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REVIEW ARTICLE

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Will climate change affect nutrient, micronutrient and bioactive bioavailability?

Emmanuelle Reboul[a*], Ana M. Gomes[b*], Katia Petroni[c*], Patrizia Riso[d*], Marta Toccaceli[c], Catarina Vila Real[b], Ana P. Martins[b], Cristian Del Bo'[d], Daniela Martini[d], Mirko Marino[d] and Didier Dupont[e*]

[a]INRAE, INSERM, Aix-Marseille Univ, C2VN, Marseille, France; [b]Universidade Católica Portuguesa, CBQF - Centro de Biotecnologia e Química Fina - Laboratório Associado, Escola Superior de Biotecnologia, Porto, Portugal; [c]Department of Biosciences, Università degli Studi di Milano, Milan, Italy; [d]Department of Food, Environmental and Nutritional Sciences, Division of Human Nutrition, Università degli Studi di Milano, Milan, Italy; [e]INRAE, l'Institut Agro, STLO, Rennes, France

ABSTRACT

Climate change is projected to profoundly affect global food systems, directly altering food availability and composition and, as a result, nutritional outcomes. Modifications to the composition and properties of food matrices may, in turn, influence the digestion, absorption, and metabolism of food compounds. This can lead to changes in the bioavailability of macronutrients, micronutrients, and bioactive compounds. Additionally, strategies implemented to mitigate climate change, such as transitioning to green food processing methods or modifying diets, may also affect the content and bioavailability of (micro)nutrients in foods.

In this review, we will discuss, for the first time, the direct and indirect relationships between climate change and the bioavailability of selected food compounds: proteins, fat-soluble micronutrients, minerals, phenolic compounds, and glucosinolates.

KEYWORDS
bioaccessibility; CO2 levels; temperature; drought; sustainable diet

Introduction

There is overwhelming scientific evidence that climate change is a reality, and human activities are the main driver of this change. Global temperatures have risen by approximately 1.1 °C since the pre-industrial era, and 19 of the 20 warmest years on record have occurred since 2001 (NASA Earth Observatory 2020). Climate change is causing changes in rainfall patterns, with some areas experiencing more frequent and severe droughts, while others experience more intense rainfall events and floods. The Arctic Sea ice has declined rapidly in recent decades, and glaciers around the world are retreating at an accelerating rate. Sea levels have risen by about 20 cm since the start of the twentieth century, and the rate of sea level rise has increased in recent decades (European Environment Agency, 2023). All these climatic events can have devastating impacts on communities, economies, and ecosystems. The overwhelming consensus among climate scientists is that human activities are causing the Earth's climate to change at an unprecedented rate, and urgent action is needed, especially to reduce greenhouse gas emissions.

Climate change is expected to have significant impacts on global food systems (Zurek et al. 2022), which in turn will have important consequences for nutrition. Firstly, climate change is likely to cause changes in temperature and precipitation patterns, increase pest and pathogen pressures and reduce pollinator populations (Myers et al. 2017), which can (negatively) affect crop yields. For example, extreme weather events such as droughts, floods, or elevated ground-level ozone can reduce crop yields, leading to food shortages. This can result in reduced availability and affordability of nutritious foods, which may lead to inadequate dietary intake and malnutrition. Secondly, climate change can also lead to changes in food access, particularly in vulnerable populations. For example, droughts and other extreme weather events can impact agriculture and fisheries' productivity, and drive food prices and volatility up, making it harder for low-income households to access sufficient nutritious foods. While we currently lack the capacity to fully quantify the net impacts of climate change on the livestock sector, there is strong evidence that every stage of the supply chain will be affected (Godde et al. 2021). Thirdly, climate change may contribute to the spread of foodborne illnesses. Indeed, warmer temperatures may provide ideal conditions for the growth of bacteria/fungi in foods that can cause food poisoning and other enteric infections and illnesses, which can negatively impact nutrition and health outcomes. Finally, climate change can impact food quality as rising temperatures and changes in rainfall patterns can also modify the nutrient content of crops. For example, some studies suggest that increased CO_2 levels may lead to lower

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CONTACT Emmanuelle Reboul Emmanuelle.Reboul@inrae.fr

*These authors contributed equally to this work.

concentrations of nutrients, including protein and specific minerals (Beach et al. 2019). This could lead to deficiencies in these key nutrients and alter health outcomes in specific populations. Addressing these challenges will require a coordinated and multi-faceted approach that includes investments in sustainable and regenerative agriculture, new product development and fortification, nutrition education, and efforts to mitigate the impacts of climate change. The development of staple crops capable of tolerating such abiotic stressors as elevated CO_2, temperature and soil salinity is also among mitigation strategies to be sought (Semba et al. 2022).

The United States Food and Drug Administration (FDA) defines bioavailability as the rate and extent to which a nutrient, a micronutrient or a bioactive is absorbed and becomes available at a site of action (Chow 2014). In addition to the direct influence of climate change on food composition, climate change may also influence nutrient, micronutrient, and bioactive bioavailability, as modifications in food composition and matrices can modulate food compound digestion, absorption, or metabolism. Moreover, the strategies set up to tackle climate change, i.e., changes in food transformation toward green processes or diet modifications, may also modulate both food (micro)nutrient content and bioavailability. In this review, we will specifically discuss the direct and indirect relationships between climate change and selected food compounds' bioavailability: proteins, fat-soluble micronutrients, minerals, phenolic compounds, and glucosinolates (GLSs).

