 2 summarizes the MFW and ecological impact data by considering all MCs and NECs overweight and obese individuals. Overall, negligible differences are found between MCs and NECs overweight individual values, as well as between MCs and NECs obese values. However, when comparing values for overweight and obese individuals—regardless of MCs or NECs—the impact values for obese individuals are two to three times higher than those for overweight individuals (Figure 2).

The analysis of the food groups contributing to the EBF of 100,000 citizens of the considered countries is shown in Figure 3. Dairy products/milk/eggs had a high impact on food waste, with MC countries accounting for ~1.1×10^4 tons of wasted food (29.7% of the total) and NEC countries accounting for ~1.2×10^4 tons of food wasted (30.7% of the total).

Alcoholic beverages, cereals, and meat/offals were also among the most impactful food groups, with a combined waste of ~1.7 10^3 tons (46.1% of the total) in MC and ~1.6 10^3 tons (42.4% of the total) in NEC. Conversely, meat/offals were the largest contributors, accounting for ~50 to 55% of the total ecological impact due to MFW, with very similar values as in MCs and NECs, water footprint: ~6×10^{10} L, carbon footprint: ~5×10^7 kg/CO_2 eq, and land footprint: ~3×10^8 m^2 (Figure 3). In particular, Spain and France were the main contributors

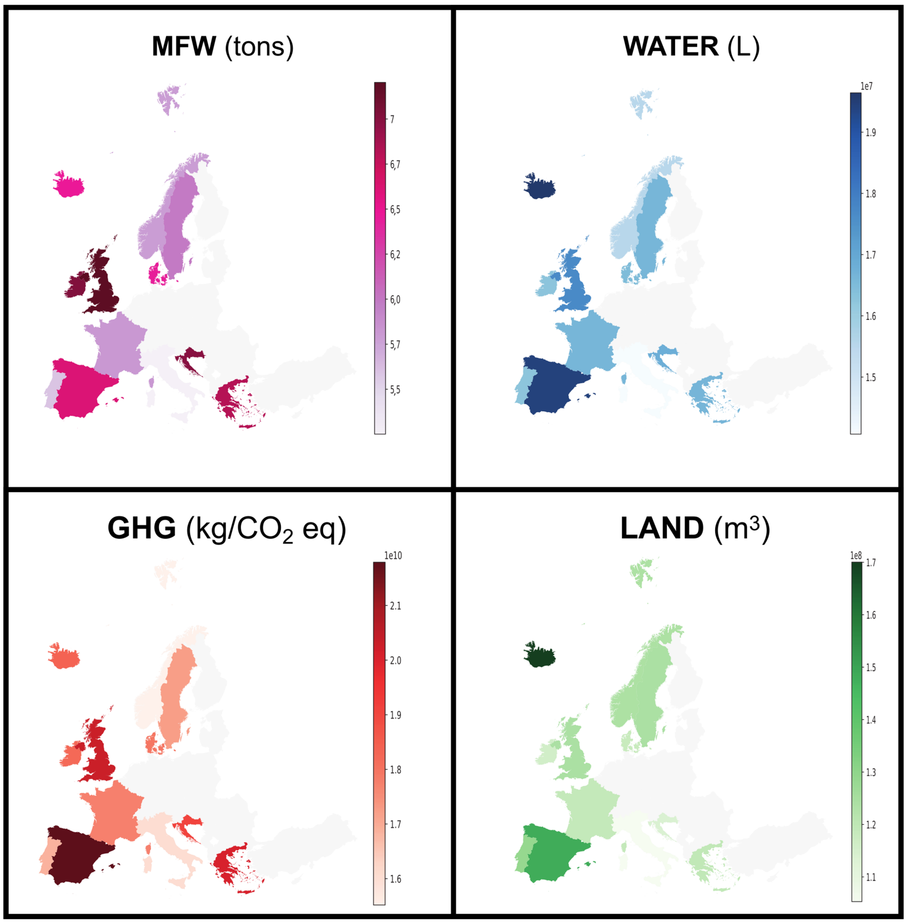

FIGURE 1
Metabolic food waste expressed as amounts of wasted food (tons), water (L), GHG emissions (kg/CO_2 eq), and land (m^2) associated with EBF in the MCs and NCEs. The data are normalized per 100,000 citizens.

TABLE 3 Metabolic food waste expressed as amounts of wasted food (kg) and GHG emissions (kg CO_2 eq), water (L), and land (m^2) associated with EBF for each overweight and obese individual living in MCs and NECs.

	Overweight (24.9 < BMI < 30 kg/m^2)				Obese (BMI > 30 kg/m^2)			
Country	MFW (kg)	CO_2 (kg)	Water (L)	ECO (m^2)	MFW (kg)	GHG (kg)	Water (L)	ECO (m^2)
Mediterranean countries								
Italy	27.1	72.5	8.3×10^{04}	451	102	273	3.1×10^{05}	1697
Spain	41.6	122	1.4×10^{05}	742	105	309	3.5×10^{05}	1878
France	33.3	94.8	1.0×10^{05}	560	103	292	3.1×10^{05}	1726
Portugal	32.0	92.8	9.6×10^{04}	534	98.7	286	3.0×10^{05}	1646
Greece	45.5	111	1.3×10^{05}	698	103	251	3.0×10^{05}	1577
Croatia	48.5	117	1.3×10^{05}	699	101	243	2.8×10^{05}	1451
Average values (Mean ± SD)	**38.0 ± 8.45**	**102 ± 18.5**	**$1.1 \times 10^5 \pm 2.3\ 10^4$**	**613 ± 115**	**102 ± 2.21**	**276 ± 25.5**	**$3.1 \times 10^5 \pm 2.4\ 10^4$**	**1663 ± 144**
Northern European countries								
Denmark	35.3	95.2	9.9×10^{04}	559	118	317	3.3×10^{05}	1861
Iceland	39.1	115	1.1×10^{05}	649	114	335	3.2×10^{05}	1889
Ireland	50.6	117	1.3×10^{05}	736	99	227	2.6×10^{05}	1432
Norway	43.2	102	1.1×10^{05}	664	101	238	2.6×10^{05}	1546
Sweden	35.0	96.0	1.0×10^{05}	595	106	289	3.0×10^{05}	1795
UK	56.8	137	1.6×10^{05}	863	95.0	229	2.7×10^{05}	1442
Average values (Mean ± SD)	**43.3 ± 8.81**	**110 ± 16.0**	**$1.2 \times 10^5 \pm 2.3\ 10^4$**	**678 ± 109**	**105 ± 8.91**	**273 ± 47.5**	**$2.9 \times 10^5 \pm 3.2\ 10^4$**	**1661 ± 212**

Bold values, for each column, corresponds to the sum of the values of each single country belonging to Mediterranean or Nothern European countries.