Methodology

A comprehensive literature review has been performed to explore the relationship between climate change and food compound bioavailability. The search was carried out across multiple databases, including PubMed, Google Scholar, Web of Science and Embase, using specific keywords for each sub-section of the review dealing with a "*specific food compound*," namely "protein", "amino acid", "mineral", "iron", "zinc", "vitamin A", "vitamin D", "vitamin E", "vitamin K", "carotenoid", "polyphenol", "flavonoid", "glucosinolates". For the section on food source availability, we performed two separate searches with the following keywords: *i*) "climate change" AND "plant-based diet" OR "dietary changes"; *ii*) "climate change" AND "*specific food compound*" OR "*specific food compound*" AND "climate resilient crops". For the section on food composition, we used the keywords "climate change" OR "UV" OR "CO_2" OR "temperature" OR "global warming" OR "drought" OR "salt" OR "water stress" AND "*specific food compound*" OR "*specific food compound* composition" eventually followed by a refined search on specific plants or compounds (for instance "tea", "grapevine", "strawberry", "anthocyanins" in the case of polyphenols). For the section on bioavailability, keywords used were "*specific food compound*" AND "bioaccessibility" OR "bioavailability" or "digestibility". For the section on food processing, keywords included were "*specific food compound*" AND "food processing" OR "green processing" AND "bioavailability" OR "bioaccessibility" followed by more refined searches using "*specific food compound*" AND "food processing" AND "milling" OR "microfluidization" OR "fermentation" OR "sprouting" OR "germination" OR "food by-products". These sub-sections of the review included studies published between 2010 and 2023, focusing on peer-reviewed articles which addressed relevant topics related to climate change and "*specific food compound*" content and/or bioaccessibility and/or bioavailability. A few relevant articles published earlier than 2010 were also included. Articles were chosen based on their relevance to the topics addressed in this review, with no strict exclusion criteria except non-English articles, thus allowing a broad exploration of the literature.

Climate change and food source availability

Climate change and the need to tackle it will significantly affect our diets, potentially leading to the extinction of certain food sources while also prompting the development of new ones. For example, climate change is most likely to disrupt two primary food production systems: agriculture and fisheries (Myers et al. 2017). Consequently, both humans and other organisms in the biosphere, who depend directly or indirectly on these systems, will be affected (Myers, 2019).

Moreover, adopting plant-based diets or increasing the consumption of plant-based foods is considered an effective strategy to reduce the environmental impact of food production (Pye et al. 2022). The environmental impact of food production accounts for about 26% of greenhouse gas emissions, 70% of freshwater use, 40% of arable land use, 32% of acidification and 78% of eutrophication. These environmental impacts are not equal among all food groups. Regarding greenhouse gas emission, meat from ruminant animals has the highest negative impact; dairy, eggs, fisheries and meat from pork and poultry have an intermediate impact, whereas plant-based foods have the lowest environmental impact (Poore and Nemecek 2018). An improvement of agricultural techniques may reduce greenhouse gas emissions by 10%, but a shift to an increased consumption of plant-based foods is estimated to lead to an 80% reduction in agricultural emissions (Willett et al. 2019).

Protein sources

In the era of climate change, where major crops like rice, wheat and maize are struggling to survive, millets (small-seeded cereals) and sorghum have emerged as sustainable food sources to end hunger and poverty (Mahajan et al. 2024). Sorghum sourced from various parts of the world, including India, China, and African countries, finds new applications in the food industry, leading to the emergence of a range of innovative products, including beverages, porridges, snacks, confectionery, bakery items, and extruded products. It has even been incorporated into main meals such as pasta, couscous, noodles and fermented foods (Khoddami et al. 2023).

Millets and sorghum can grow well in harsh climatic conditions and be used as a major source of human food. They are better sources of carbohydrates, proteins, essential amino acids, fiber, minerals, vitamins and phytochemicals than major cereals. For instance, millets are rich in proteins, vitamins, and minerals, including iron, zinc, copper, and manganese, compared to other staple cereals. However, they also contain some anti-nutrients, such as phytic acid, negatively affecting mineral bioavailability (Sarita 2016). Cereal and legume crops are generally complementary. However, current global consumption patterns indicate that cereal and legume proteins are consumed at an unbalanced ratio of 6:1 (i.e., 6 g of cereal protein is consumed per 1 g of legume protein)—where *a* ~2:1 ratio would be required to optimize plant protein quality scores. In developed regions, imbalanced intake of plant protein is not a major issue as it is typically offset by animal protein consumption, which accounts for ~40% of global protein consumption (from 16% in East Africa to 65% in Oceania). Nevertheless, if animal protein intake is low or needs to be lowered, it is necessary to direct attention toward the quality of the plant protein component of the diet. As such, protein complementation is a well-known, long-established, but often overlooked dietary strategy to improve plant protein quality. It is important to recall that protein deficiency may lead to stunting and increase infant mortality or reduce longevity among the elderly. Other alternative proteins could be of interest in the future. A first example is single-cell proteins (SCP). SCPs derive from yeast, bacteria and molds and are produced by high-scale culture on available wastes and by-products from the food and agricultural industries. They have a high substrate conversion efficiency, and various types of waste can be used as substrate and nutrient solutions. Biomass production from SCP is also independent of seasonal factors, and maximum yield can be obtained regardless of weather conditions. Their protein content varies between 40–80% for bacteria, 30–75% for algae and yeasts and 20–45% for molds (Grde and Solowiej 2022). Proteins from edible insects and microalgae are also getting more and more attention. Nutritionally, insect proteins exhibit a favorable amino acid profile and, besides proteins, they also provide a significant amount of minerals like iron, zinc and calcium (Grde and Solowiej 2022). Spirulina and chlorella are the most well-known microalgae. Spirulina can have a high protein content (>60% of dry matter), and its amino acid profile is mostly in line with the recommendations of the Food and Agriculture Organization of the United Nations (FAO), except for lysine and, in some cases, for methionine (Danesi et al. 2002). Finally, potato protein, an allergy-free protein source (Hussain et al. 2021), is of high nutritional quality and contains all essential amino acids with the best profile among plant protein sources, having an amino acid score of 65% (Levy et al. 2021). One drawback of potato protein sources is that they may contain high levels of glycoalkaloids, which can have toxic effects on humans. Nevertheless, these toxic compounds can be removed by ultrafiltration during the extraction of potato proteins. With their adaptability to diverse agroecological zones, high caloric yield, and potential to enhance food security, potatoes represent a climate-resilient protein source, especially when cultivated through sustainable and inclusive farming practices. Bozan et al. developed a *potato super pangenome* by sequencing nearly 300 varieties of potatoes and their wild relatives. This genetic resource aims to identify traits that can help breed potatoes that are more nutritious, disease-resistant, and better able to withstand extreme weather conditions like drought and frost (Bozan et al. 2023).

Fat-soluble micronutrient sources

Fat-soluble micronutrients comprise 4 vitamin families essential to our development and health: vitamins A, D, E and K. Although carotenoids are not considered micronutrients due to the lack of proven essentiality in humans, they are fat-soluble compounds of interest because of their numerous health-promoting properties. Provitamin A carotenoids, which can be metabolized into one or two molecules of vitamin A in humans, may become essential in meeting vitamin A requirements in the future due to the transition toward plant-based diets. Therefore, carotenoids will also be included in this review. The digestion and absorption mechanisms of fat-soluble vitamins and carotenoids have recently been reviewed in detail (Reboul 2023). Climate change has the potential to alter food availability and production, which may in turn influence human intakes of vitamins and carotenoids. Indeed, projected changes in fishery production yields and ocean fauna due to climate change, driven by factors such as ocean warming (Deutsch et al. 2015) and declining oxygen levels in marine and coastal waters (Breitburg et al. 2018), could affect the availability of key dietary sources of vitamins and other nutrients (Vermeulen et al. 2012; Pinsky et al. 2019; Murphy and Allen 2003). Fish, and especially fatty fish, are almost the only natural source of vitamin D (Ciqual 2020). It also provides several other key micronutrients such as vitamin B_{12}, vitamin A, minerals and omega-3 fatty acids (Ciqual 2020). In a study conducted in First Nation populations, Marushka and colleagues estimated that the average climate-related decline of seafood species by biomass consumed ranged from 21 to 31%. This significantly decreased the nutritional quality of the diet in individuals who substantially rely on traditional seafood consumption (e.g., men and older age groups), especially for nutrients that are primarily obtained from marine sources, such as long-chain omega-3 fatty acids, vitamin D, selenium and vitamin B_{12} (Marushka et al. 2019).

Climate change may also change the availability of plant-based foods. As CO_2 concentration rises, most plants are growing faster, and agricultural yields for micronutrient-rich sources such as legumes (Singer et al. 2020), fruits and vegetables (Dong et al. 2020) were shown to increase. However, when elevated CO_2 is combined with elevated temperature, a decrease in production is generally observed (Alae-Carew et al. 2020). Climate change may also induce a decline in pollinators, which can impact agricultural production significantly. About 70% of the vitamin A in the food supply is estimated to come from pollinator-dependent crops (Eilers et al. 2011), which include carrot, sweet potato, spinach, pumpkin, melon, and tropical fruits (Chaplin-Kramer et al. 2014). A complete removal of pollinators would induce a global decrease in fruit and vegetable production of 16 to 23% and potentialize vitamin A deficiency in low-income countries where vitamin A is mostly from plant origin (Smith et al. 2015).

Interestingly, edible insects could become a promising source of micronutrients. Rearing black soldier fly larvae on by-products or waste rich in provitamin A carotenoids may be a sustainable strategy for recycling a fraction of vitamin A back into the food chain. This approach could represent a novel way to combat vitamin A deficiency (Borel et al. 2021).