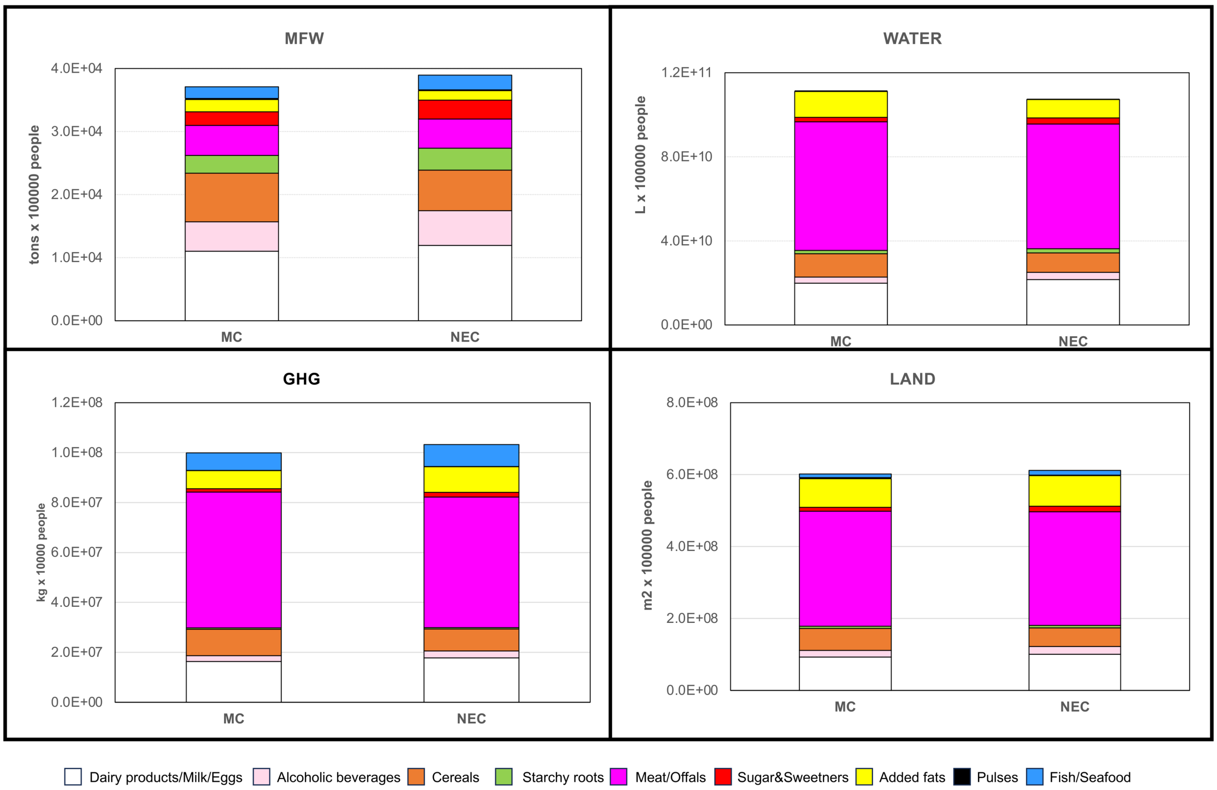

FIGURE 2
Metabolic Food waste expressed as amounts of wasted food (kg) and as GHG emissions (kg CO2 eq), water consumption (L), and land use (m2) for the overweight and obese populations in the Mediterranean and Northern European regions.

to the MFW ecological impact from animal-based food groups, while the UK and Iceland had the greatest impact due to high meat consumption and its derivatives (Supplementary Table 1).

4 Discussion

The main finding of this study supports the role of malnutrition in affecting not only human health but also the planet's health, confirming the intricate and inseparable link between human dietary habits and the planet's response to overeating. Demographic data indicate that more than half of European citizens are in a state of overnutrition. Although MCs have double the number of citizens compared to NECs, data show similar percentages of overweight and obese individuals in both groups, with peaks of 38.8 and 27.8%, respectively. Additionally, the two conditions do not impact the planet's environmental resources similarly, as obese individuals have EBF and MFW values at least three times higher than those of overweight individuals. This aspect has also been confirmed by data from the NHANES cohort, where the "sustainable diet index-US" was inversely associated with higher odds of obesity (14). Normalizing MFW and ecological footprints per 100,000 citizens allowed us to avoid bias due to differences in the populations of the countries, leading to two main results: (i) small countries are significant contributors to MFW and emissions and (ii) there is not a substantial difference in the sustainability of the diets of overweight and obese individuals living in MCs and NECs. This latter aspect is worth discussing, as historically, countries in the Mediterranean basin were characterized by strict adherence to the Mediterranean diet, one of the most sustainable dietary patterns for human and planetary health (15). However, in recent decades, research has shown that adherence to the Mediterranean Diet among citizens living in MCs has significantly decreased, particularly in countries such as Spain, Italy, Greece, and France. Conversely, NEC countries such as Denmark, Norway, and even the UK have seen a slight increase in their adherence to this diet (16). Castaldi et al. (17) clearly described a significant deviation of some MCs from the ideal Medi*terranean diet in terms of fo*od intake and GHG emissions. This was primarily due to higher intakes of cereals, added fats, and red and poultry meats compared to the ideal Mediterranean diet, demonstrating a three-fold increase in GHG emissions from 1960 to 2010 attributable solely to the rise in meat consumption (mainly pork and poultry), together with other 21 factors (17). Such data have also been corroborated by the present study, where meat/offals and added fats are primarily responsible for carbon, water, and land waste in both MCs and NECs.

Except for low consumption of animal-based products, the Mediterranean diet is globally recognized for its rich daily intake of vegetables and minimally processed foods, which play a dual role in enhancing human health and reducing environmental footprints compared to other dietary patterns (18). Although the primary vegetable-based food categories are not included in this study—as they

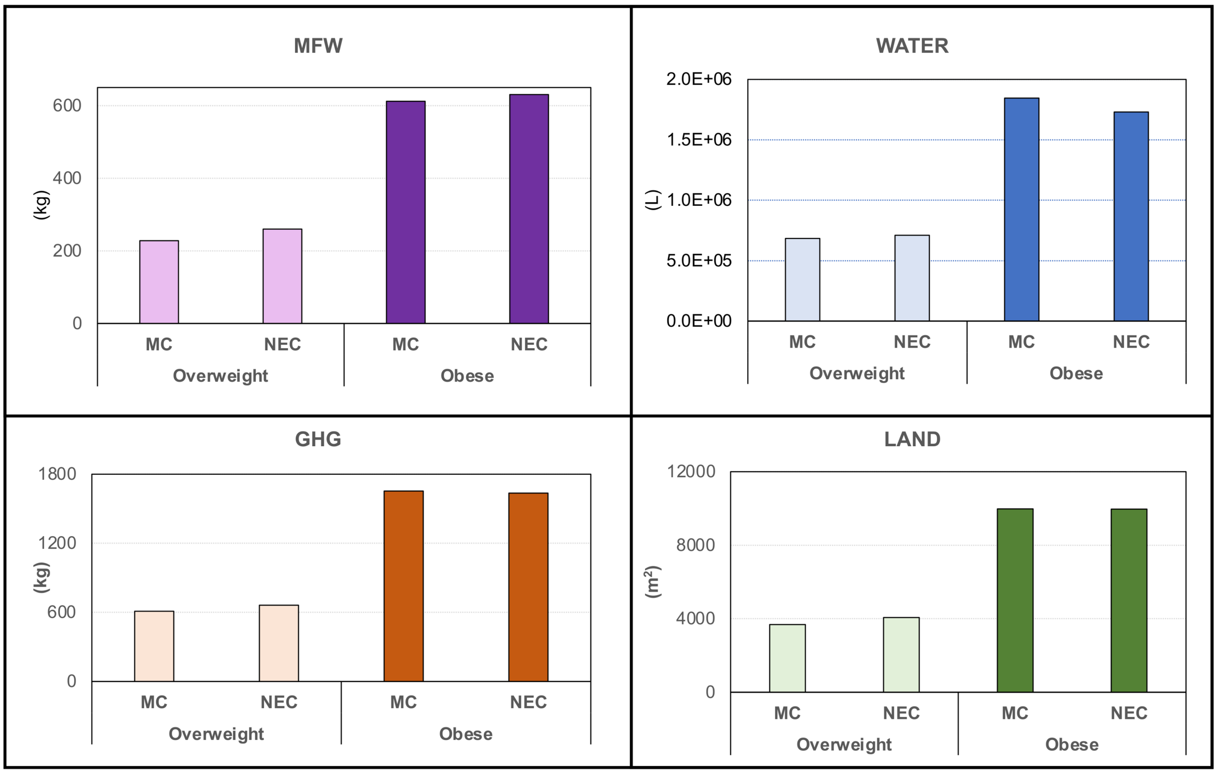

FIGURE 3
MFW corresponds to EBF from food balance sheet commodities in a population of 100,000 overweight and obese individuals living in Mediterranean (MC) or North European (NEC) countries. The data are expressed as tons per 100,000 citizens of wasted foods (MFW), liters per 100,000 citizens of water (WATER), kgCO$_2$eq per 100,000 citizens (GHG), and millions of m$_2$ per 100,000 citizens (LAND).

do not significantly contribute to EBF in individuals—the consumption of fruits, vegetables, cereals, and nuts is declining in MCs, posing a risk factor for obesity and other chronic diseases. Surveys conducted using the MEDAS questionnaire indicated that MC and NECs do not differ significantly in their low intake of fruits (< 3 servings/day), vegetables (< 2 servings/day), and nuts (< 3 servings/week) (19). This study also suggests a need to decrease the consumption of animal-based products and reverse the declining trend in vegetable intake to lower EBF and MFW overall. A French study also aimed to quantify the total food amounts and individual food categories that should be adjusted in certain MC and NEC to achieve ecological adequacy for GHG emissions (20). Overall, at least a 1 kg/day change in total absolute food weight was required to reach a nutritionally adequate and sustainable diet, with only minor differences between MC and NEC. Regarding food categories, an increased energy intake and GHG emissions from fruits and vegetables, alongside a decreased energy intake and GHG emissions from the sugar/fat/alcohol food group, are necessary to achieve this goal (20).

While MCs are experiencing a decline in adherence to the Mediterranean diet, there is a growing interest in NECs adopting the Nordic Diet (21). Due to the high intake of animal-based products in NECs, this relatively new sustainable dietary pattern promotes a shift toward increased consumption of plant-based foods over animal-based ones, particularly focusing on locally sourced vegetables, such as berries, cabbages, root vegetables, and legumes while also ensuring an adequate intake of fish as a source of protein and unsaturated fats (21). Adhering to this dietary pattern may be—and should be—an effective strategy to reduce malnutrition and lower the ecological impact of diets in these countries (22, 23). Moreover, the authors suggest that it can also be considered a healthy and sustainable option in southern European countries (24).

The present study shows some methodological limitations. First, by using epidemiological data from WHO databases on the anthropometrics of European countries, the level of EBF has been empirically calculated by assuming that the difference between the ideal and actual BMI of citizens is theoretically represented by fat mass. This assumption may not be accurate, as a single value of body weight—and consequently BMI—does not clearly indicate which tissue constitutes the weight. Another limitation is the heterogeneity among data sources and the availability of different databases evaluating the ecological footprints of foods, which may affect the actual calculation of the environmental impact of food and food overconsumption (25). Finally, data regarding the intake of food groups may be biased since food balance sheets report the availability of food commodities rather than consumption or intake data.

5 Conclusion

The present study confirms the utility and reliability of the MFW as a tool for describing the contribution of overeating not only to promoting overweight and obesity but also to quantifying the amount of MFW in terms of GHG emissions, as well as water and land consumption resulting from excess food production. In the future, this tool may be integrated into the daily practices of healthcare professionals to evaluate not only the healthiness of subjects' diets but also their environmental sustainability.

Data indicate a shift in the dietary habits of European citizens, particularly showing that MC countries seem to be less sustainable than NEC countries. This situation arises from high rates of overweight and obese individuals, coupled with the overconsumption of food categories that are not typical of the Mediterranean diet, recognized as one of the most sustainable dietary patterns. Such conclusions should encourage the planning of public information campaigns and initiatives—targeting both children and adults—to enhance the understanding of the role of lifestyle, particularly diet, in the crucial link between human health and the planet's health. Citizens should remain aware that their dietary choices and caloric intake from unbalanced diets increase the risk of obesity and related metabolic diseases and contribute to unnecessary ecological footprints that affect the planet's health.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Ethics statement

Ethical review and approval was not required for the study on human participants in accordance with the local legislation and institutional requirements. Written informed consent from the patients/ participants or patients/participants legal guardian/next of kin was not required to participate in this study in accordance with the national legislation and the institutional requirements.

Author contributions

DA: Data curation, Writing – original draft. ET: Data curation, Formal analysis, Methodology, Writing – review & editing. MR-S: Writing – review & editing. VD'A: Writing – review & editing. CB-T: Writing – review & editing. MS: Conceptualization, Funding acquisition, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fnut.2025.1505238/full#supplementary-material

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Africa's contribution to global sustainable and healthy diets: a scoping review

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Background: A healthy diet is essential for human wellbeing and environmental sustainability. Africa possesses diverse traditional food systems that are nutritionally rich and environmentally sustainable. However, modern dietary transitions and increasing reliance on imported and processed foods threaten the continent's food sovereignty and public health. This review explores Africa's contributions to healthy diets and sustainable food systems.

Objective: To examine the role of Africa's traditional diets in promoting global health, and to assess the impact of dietary transitions on nutrition and food security.

Methods: A scoping review was conducted using PubMed, Scopus, Web of Science, Google Scholar and some information from FAO repositories. Studies published between 2015 and 2024 were included, with some earlier studies providing historical context. Thematic analysis was used to synthesize findings on African diets, dietary transitions, and global contributions.

Findings: Traditional African diets are rich in whole grains, legumes, vegetables, and fermented foods, offering high nutritional value and health benefits. Dietary transitions toward Westernized diets have led to increased consumption of processed foods thus contributing to rising rates of obesity and non-communicable diseases. Africa's indigenous foods, such as sorghum, millet, teff, amaranth, and baobab, are gaining global recognition for their health benefits. Sustainable food systems in Africa present solutions for addressing global food security challenges.

Conclusion: Africa's traditional food systems provide valuable insights into healthy and sustainable diets. Promoting indigenous African foods and preserving traditional dietary practices can enhance global food security and nutrition. Policies and investments should focus on revitalizing traditional African diets to address nutrition and food security challenges.

KEYWORDS

African diet, Western diet, food security, nutrition transition, food systems, Africa

Introduction

The World Health Organization (WHO) defines a healthy diet as one which provides all the essential nutrients required by the human body to support an individual's physical and mental wellbeing (1). The description of a healthy diet is deduced from the Food and Agriculture Organization (FAO) 1996 World Food Summit in Rome food security definition which stated that food security exists when all people, at all times, have physical and economic access to sufficient, safe and nutritious food that meets their dietary needs and food preferences for an active and healthy life (2, 3). A healthy diet consists of a variety of foods that deliver the essential carbohydrates, proteins, fats, vitamins, minerals, antioxidants and fiber while minimizing the intake of harmful substances such as excess sugars and salt, saturated fats and highly processed foods (4). A healthy diet emphasizes the adequate consumption of whole grains, plant and animal- based proteins, healthy fats, and water (5). Globally, the World Economic Forum (WEF) estimated that 3 billion people cannot afford a healthy diet (6, 7). The FAO shows that nearly three-quarters of the African population cannot afford a healthy diet (Figure 1) and more than half cannot afford a nutrient adequate diet (8). The increasing food imports into Africa has worsened the situation and the resultant food importation bill is about $35 billion which is estimated to rise to $110 billion by 2025 (9). This weakens the African economies and lowers agricultural production.