Mineral food sources

It is well established that humans require both major minerals (also known as macrominerals) and trace elements (microminerals) to maintain essential physiological functions. Macrominerals, including potassium (K), chloride (Cl), calcium (Ca), sodium (Na), phosphorus (P), magnesium (Mg), and sulfur (S), are needed in amounts of 100 mg per day or more (Mahan and Escott-Stump 2008). In contrast, microminerals such as iron (Fe), zinc (Zn), copper (Cu), fluoride (F), iodine (I), selenium (Se), molybdenum (Mo), manganese (Mn), chromium (Cr) and boron (B) are required in much smaller quantities, normally in the milligram or microgram range (Mahan and Escott-Stump 2008). Mineral deficiencies, notably in I, Fe, and Zn, are widespread globally, with low and low-medium income countries bearing the most severe impact (Gedfie et al. 2022; Hatch-McChesney and Lieberman 2022; Caulfield and Black 2004; Wessells and Brown 2012). A 14 to 20% reduction in the global availability of Fe, Zn and protein is anticipated by 2050, which is expected to increase the number of individuals likely to be vulnerable to mineral deficiencies. Simultaneously, the population segments grappling with these deficiencies are expected to experience their effects more profoundly (Myers, 2019).

It is important to note that the well-established dietary sources of minerals, such as cereal grains (wheat, oats, rice and barley), legumes, nuts and seeds, fruits, and animal-based foods (including fish, meat, eggs, and dairy products), come from the primary food production systems that are increasingly at risk due to climate change, as mentioned earlier in this section. In low-middle income countries, plant foods assume a pivotal role in providing mineral intake (Semba et al. 2022), since these are staple foods. Legumes, nuts and seeds are rich in Mg, P, Zn and Fe, while vegetables and fruits are a good source of Ca, Mg and Fe (Mahan and Escott-Stump 2008). Within the fisheries sector, including those in low- and middle-income countries, artisanal and coastal fisheries associated with mangrove-associated practices play a vital role in providing essential micronutrients to local populations (Semba et al. 2022). However, as previously discussed, these fisheries are increasingly threatened by climate change. Rising temperatures are altering the chemical composition of aquatic environments, affecting oxygen levels, acidification and salinity. These changes can lead to reduced fish body weight and lower concentrations of key nutrients such as long-chain omega-3 fatty acids and Fe. Given these challenges, whenever possible, the consumption of marine fish should be encouraged as a strategy to help mitigate dietary micronutrients losses in vulnerable communities (Semba et al. 2022; Giulia et al. 2020; Agostoni et al. 2023). Meat products are important sources of Zn, Cu, Fe, Se and P; while eggs and dairy products contribute significantly to the intake of Cu, I and Se (Mahan and Escott-Stump 2008). Climate change may affect these product yields, potentially reducing access to these essential minerals. For instance, dairy cows in southern European countries under heat stress have been reported to produce less than 5.5 kg of milk/cow/day (Climate Change and Food Security, 2024).

Phenolic compound sources

Polyphenols, abundant in fruits, vegetables, cereals, nuts and legumes, have significant antioxidant and anti-inflammatory properties (Bolling et al. 2011; Nani et al. 2021; Pap et al. 2021; Bucciantini et al. 2021; Cappellini et al. 2021), which depend on both their dietary intake and bioavailability. These secondary metabolites include phenolic acids, stilbenes, lignans, flavonoids and tannins. A dietary shift toward plant-based foods may concurrently increase polyphenol intake and bioavailability, potentially resulting in improved prevention of chronic diseases (Koch 2019). Indeed, higher polyphenol intake, as measured by the polyphenol antioxidant content (PAC) score, correlates with low-grade inflammation and lower cerebrovascular and cancer mortality in a large Mediterranean population-based study (Pounis et al., 2016; Pounis et al., 2016; Pounis et al. 2018).

Despite their health-promoting properties, many polyphenol-rich plant species are either underutilized or not consistently available year-round. As mentioned before, climate change further threatens their availability by reducing crop yields and altering growing conditions, potentially lowering total polyphenol intake. To address this challenge, the identification and cultivation of climate-resilient, polyphenol-rich crops is essential for ensuring a stable supply of these bioactive compounds globally (Scarano et al. 2020). Agronomic strategies, such as reducing nitrogen fertilization in crops like broccoli, basil and tomato (Nguyen and Niemeyer 2008; Fortier et al. 2010; Bénard et al. 2009), or applying UV light treatments to tea, red lettuce and tomato (Li et al., 2020; Goto et al. 2016; Calvenzani et al. 2010), have shown promise in enhancing polyphenol content.

As mentioned above, millets, including pearl millet and six other small-grained varieties (i.e., finger, foxtail, kodo, proso, barnyard and little millet), as along with sorghum, have been identified as climate-resilient crops (Gupta et al. 2017). Black- and brown-colored millet varieties are rich in polyphenols concentrated in the outer seed layers, though these are significantly reduced (by 65–80%) during dehulling. Nevertheless, whole husked grains remain highly nutritious and can be eaten whole, boiled, or cooked like rice (Bhat et al. 2019). Millet grains are rich in phenolic acids, such as gallic, caffeic, gentisic, p-coumaric, vanillic, p-hydroxybenzoic, syringic, sinapic, and chlorogenic acids, as well as kaempferol. These compounds contribute to a range of significant health benefits (Ofosu et al. 2020; Xiang et al. 2019), including the prevention of cancer, heart and liver diseases, and diabetes (Devi et al. 2014; Satyavathi et al. 2021). Similarly, sorghum grains are rich in phenolic acids, proanthocyanidins and flavonoids, depending on cultivar and pericarp color. Major sorghum phenolic acids include ferulic, protocatechuic and caffeic acids, while chlorogenic, gallic, and vanillic acids are notable in yellow-pale and yellow cultivars. Black cultivars contain three to four times more 3-deoxyanthocyanidins, which include apigeninidin (yellow) and luteolinidin (orange), compared to red and brown varieties. Red cultivars have the highest total phenolic and flavonoid content, reinforcing the observation that pigmented cultivars generally possess higher polyphenol concentrations than their non-pigmented counterparts (Mawouma et al. 2022).