The high food prices, low income levels and some consumer preferences have been reported as major barriers to affording healthy diets in some African countries (10, 11). In some of the African countries like Angola, the cost of a healthy diet is as high as USD 4.5, in Sudan USD 4.3 and for both Nigeria and Guinea it is USD 4.1 (7). Households which cannot afford the least-cost healthy diet in their countries are likely facing some degree of food and nutritional insecurity and thus face the risk of child and adult malnutrition (12). The demand for food in Africa is increasing with the increase in population and the intensifying climate change impacts and thus improving the agricultural infrastructure will be crucial to produce affordable foods to the population (13, 14). The State of Food Security and Nutrition in the World, 2024 emphasizes the more innovative investments in agrifood systems to ensure that households can access and afford a healthy diet (15). Therefore, the review aims to explore Africa's contribution to global dietary health and environmental sustainability.

Methodology

Review approach and justification

This review article synthesizes existing literature on African traditional diets, comparisons with the Western diet, evolution of Africa's food sources and dietary transitions and the implications of African diets on global health and sustainability. The review methodology employed a narrative and scoping review to ensure a systematic and comprehensive approach to articles selection and data synthesis. This approach allows for the synthesis of diverse literature sources such as empirical studies, policy documents and historical analyses thus providing a broad and structured understanding of the topic.

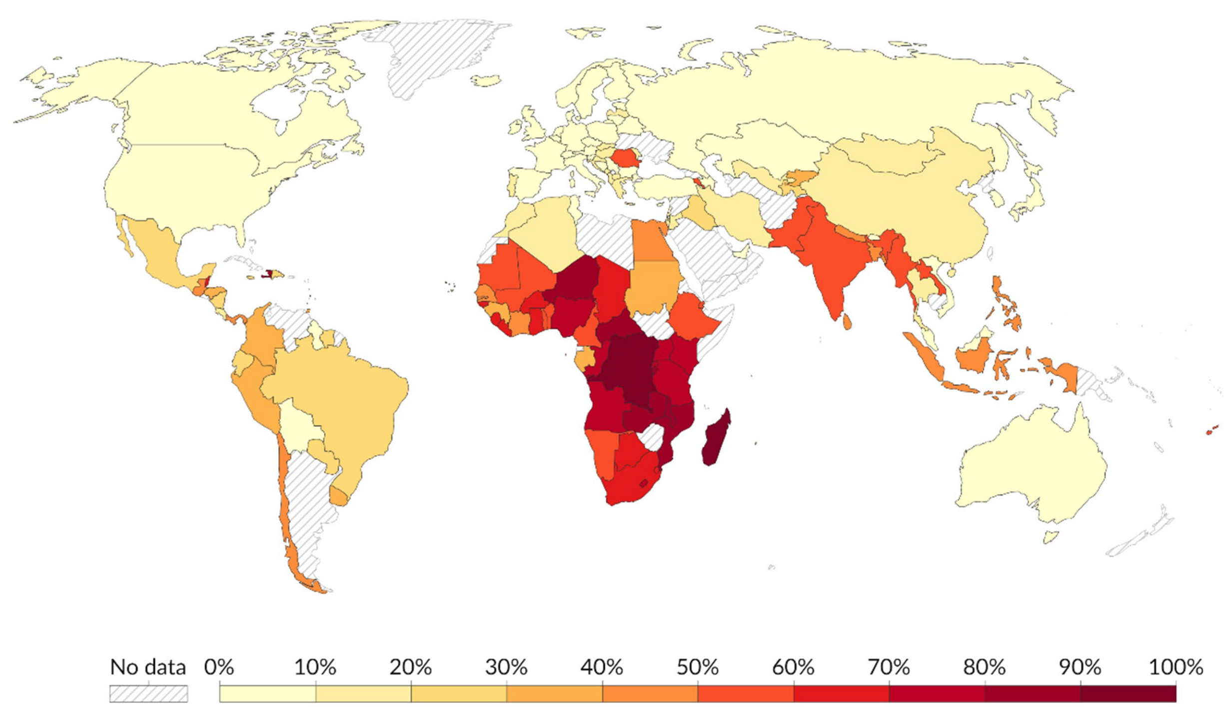

FIGURE 1
Global distribution of the population that cannot afford a healthy diet in 2022. Data source FAO and World Bank (106), licensed under CC BY 4.0, using data and methods from Herforth et al., (110), licensed under CC BY-NC-SA 3.0 IGO.

Search strategy

A structured literature search was conducted from PubMed, Scopus, Web of Science and Google Scholar databases. A further search was conducted from the FAO repositories since they provide authoritative data on food composition, dietary transitions, food security and policy recommendations relevant to African traditional diets and their global implications. Foundational studies relevant to traditional African diets were also considered. The search was restricted to studies published between 2015 and 2024 to ensure the inclusion of recent empirical research. However, some papers published before 2015 that provided essential historical context relevant to understanding dietary transitions in Africa were included. The keywords and Boolean operators used in the search were: ("African traditional diets" OR "indigenous African foods") AND ("nutrition" OR "health benefits" OR "dietary transitions"), ("African food systems" OR "African food sources") AND ("historical trends" OR "food evolution"), ("Western diet" OR "modern diets" OR "processed foods") AND ("health effects"), ("African diet" AND "Western diet") AND ("nutritional comparison" OR "health impact"), ("African diet" OR "traditional African foods" OR "indigenous African nutrition") AND ("Western diet" OR "modern dietary patterns") AND ("nutrition transition" OR "health outcomes" OR "sustainability").

Article selection

Following recommended protocols for scoping reviews, at least two reviewers were involved in the abstract and full text screening of each article in order to minimize reporting bias (16). The database search resulted in 627 articles. After removing duplicates, 398 articles remained. The initial round of title and abstract screening yielded 125 eligible articles. A further round of full-text screening resulted in 96 original articles for inclusion in this review (Figure 2). There were no conflicts between independent reviewers regarding the eligibility of articles for inclusion.

Inclusion and exclusion criteria

The selection of studies for this review was guided by defined inclusion and exclusion criteria designed by the authors to ensure relevance and quality.

Inclusion criteria: we considered peer-reviewed journal articles, government reports and policy documents published in English that specifically address African diets and nutrition. The review prioritized research articles that presented comparative analysis of African traditional diets with Western diets. Additionally, studies that

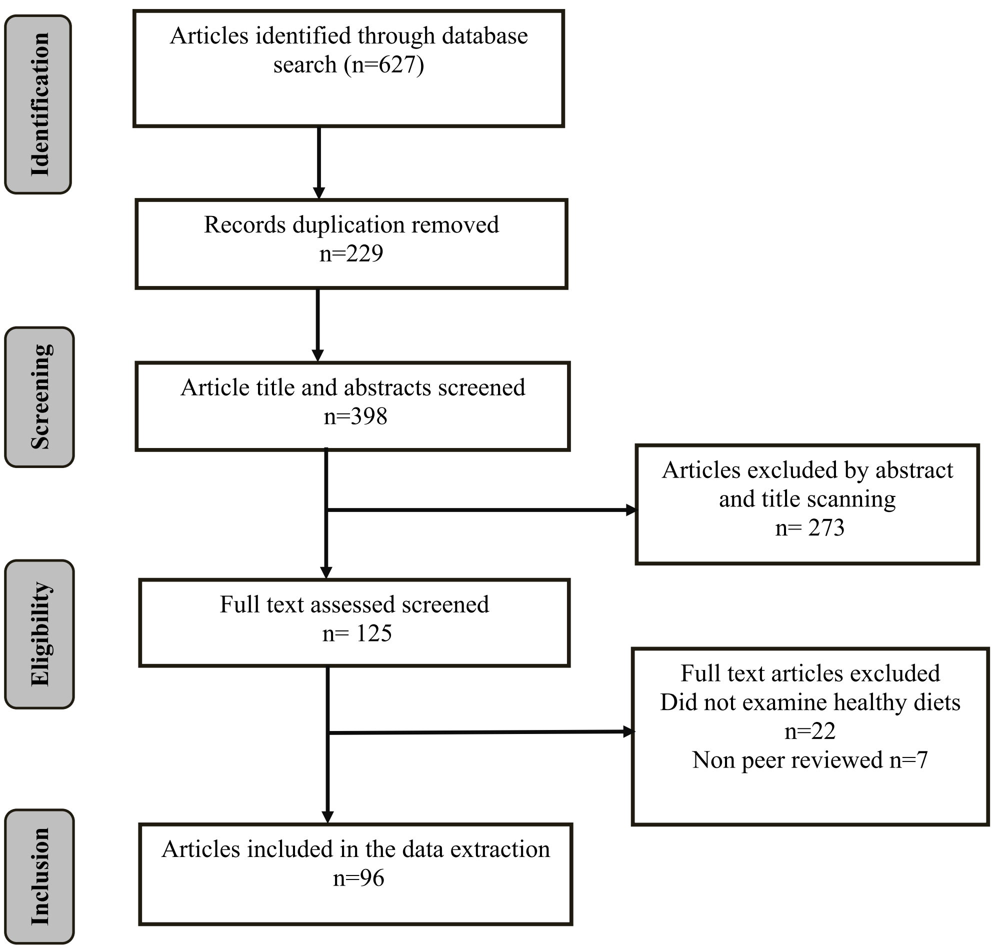

FIGURE 2
PRISMA flow diagram of article identification and selection.

provided empirical data on dietary transitions, nutrient composition and health impacts were also included.

Exclusion criteria: the review excluded articles that lacked primary data or were not systematic reviews of existing literature. Studies that focused exclusively on food processing technologies without addressing dietary impacts were also excluded.

Data extraction and synthesis

The thematic data extraction and synthesis focused on the composition of the African traditional diet, historical dietary evolution, and shifts influenced by modernization and globalization. Comparisons between the African and Western diets were drawn to highlight their nutritional value, health impacts and environmental sustainability. The review also examined the challenges posed by modern dietary transitions. Additionally, it explored Africa's contributions to global nutrition and sustainability through indigenous food systems and eco-friendly agricultural practices. Finally, the synthesis identified the solutions Africa offers to improve both local and global dietary health. This provides key insights through thematic categorization, comparative analysis and conceptual mapping to highlight knowledge gaps and research opportunities.

Results and discussion

Articles reviewed by thematic area

The review included a total of 96 articles, categorized into six thematic areas based on their focus. Thirty-one articles examined the evolution of Africa's food sources, outlining the past dietary trends and contemporary shifts. Twenty-three articles explored the composition, nutritional value and cultural significance of a typical African diet. Twenty-two articles covered the comparisons between the African diet and the Western diet. These articles provided insights into key differences in food sources, processing methods and health implications. The Western diet was analyzed in seven articles that primarily focused on its characteristics and associated health risks while eight articles discussed the challenges of modern diets. Lastly, five articles examined the global contributions of the African diet to healthy diets and solutions Africa has for itself and for other continents.

The typical African diet

The traditional African diet varies widely across the African regions due to food production, consumption and cultural patterns. However, the African diet is generally characterized by reliance on starchy foods such as maize, millet, sorghum, cassava, and yams complemented by leafy vegetables, legumes, nuts, seeds and fruits (17). The cereal based starchy foods made from maize, sorghum, millet and wheat are most consumed in the form of porridge, *ugali* (a stiff porridge made by mixing cornmeal with boiling water) and bread while the tubers are boiled, roasted or fried. The most widely consumed African indigenous green leafy vegetables include: amaranth (*Amaranthus spp*), spider plant (*Cleome gynandra*), jute mallow plant (*Corchorus olitorius*), pumpkin leaves (*Cucurbita spp*), African nightshade (*Solanum spp*), nettles (*Urtica massaica*) and cowpea (*Vigna unguiculata*) (18, 19, 101). The ALVs though underutilized have great nutritional and medicinal value to humans, for example jute mellow provides antioxidants to the body while other vegetables are rich in B1, B2, C, and carotenoids, and minerals (20, 21). Amaranthus is rich in carotenoids (9.0 ± 0.2 mg), vitamin C (43.0 ± 1.6 mg) and lutein (14.7 ± 0.8 mg) and Retinol Activity Equivalent (RAE −0.8 ± 0.02) when raw; these nutrients have anti-inflammatory role in the human body (22, 23). Some animal products such as fish, meat, fermented milk, poultry, beef and mutton and to a small extent game meat also dominate the African diet (24). However, these animal proteins are consumed less frequently in some areas due to economic or cultural reasons, and this makes the African diet naturally lower in fats (25, 99). There are communities which, by culture, take considerably more meat and milk, such as the Masaai in Kenya and Tanzania (104, 105).

West African cuisine is majorly composed of rice, millet and sorghum as main staple foods which are served together with plenty of vegetables along with a variety of spices and seasonings for flavor (26). However, the increasing intake of dietary energy, fat, sugars and protein and low consumption of fruit and vegetables in West Africa represents a critical nutrition transition (27). The diet also consists of cassava and yams as the main staple tubers (28). Beans (*Phaseolus vulgaris*), black-eyed peas (*Vigna unguiculata*) and peanuts (*Arachis hypogaea*) also feature prominently as the main legumes in the West African diet. The significant sources of proteins in the West African diet includes dried or smoked, poultry, goat or beef (29). The diet depends on access to diverse food sources and is rich in complex carbohydrates, fiber and vitamins but it can sometimes be low in protein and essential micronutrients (30). In other words, legumes for many communities have been the main providers of proteins, and therefore mostly plant proteins.

The diet in Central Africa comprises diverse plant and animal products that reflect the region's agricultural practices, geographical diversity and cultural traditions. These include cassava and other tubers such as yams and sweet potatoes, while the grains include millet, maize and sorghum. People also eat plantains as the main carbohydrate source (31). Some traditional staple vegetables include the dark green leafy vegetables such as amaranth and cassava leaves. The preparation of protein- rich legumes offers Central African populations an important protein source. Animal proteins are from fish, poultry, goat, beef and among others, and are less commonly consumed in low and middle income African countries due to cost or availability (32, 100).

The East African diet is normally composed of high intakes of minimally processed foods and most of the foods are cooked through boiling, steaming and fermentation. The East African diet is dominated by cereals like maize, sorghum and millet, tubers and legumes-based food products (33). In addition, beans, peas and lentils are important sources of protein while vegetables such as kale, spinach and other indigenous green leafy vegetables such as amaranth, jute mallow, cowpea and pumpkin leaves are rich sources of vitamins and minerals in the diet. Uganda has a unique cuisine of bananas and plantains which are consumed as either boiled, roasted or fried and *ebinyebwa* (Ugandan groundnut stew) (34). Most protein in the East African region comes from fish, poultry, beef or goat but it is sparingly consumed in some areas because of the high cost of purchase (35). Fruits include mangoes, oranges, pineapples and papayas, and dairy products are usually obtained from the pastoral communities, particularly in Kenya and Tanzania. The East Africans' regard of processed foods is traditionally generally low but is gradually changing due to factors such as urbanization and the adoption of western diets (36).