In addition to whole foods, some food processing by-products also represent valuable sources of polyphenols. When incorporated into food formulations, these by-products can enhance overall dietary polyphenol intake (Melini et al. 2020). For example, wheat bran fractions have been effectively used to enrich pasta, bakery products, and bread with polyphenols, offering a sustainable strategy to improve nutritional quality (Zanoletti et al. 2017; Ficco et al. 2018).

Glucosinolate food sources

GLSs are secondary metabolites predominantly found in the Brassicaceae (or Cruciferae) family (Nguyen et al. 2020) (e.g., broccoli, cabbage, kale). They play a crucial role in plant defense mechanisms. GLSs exhibit remarkable structural diversity, leading to their classification into various chemical classes, with aliphatic, aromatic, and indole GLSs. Their metabolic products (i.e., isothiocyanates), obtained after hydrolysis by plant or intestinal microbial myrosinase (Connolly et al. 2021), have gained attention for their numerous biological activities and, above all, for their anticancer properties and ability to modulate cytoprotective factors (Mitsiogianni et al. 2019).

Climate change threatens the survival of certain GLS-rich crops in traditional growing regions. Brassica species, which typically flourish in cooler climates, are particularly vulnerable to rising temperatures, which increase their susceptibility to diseases and pests and exacerbate the risk of crop failure (Cohen and Leach 2020). In addition, drought conditions can also severely reduce crop yields, while excessive rainfall and resulting waterlogging can damage root function and overall plant health (Kaur et al. 2020). Changes in precipitation patterns may also necessitate the geographical relocation of crop production, potentially leading to the loss of GLS-rich crops in regions unable to adapt (Kang et al. 2009). Elevated atmospheric CO_2 levels further complicate this scenario: while they may stimulate plant growth (Ziska 2008), they can also alter secondary metabolite profiles, including increasing GLS concentrations, with implications for both crop resilience and nutritional quality (Klaiber et al. 2013).

As traditional GLS sources face challenges, climate change might also lead to the emergence of new sources. Areas previously unsuitable for Brassica cultivation may become viable due to changing climate conditions, presenting new opportunities for agricultural expansion. Additionally, the cultivation of novel or underutilized Brassica species, or other GLS-rich crops with greater resilience to climate stress, could provide alternative sources of GLS. For example, certain wild Brassica species may gain prominence in future agricultural systems adapted to emerging environmental conditions (Quezada-Martinez et al. 2021).

Climate change and nutrient and micronutrient/bioactive composition of foods

Various methods have been applied to comprehend the influence of climate change (by investigating variables such as $C0_2$ levels, temperature, drought, salinity) on plant growth and composition. These methods encompass studies such as Free-Air CO_2 Enrichment (FACE, the most realistic), controlled CO_2 chambers in greenhouse and laboratory settings, and field studies observing plants in their natural habitats. Some data obtained from these diverse studies have been meticulously gathered and analyzed in meta-analyses, leading to comprehensive conclusions. Furthermore, computational models and simulations in modeling studies offer predictions on the potential effects of elevated CO_2 on food composition. Examining the combined effects of elevated CO_2 and elevated temperature, a scenario reflecting future climate change, is feasible through temperature FACE (T-FACE) platforms. These platforms, incorporating infrared heaters to control temperatures, provide insights into the combined impacts of elevated CO_2 and elevated temperature alongside traditional FACE conditions (Semba et al. 2022).

Protein composition

Plants grown in natural environments can encounter either a specific stress or multiple stresses at the same time. Salinity stress has been shown to reduce the protein content of wheat grain by 23% (Abbas et al. 2013). In contrast, droughts were shown to increase grain protein, gliadin, and glutenin contents (Thungo et al. 2020). The effects of high temperature and heat stress on grain quality are generally detrimental, but may vary according to the genotype. For instance, heat stress resulted in lower gluten content (−18%) in one spring wheat variety (Sattar et al. 2020), while increasing grain protein content (+17%), albumin/gliadin ratio (+17%) and glutenin content (+4.5%). In contrast, another spring wheat genotype revealed a 40% decrease in gliadin content under similar conditions (Singh et al. 2012). Tomás and colleagues investigated the heat tolerance potential by increasing the temperature gradually from 20 to 40 °C during 6 h for 17 days after anthesis in seven commercial wheat varieties recommended for production in Portugal, and observed a lower predicted protein content (Tomás et al. 2020). Finally, Li and colleagues noted that warm soil (+2.4 °C) conditions affected grain amino acid carbon and nitrogen content, with the following increases/decreases in average percentages of amino acids, respectively: alanine (−2.08 and −1.79%), glycine (−2.38 and + 0.69%), valine (−1.33 and + 2.78%), leucine (+2.19 and + 0.96%), isoleucine (0 to −7.14%), proline (2.39