Traditional and novel food interweave the typical Southern Africa diet citing the region's culture (37). The staples in the Southern Africa region are based on maize and sorghum. Meat barbecues originating from beef, lamb, chicken and pork among others are commonly consumed in this region (38). They also take different vegetables such as pumpkins, potatoes, spinach and cabbages. The traditional diets include legumes and indigenous leafy greens such as amaranth leaves, spider plant, cowpea leaves, and African nightshade. The increased trend towards the Western way of living has resulted in a change in diet in the Southern Africa Region due to the influence of urbanization and economic development (39). However, the food systems transformation pathways in the Southern Africa region encourage consumers to take healthier traditional meals in spite of such changes (40).

The North African diet is characterized by a rich blend of flavors, ingredients and culinary traditions. Some products which can be considered staples include: couscous, semolina and bread from wheat or barley (41). Lentils (*Lens culinaris*) and chickpeas (*Cicer arietinum* L.) are the most widely consumed legumes which are accompanied by tomatoes, eggplants, peppers and others with animal protein. Most of the commonly consumed meats are lamb, chicken and beef while seafood is usually found in the coastal regions. Majority of the foods identified for preparation are cooked with olive oil and spices including cumin, coriander and saffron among others. Dairy products are also important food components. Some of the fruits include date fruits, figs and citrus which are usually eaten as snacks or dessert. Some traditional fermented foods as *injera* from Ethiopia [made from teff (*Eragrostis tef*), a tiny, gluten-free grain native to the Horn of Africa], contain natural sources of probiotically active substances that influence the state of gut microbiota (42–44). Some of the ingredients for the North African cuisine are produced locally and, therefore, are affected by seasonal changes.

Evolution of Africa's food sources: past trends and contemporary shifts

Historically, during the pre-colonial period, African food systems were highly localized, built around native crops cultivation, foraging for wild plants, hunting and pastoralism (45). Communities relied on traditional methods of farming, where both crop cultivation and animal husbandry were integral parts of their food systems (109). Smallholder farmers grew resilient crops like millet, sorghum, cassava, yams, and green leafy vegetables, while raising livestock such as cattle, goats, sheep, and poultry (46). Foods and medicines were also sourced from the wild and included honey, fruits, birds and game meat. These practices ensured that Africa fed herself with a balanced diet of nutrient-rich plant and animal foods. Food production in Africa remained at subsistence level and the farming system was based on shifting cultivation and bush fallow farming. Under these practices, soil fertility was maintained by opening fresh cultivation ground thereby allowing the most recently cultivated land to rejuvenate (18). Farmers applied organic manure once in a while and chemical fertilizers were not even known. Likewise, animal production was by pastoralism where herders migrated from one area to another in search of pasture land usually after every rain season (107). The combination of crops and livestock allowed healthy diets and diversified nutrition. The crops provided carbohydrates, vitamins and fiber, while animals offered essential proteins, fats, and micronutrients which are key for optimal nutrition status. The indigenous leafy vegetables also served as medicine.

It is estimated that Africa is comprised of about 30,000 species of edible plants which, out of these, about 7,000 are traditionally consumed (47). This large wealth of genes in agriculture and food production is a clear representation of the great ecological base of the continent and the possibility to achieve food security in the region (48). Africa's rich bio-diversity demonstrates the ability to support a variety of food production systems with proper utilization and management of the indigenous plant and animal genetic resources. African countries have the resource endowment needed towards attaining food security and sustainable agriculture (109). With the evolution of society and agriculture, numerous foods that once shaped diets and cultural identity across Africa have been gradually displaced (49). Many of these crops are now considered neglected and underutilized species, having fallen out of mainstream agricultural and dietary practices despite their historical significance and nutritional benefits. Currently, 60% of African food is based on wheat, maize and rice (47). The change could be linked to the Green Revolution of the 1950s and 1960s that focused on monocrops like maize, wheat and rice, grown on a mass scale. Monocrops did not translate to success of food systems in Africa but undermined small scale farmers that ensured sufficiency of traditional foods, making food productions unsustainable (50). The much acclaimed Green Revolution made sense at the time as it was feared masses would starve.

African food self-sufficiency has changed significantly over the last five decades (47). Today, Africa finds itself increasingly dependent on imported foods, a shift driven by global economic forces, changing diets, and urbanization (46, 102). While agriculture remains a dominant part of the economy, the continent's focus has further shifted from producing food primarily for local consumption to exporting crops like tea, coffee, cocoa, and flowers, to generate much needed foreign exchange. This emphasis on cash crops, grown mainly for international markets, has weakened Africa's ability to feed her own population. Staple foods that were once widely produced locally in Africa such as millet and sorghum are now often imported (51). A recent report by the United States Department of Agriculture (USDA) foreign agricultural service showed that South Africa Alone was estimated to import about 40,000 metric tons of sorghum to meet the local demand (52). Maize that was introduced and adopted in Africa from Mexico in the early 20th Century is also currently being imported since most of the maize production in Africa is done under rain-fed conditions (53), and cannot meet increasing consumer demand. Africa imports 28% of its required maize grain from countries outside the continent and according to Famine Early Warning Systems Network (FEWS NET) in the 2023/2024 year alone, maize imports in Africa exceeded 2 million metric tons (54). Imported rice, wheat, processed foods, and frozen meats have become common across Africa especially in urban areas with the growing populations. The shift has impacted negatively on the access of traditional, health foods in many African countries and increasing the reliance on calorie dense and over processed food posing a risk for lifestyle diseases (WHO, 2023).

Africa spends US$78 billion annually on food imports, with some countries like Zimbabwe, Guinea, and Sudan exceeding 100% of their foreign currency earnings on these imports (55). According to the African Development Bank, the continent's food and agriculture market, valued at US$280 billion in 2023, could rise to US$1 trillion by 2030 with strategic investment (56). The trend in the level of food imports and exports is one of the areas that underlines a marked change in African food systems (57, 58). Sustainable organic farming that was the mainstay of the traditional agricultural system is progressively being substituted by monoculture and commercial farming. Such contemporary systems are inclined toward the production of export crops which deprive people their sovereignty right over the kind of foods they consume. As a result, it is concerning that African countries have become reliant on imports for a sizable percentage of the food they eat today with much of it consisting of ultra-processed foods that do not provide the same nutritional benefits as was once the case (103). This change of diet not only reduced dietary diversity but also has led to an epidemic of non-communicable diseases, as processed, calorie-dense foods have replaced whole nutrient-dense foods, eradicating the nutritional bulwark of Africa.

Compounding this problem is the forces of climate change which have destabilized food production across the continent. Various changes in environmental conditions such as long dry seasons, irregular rainfall and high temperatures have had negative impacts on agricultural production and rearing of livestock, respectively (59). An analysis of countries in sub-Saharan Africa show that, an increase in the temperature by one degree lowers the value of agricultural production. Households that engage in diverse farming activities are better equipped to handle high temperatures. This adaptability reduces the negative impacts of climate change and helps these households build resilience, especially in areas that rely on rain-fed agriculture (60, 98). These climate changes have led to low productivity and food insecurity. Farmers have lost earnings because they cannot adapt to change and many have had to ditch crops which were clearly suited to their local climate conditions (61). The level of imported foods has risen as a result of the low yields, thus degrading food sovereignty in Africa.

Huge changes are being observed through the process of urbanization in Africa through a shift in diets towards processed and convenience foods (62). One of the impressions that cities give is that when people leave rural places to acquire residence in the urban centers, they leave behind customized production practices and knowledge of how to feed the world. In the urban areas, fast foods, refined grains, and sugary beverages dominate the market resulting in high consumption of processed foods. This not only changes the trend of meal taking, but also continues pulling away Africa from its farming base by discouraging indigenous food practices (63). In Burkina Faso, where participants from both urban and rural areas were compared, the researchers found that the urban group consumed more animal protein and simple sugars. However, the group of rural and semi-urbanized people consumed significantly more fiber (64). This is in conformity with the general changes in dietary habits of urban people from traditional diets to processed foods.

There is still an issue for the agricultural systems to meet the standards of modern technologies and most African countries still use labor-intensive farming techniques. Mechanization that is a potential to augment productivity remains wanting in most parts of the continent owing to costs and infrastructure (49). Agricultural practices rooted in hoe and plough mean that farmers' technologies are incapable of meeting food demands that come with a more urbanized population. The late industrialization of mechanization reduces agricultural productivity and increases Africa's food systems' susceptibility to climate change and population trends (65).

Another area of controversy is genetic engineering of foods. Where some believe that adopting genetically modified (GM) crops is the solution to the food security challenges facing Africa due to the increased crop yields, tolerance to pests and droughts many remain skeptics (66). Misconceptions relating to GM foods remain prevalent, coupled with apprehension that the genetically modified crops may have deleterious effects on health, environment or that this makes farmers heavily dependent on multinational companies for seeds and other production necessities (67). Most African nations have approached GMOs with apprehension, fearing the dangers they present to agriculture and the natural foods world. But some have considered it timely, economical and immune to climate spikes and have been making incomes out of it. This means that if the fears are brought to task, GMO could be the food solution for the next generation (113).

Cultural factors also play a significant role in shaping Africa's food systems, and there is a need to understand cultural dimensions in the realignment of food systems in Africa. In many communities, the local population has increasingly shifted its palate towards consuming foods that are marked as "imported" or "western" pending their social-economic status (63). This shift in culture has seen the dumping of traditional food patterns which were so relevant to the diets of Africa (50). Locally grown crops, vegetables and naturally raised animals are now increasingly losing out to easily available processed foods, milled grains and commercially produced meats. As these traditional foods are replaced with western foods in our society and people's diets, so is a wealth of relevant information on how to preserve, process, prepare, and consume food in a way that is healthy and sustainable (68).

There is renewed effort to promote traditional food systems in Africa due to the difficult factors mentioned above. Currently, there is a trend to support and produce near-shore crops, use of organic products and appropriate agricultural soil for local production than the foreign products (112). Such a strategy is being promoted by advocates of food policies that cover issues ailing small- holder farmers and policies that promote consumption of traditional crops which are healthy and sustainable to the environment than the processed foods (64). African governments should also be able to develop national bio-economy policies to help appreciate natural resources for human and animal health and for the conservation of mother nature.

The Western diet

The Western diet is characterized by a high intake of animal proteins, refined sugars and saturated fat (69). It also consists of natural and artificial food additives due to the presence of ultra-processed food and high amounts of refined salt. Fiber intake in the Western diet is often inadequate due to a lack of whole grains and legumes (70). The emphasis on convenience over quality in

TABLE 1 Major comparisons between the African diet and the Western diet.

Aspect	African diet	Western diet
Nutritional composition	- High in plant-based foods such as whole grains (millet, sorghum, maize), legumes (beans, lentils), vegetables, fruits, and tubers (cassava, yams) (81)	- High in processed foods, refined sugars, and unhealthy fats (saturated and trans fats) (69).
	- The indigenous African diet is characterized by vegetables, wild fruits, lean meats, legumes, and staple starches with high fibre and phytochemical profiles (82)	- Low in fiber, fruits, vegetables, and whole grains with fiber marketed as a single product (69)
Food sources	- Food production is usually from localized, small-scale farming indigenous crops with high diversity across regions and food availability is affected by seasonal variabilities (50, 83)	- Large-scale industrial agriculture producing monoculture crops (corn, wheat, soy) (84)
	- Traditional diets are sourced from natural and less industrialized environments although urbanization is increasing processed food consumption (85)	- High reliance on processed, pre-packaged and convenience foods (74)
Cultural context	- Deeply embedded in cultural traditions and rituals and food is often shared communally with an emphasis on family and social connections (86)	- Less emphasis on communal eating. Food choice is driven by convenience with a fast-paced lifestyle influencing food choices (87)
	- Traditional cooking methods include boiling, fermentation and drying which preserve nutrients and enhance their bioavailability (24)	- Most commonly used cooking methods include frying, grilling and baking which may destroy proteins and vitamins at high temperatures (88)
Dietary trends and transition	- Rapid nutrition transition in urban areas with increased consumption of Westernized diets and processed foods (89) - Urbanization is driving a transition toward Western diets with increased consumption of fast food, sugary beverages and processed products. - There is a growing interest in revitalizing traditional African foods, particularly indigenous grains like millet, sorghum, and teff, to improve food security and nutrition (91, 92)	- Already fully industrialized, with minor shifts toward healthier and plant-based diets in response to public health campaigns and consumer demand (90) - Emerging health-conscious movements promoting plant-based, organic, and whole-food diets. - Growing popularity of vegetarian, vegan and flexitarian diets (93, 94)
Health concerns	- Historically associated with lower rates of chronic diseases in rural areas where traditional diets are predominant. However, starchy diets commonly consumed in Sub-Saharan Africa often lack various micronutrients, including iron, zinc, calcium, folate, iodine, vitamin A, and vitamin B12. This poses the risk of triple burden of malnutrition with undernutrition and micronutrient deficiencies being prevalent in food-insecure areas while obesity and non-communicable diseases rates rising in urban areas (30, 95)	- The diet is usually calorie-dense, nutrient-poor, leading to increased risks of chronic and non-communicable diseases such as obesity, heart disease, hypertension and diabetes due to excessive consumption of ultra-processed foods, high sugar intake, unhealthy fats and sodium. This has raised concerns over high mortality rates originating from these diseases (96, 97)

Source: researchers review of literature.

many Western countries has led to a disconnection from the source of food, making it difficult for people to trace the origins of what they are consuming. Excessive consumption of red meat, dairy products and sugary beverages has contributed to a wide range of health issues including obesity, heart disease, diabetes and other chronic conditions (71, 72). The high consumption of refined sugars and salt has led to public health concerns over hypertension and metabolic disorders (73). Western diet is said to lead to dysbiosis, with a decreased richness and diversity of total bacteria with a reduction in numbers of beneficial microbiome and an increase in the harmful ones in comparison with a plant-based diet (74). The detrimental effects of the Western diet on gut microbiota may also be driven by food additives inducing dysbiosis and consequently adverse intestinal mucosal effects and inflammation (108).

Comparisons between the African diet and the Western diet

The African diet significantly differs from the Western diet in several aspects such as the nutritional composition, the sources, consumption trends, processing methods, among others. The information in Table 1 shows how the two diets compare.

The challenges of modern diets

One of the biggest challenges of the present day diet in different countries is an insufficient consumption of fiber (62). The traditional African diets included vegetables, legumes and whole grains most of which provide dietary fiber that is important for good digestion (111). Fiber has confirmed obligations when it comes to bowel movement, avoiding constipation, and promoting gut health. Such fiber-rich foods have for a long time been linked with decreased chances of developing several chronic disorders such as heart disease, obesity, as well as type 2 diabetes and colon cancer.

However, the changes in food habits from whole grains and high fiber products to refined carbohydrates, processed foods and soft / sugar sweetened beverages have essentially removed this component, making fiber intake way below today's standard. Current foods include over processed foods like white bread and pastries that in the process of refining are deprived of fiber (69). Further, it noted that the consumption of foods such as cakes and soft drinks is now frequent and yet fiberless. This change in diet has some serious ramification for health as pointed out by Akinola et al. (50). The effect of low fiber diet is gradually emerging, which poses numerous health risks. A lack of fiber can also cause minute injuries or inflammation to the intestines, which result in constipation and other gastrointestinal illnesses. Fiber helps to fill the colon and, therefore, assists in its functioning; in its absence, people develop conditions as diverticulitis, hemorrhoids, among others. Also, foods rich in fiber contribute greater satiety or will power, and help to ease the weight problem. Diets devoid of fiber may lead to over-consumption of food and lead to weight gain, unlike when fiber is consumed.