and + 1.22%), phenylalanine (+4.17 to +3.33%), methionine (0 and −1.47%), threonine (0 to −1.37%), serine (+1.59 and −0.68%), tyrosine, (+22.45 and + 26.67%), cysteine (0 and −4.72%), arginine (−1.67 to −2.97%), aspartic acid (+1.82 to +0.53%), histidine (+2.78 and + 1.2%), glutamic acid (+4.75 and + 3.66%), and lysine (+4.65% and + 4.21%) (Li et al. 2013). Notably, the timing of temperature stress is crucial; early-stage stress may enhance certain amino acids, while late-stage stress can diminish them.

Some varieties are particularly sensitive to elevated CO_2, while others are more adapted to these changing environmental conditions. Elevated CO_2 alone or in combination with warming reduced shoot plant nitrogen, while root nitrogen was significantly reduced only by elevated CO_2 (Jayawardena et al. 2021). Decreased plant nitrogen was greater for woody and non-woody dicots than for grasses, and for legumes than for non-legumes. Protein concentration also decreased with elevated CO_2 in grain but increased with warming, while the association of elevated CO_2 and warming was globally negative on grain protein concentration.

Elevated atmospheric CO_2 has been significantly associated with an overall decrease in protein content of major food crops (Taub et al. 2008). This is often due to dilution effects (increased carbohydrate production) and altered nitrogen metabolism, which shifts the plant's resource allocation away from nitrogen-rich compounds like amino acids. For wheat, barley, and rice, the reduction in grain protein ranged from 10% to 15%. A similar decrease was observed for protein concentration in tubers like potato, whereas a smaller decrease (1.4%) was observed for soy. However, this study did not investigate potential qualitative changes in the different constitutive protein concentrations. Under combined abiotic stresses (e.g., heat + drought), plants undergo metabolic reprogramming, which can lead to shifts in amino acid synthesis pathways. This reconfiguration can affect both the quantity and balance of essential amino acids (Zandalinas et al. 2022).

Plants have developed numerous strategies to mitigate the detrimental impact of temperature stress. Exposure to stress leads to the accumulation of various metabolites, e.g., sugars, sugar alcohols, organic acids, and amino acids. Plants accumulate proline in response to several abiotic stresses, including temperature stress (Raza et al. 2023). Proline abundance may result from *de novo* synthesis, hydrolysis of proteins, reduced utilization, or degradation. Proline also leads to stress tolerance by maintaining the osmotic balance (although it is still controversial), cell turgidity, and indirectly modulating the metabolism of reactive oxygen species. Furthermore, the crosstalk of proline with other osmoprotectants and signaling molecules, e.g., glycine betaine, abscisic acid, nitric oxide, hydrogen sulfide, soluble sugars, helps to strengthen protective mechanisms in stressful environments. The development of less temperature-responsive cultivars can be achieved by manipulating the biosynthesis of proline through genetic engineering.

Fat-soluble micronutrient composition

By increasing the production of carbohydrates in crops, elevated CO_2 concentrations can, in turn, "dilute" crop micronutrient content if micronutrients are not increased concomitantly. Although elevated CO_2 was not associated with modifications in carotenoid (β-carotene, lycopene) concentrations in sweet pepper (Piñero et al. 2017) or spinach (Kumari et al. 2013), it reduced carotenoid content in canola (Qaderi et al. 2006), lettuce (Pérez-López et al. 2015), and sweet potato (Lu et al. 1986). Overall, a recent meta-analysis estimated that elevated levels of atmospheric CO_2 could decrease plant carotenoid concentrations by 15% (95% CI: −26% to −6%), a decrease driven by mechanisms that can be classified as passive (e.g., dilution by carbohydrates) or active (e.g., lower carotenoid synthesis)(Loladze et al. 2019). Again, such results can be very variable depending on the plant considered. For instance, in *Panicum maximum*, a widespread fodder plant, warming treatment induced a 58% decrease in α-tocopherol contents, while carotenoid composition (zeaxanthin and β-carotene) was not altered by elevated CO_2 and warming (Approbato et al. 2023). Such modifications may impact both meat and milk quality from stocks fed with this plant.

Because they are involved in the photosynthesis process, carotenoids are likely to be impacted by factors including sun exposure. Sun's UV index was positively associated with provitamin A carotenoid levels in selected plantain cultivars that are a popular starchy staple grown in the humid tropics, where micronutrient deficiency is prevalent (Dzomeku et al. 2020).

Similarly, vitamin D content in meat, milk, or eggs is expected to increase with sun exposure of cattle (Hodnik et al. 2020) and hens (Kühn et al. 2014).

Mineral composition

Recent literature extensively supports the notion that climate change, particularly elevated CO_2, significantly influences the concentrations of minerals in various plants, including wild species, fruits, vegetables, and grains (Semba et al. 2022; Loladze 2014; Owino et al. 2022).