Excessive sugar and refined salt are pervasive in today's diets. These additives are found in processed snacks, cereals, and drinks, contributing to high blood pressure, diabetes, and cardiovascular diseases (64), all conditions that are alien to Africans. Furthermore, the over-processing of food destroys its nutritional value. Many of us now consume food that is far removed from its natural state (18). Packaged and processed items are loaded with preservatives and additives, making it hard to even recognize what we are eating. The world is at a critical juncture, and Africa has a great deal to offer. There is need for a roadmap to reversing the damage caused by over-processing and unhealthy dietary habits by reverting to the traditional African food systems rich in minimally processed or unprocessed plant-based foods (75, 76).

Global contributions of the African diet to healthy diets

Nutrient-dense foods such as cassava, yam and sweet potatoes in the African diet contribute to the vital calories. Sorghum and millet, containing fiber, B vitamins, iron, and zinc, are global contributions for better grain substitutes. A grain called Teff, now referred to as a "superfood" from Ethiopia and packed with protein, calcium, and iron, joins the world diet to meet the gluten intolerance demand. Beans and pulses such as cowpeas, pigeon peas, and bambara groundnuts are vital plant sources of protein for Africa and provide valuable fiber and lower cholesterol levels. They are a source of protein, healthy fats, and antioxidants and fit well with global trends for healthier snacking and the inclusion of pulses in diets.

Vegetables like amaranth, moringa, and pumpkin leaves contain significant amounts of vitamins A and C, calcium, and antioxidants (19, 77, 78). African foods such as okro, which is very common in the West African region, are rich in fiber and hence ensure better digestion. They reinforce the Western Africa dietares' recommendations by the global nutritional policy to eat more vegetables. New-age grains and millet from the African continent are becoming known for their health-enhancing qualities. They are richer in dietary fiber, have lower glycemic values, are normally low in gluten, and are more nutritious than processed grains. Maize, which is prevalent in Africa, also avails important nutrients and fiber to the world's food basket when consumed in its whole grain form to enhance wholesome eating.

Bread from teff known as Injera, fermented maize known as "Kenkey," and sour milk are examples of fermented probiotic foods well known in sub-Saharan Africa. These traditional foods match up with the current global desire for fermented foods for the wellbeing of the gut biome, thus promoting society's value for antibiotic-free digestive health in natural unadulterated cultured foods. Foods such as red palm oil and baobab oil found in Africa are good sources of fats that are healthy and contain antioxidants, which when taken in moderation, are good for the cardiovascular system. Shea butter is well known in the Central and West African Countries such as the Central African Republic, Cameroon, Nigeria, Benin, Burkina Faso, Mali, Ghana, and Guinea, and its stock is becoming valuable as it is used for cooking as well as in therapeutic services (79, 80). Collectively, these oils align with current global tendencies and accredit healthier and naturally occurring sources of fat nutrients. Innovative exotic fruits that are specific to Africa, such as baobab, marula and tamarind, contain vitamins, especially vitamin C and various antioxidants, hence qualifying for the growing global market for superfoods and healthy snacks. Staple items like plantain and bananas provide potassium and other nutrients to supplement other food items; their consumption greatly contributes to the nutritional requirement worldwide.

Solutions Africa has for itself and for other continents

Africa must revert to diets that prioritize natural, whole foods, and high fiber intake while minimizing sugars, refined salts, and over-processed foods. The lessons of Africa's traditional dietary wisdom could be one of the most powerful offerings to the global health movement, as we strive for healthier, more sustainable food systems. Current African diets are aligned to new global dietary patterns that include reduced consumption of meats and increased intake of dietary plant-based products like grains, pulses, and vegetables. This is not only good for the individual's health but also for the environment. There is an appeal to people's altruism that if they change their diet, they will not only become healthy themselves but also help save the planet as plant-based diets are considered to have a smaller negative impact on the environment.

These foods can be processed by steaming, grilling, or boiling; this drastically reduces the fat content while retaining nutrients in food. Essentials of Ghanaian foods such as jollof rice, *waakye* (Ghanaian dish made of cooked rice and beans), and kuku *paka* (made from grilled chicken, coconut milk, cream, and curry spices) incorporate natural foods and spices, yielding a nutritive value to the preparation and thus making a contribution to the knowledge of healthy preparation methods across the globe. Food systems across Africa are diverse and play a critical role in the preservation of global biological and ecological diversity. Baobab (*Adansonia digitata*), moringa (*M. oleifera*), and local leafy vegetables use minimal amounts of water and fertilizers since they adapt easily to adverse conditions and are native crops. It also underpins climate-smart and sustainable consumption of diets that are safe for human health and also friendly to the earth.

Conclusion

In conclusion, the affordability of healthy diets for human consumption continues to be a great challenge in Africa due to the costs associated with it. Most of the traditional African foods that were both healthy and climate resilient have been neglected over time. There is a witnessed dietary shift to the energy dense convenient foods from the western diet due to cultural changes and increased urbanization. The advent of genetically modified foods continues to threaten the African traditional foods and the possibility of reversal trajectory remains unknown. The possibility of reverting to the traditional African foods remains a big debate with no solution in sight. However, we remain hopeful for more resources to go towards more research and sharing of knowledge.

The study findings highlight the need for policies that promote the preservation and integration of traditional African diets into national and global food systems. Governments should invest in research, education and public awareness campaigns to encourage the consumption of indigenous, nutrient-rich foods while reducing reliance on ultra-processed foods. Agricultural policies should support smallholder farmers to produce healthy traditional foods by improving access to resources, infrastructure and markets. Additionally, food security policies should prioritize sustainable agricultural practices that enhance resilience to climate change. At the global level, Africa's contributions to healthy and sustainable diets should be recognized in international food policies, trade agreements and nutrition guidelines to promote food sovereignty and reduce the double burden of malnutrition across the African continent.

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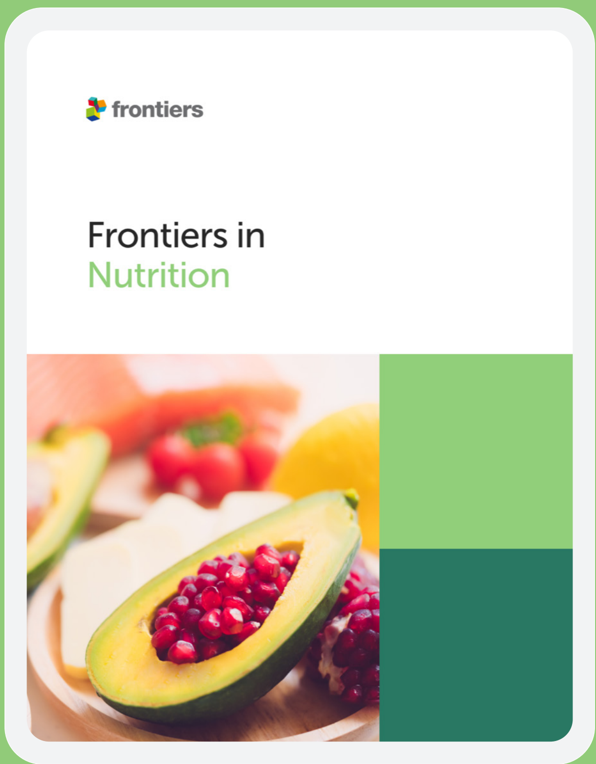

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