According to a meta-analysis performed on 7 761 pairs of observations covering 130 species and cultivars, both FACE and non-FACE studies consistently revealed reduced levels of P, K, Ca, S, Mg, and Zn (average decline ranged from 6.1 to 8.7% for all minerals except for Mn) in foliar and edible parts of herbaceous plants and crops, including wheat and rice (Loladze 2014). A higher impact might have been observed in the FACE studies if the average concentrations of CO_2 ($[CO_2]$) had been similar between the two types of experiments ($[CO_2]$ was approximately 560 ppm in FACE studies and around 732 ppm in non-FACE studies). Similarly, reductions in Fe concentrations were also observed in wheat grains under elevated CO2 conditions (Semba et al. 2022). This decline in mineral content is not dependent on location: aside from small centers in Bangladesh, Japan, and the United Kingdom, mineral reductions were observed consistently across the four continents (Loladze 2014). Although a study analyzing legumes and leafy vegetables showed no alterations in Fe and vitamin C levels under elevated CO_2 conditions (Scheelbeek et al. 2018), another research confirmed significant reductions in Fe levels under elevated CO_2

for leafy vegetables (−31%), fruit (−19.2%), and root vegetables (−8.2%), along with decreases in Zn levels (−10.7% in stem vegetables, −18.1% in both fruit and root vegetables) (Dong et al. 2018).

Mechanisms behind the decline in mineral content associated with elevated CO_2 remain unclear. One theory proposed is the dilution effect, as previously mentioned for carotenoid content. It is theorized to be connected to decreased canopy transpiration or alterations in metabolite or enzyme levels, leading to a decrease in micronutrient concentrations in the food item. Additionally, enhanced photosynthesis may lead to larger crops, yet with unchanged (and therefore diluted) micronutrient content. Myers and colleagues conducted a study quantifying proteins, minerals, and antinutrients like phytates in C3 grasses, legumes, and C4 grasses. C3 plants perform dark reactions in photosynthesis through the Calvin cycle, while C4 plants perform dark reactions in photosynthesis through the Hatch-Stack cycle: C4 photosynthesis is more efficient than C3 photosynthesis in warmer climates. Myers and colleagues' experimental results did not support the proposed theory, as there was a heterogeneous decrease in quantities across different minerals that were not consistently similar for a specific crop, indicating a more complex relationship (Myers et al. 2014). It has also been shown that nourishment with nitrogen and variations in climate may modulate the response to elevated CO_2 levels in protein, Fe, and Zn concentrations. This suggests that factors like mineralization should be considered to gain a deeper comprehension of this regulating role (Dier et al. 2020).

Elevated temperatures predominantly seem to negatively impact crop yields, rather than mineral concentrations (Semba et al. 2022). However, the combination of elevated CO_2 with elevated temperature offsets the reductions in the concentrations of Zn, P, and Mg (in wheat) and of Fe and Cu (in rice) observed when the elevated CO_2 is studied as an isolated factor (Wang et al. 2020). Indeed, the simultaneous application of both factors led to an increase in several minerals (Mn, Mo, Cr, Ni, Pb for both wheat and rice, plus Cu and Cd for wheat). Unfortunately, increased concentrations of certain heavy metals under these conditions raise toxicity concerns (Semba et al. 2022). An increase in Ca, S, Mg, P and Mn contents in oat grass was observed under both elevated CO_2 and temperature (Tang et al. 2022), but these results should be confirmed *in vivo*. Another review summarized the evidence about the combined effects of elevated CO_2 and drought stress (which is associated with elevated temperatures) and highlighted that both factors reduced Zn content in wheat (Zahra et al. 2023). The same authors reviewed the effect of salinity stress in wheat, concluding that the content of several minerals, including K, Ca, P, Fe, Mg, and Zn, significantly declined. Among vegetables, fruits, and legumes, such as lentils, fava beans, soybeans, and field peas, elevated CO_2 seems to alter their Zn and Fe contents. Elevated temperature combined with elevated CO_2 was only studied for soybeans, showing no observable relationship with the concentrations of both minerals (Zn and Fe).

Finally, some studies have explored the effects of elevated ozone, both with or without elevated CO_2, on crops such as rice, potato, and wheat (Semba et al. 2022). In a particular variety of potato, the combination of both factors reduced Zn, Fe, Mg, K, and Cu contents (Kumari and Agrawal 2014). In rice, simultaneous application of both factors showed no effect on the concentrations of K, Mg, P, Zn, Cu, and Mn (Wang et al. 2014). Nevertheless, under elevated CO_2, a significant reduction was observed for Zn and Cu, while elevated ozone conditions resulted in a significant increase, suggesting a potential neutralizing effect between the two factors (Wang et al. 2014). Regarding wheat, isolated exposure to elevated ozone increased Zn, P, K, Mg, Ca, Mn, and Cu quantities, with inconclusive results for Fe, Na, and Se (Broberg et al. 2015).

Overall, it seems that C4 crops are more resilient to mineral decline than C3 plants and legumes. While Zn and Fe were significantly reduced in all C3 plants tested, in maize (a C4 plant) only Fe content was reduced, and in sorghum (also a C4 plant) no change was observed (Myers et al. 2014). The authors rely on plant physiology to justify these differences. C4 plants concentrate CO_2 internally, causing photosynthesis to become CO_2-saturated even under ambient conditions. Consequently, there is no stimulation of photosynthetic carbon assimilation at elevated CO_2 levels under moderate growing conditions.

Phenolic compound composition

Polyphenol content in plant-based foods varies in quantity and quality, since plants generally synthesize them in response to developmental and environmental cues (Sharma et al. 2019). The effects of abiotic stressors vary across crops and varieties. For example, drought stress reduces total polyphenols in tea plants (*Camellia sinensis*) (Safaei Chaeikar et al. 2020; Wang et al. 2016; Ahmed et al. 2019), whereas it increases them in sage (*Salvia officinalis*) (Bettaieb et al. 2011), cumin (*Cuminum cyminum*) (Rebey et al. 2012), and peach (Rahmati et al. 2015). This differential effect of drought stress on polyphenols is known to occur because different plant species and/or cultivars may respond to drought stress by activating different signaling pathways (*e.g.,* abscisic acid-dependent or -independent pathways) based on their genetic background and ability to adapt to various environmental stressors (Ahmed et al. 2019; Rahmati et al. 2015; Nina et al. 2023; Juenger 2013; Soma et al. 2021). In fact, a study on nine different bean cultivars (*Phaseolus vulgaris*) showed varied responses to water deficit that differentially modulated the levels of phenolics, flavonoids, proanthocyanidins, and anthocyanins. This was also reflected in the ability of polyphenol-rich bean extracts to inhibit enzymes associated with metabolic syndrome, including α-glucosidase, α-amylase, and pancreatic lipase (Nina et al. 2023). Similarly, the grapevine cultivars Chardonnay and Cypriot Xynisteri responded differently to drought and heat stress, with Xynisteri showing better adaptation in terms of increased total phenols, flavonoids, and antioxidant capacity (Tzortzakis et al. 2020).

Although it is well known, especially for grapevine, that different genotypes respond variably to abiotic stress, there is a general consensus linking high temperatures to reduced anthocyanin content in grape berries (Rienth et al. 2021), probably due to increased degradation by peroxidase rather than inhibition of their biosynthesis (Movahed et al. 2016; Pastore et al. 2017). This indirectly leads to a reduction of anthocyanin bioavailability and health-promoting activities (Cappellini et al. 2021; Zhou et al. 2022). However, a study on Australian wines from two climatically distinct years, El Niño in 2008 and La Niña in 2009 in Australia, revealed that, despite the expected reduction in anthocyanins, wines from warmer climates revealed decreased antioxidant capacity *in vitro*, but maintained it *ex vivo* in red blood cells (Stockham et al. 2013). Besides temperature, water availability, and CO_2 concentration, alone or combined, differently affected grapevine anthocyanins. While water deficiency alone reduced anthocyanins, its combination with high temperature and elevated CO_2 reduced the total polyphenolic index without altering anthocyanin content in the Tempranillo cultivar (Kizildeniz et al. 2015; Kizildeniz et al. 2018). Similarly, ambient temperature combined with high CO_2 levels increased anthocyanin content in Tinto Velasco musts, while in Ambrosina musts, they increased polyphenol levels without affecting anthocyanins (Goicoechea et al. 2021).

High temperatures are inversely correlated with anthocyanin accumulation in apples and olives, particularly at lower altitudes (Lin-Wang et al. 2011; Ferrari et al. 2023). However, high temperature, alone or combined with high CO_2 concentration and water deficit, are positively correlated with strawberry anthocyanins, flavonoids, and polyphenols. This may increase the antioxidant capacity (Wang and Zheng 2001; Balasooriya et al. 2019; Rugienius et al. 2021; Perin et al. 2019; Adak et al. 2018) and, in turn, the health-beneficial effect of strawberries and other berries in the context of climate change (Miller et al. 2019). Alaskan wild berries, adapted to an extreme annual climate with wide temperature fluctuations, are rich in anthocyanins and show hypoglycemic activity in a type-2 diabetes model (Kellogg et al. 2010). UV radiation can also influence berry anthocyanins by inducing flavonoid accumulation. While bilberries accumulate anthocyanins even when in 90% shade, blackberries require direct sunlight to increase anthocyanin levels (Zoratti et al. 2015). Of note, an increasing content of polyphenols does not necessarily imply a stronger health-promoting activity. Tomato peel extract obtained from drought-stressed plants showed a higher total polyphenol content compared to the extract from plants grown under optimal conditions (Cesare et al. 2021). However, their antioxidant activity in an *in vitro* model of human endothelial vascular cells (HUVEC), their ability to permeate excised rat intestine, and their protective effect in an *in vitro* model of sarcopenia were comparable for both extracts (Cesare et al. 2021; Felice et al. 2022).

Glucosinolate composition

Plants often produce GLSs as a defense mechanism, and water stress can trigger their production in response to perceived threats (Khan et al. 2011). However, the effect of drought on GLS content varies among plant species, and some may respond with higher GLS production, while others may not show a significant change (Ben Ammar et al. 2023; Sun et al. 2020). Examining the GLS content in three Cruciferae species (*B. oleracea*, *B. rapa*, and *Raphanus sativus*) has unveiled a significant correlation between low 10-day average rainfall during the vegetation period and increased GLS levels. However, the impact of water supply on GLS content within the Brassica genus suggests a complex response to water availability, influenced by various environmental determinants (Ciska et al. 2000). Reduced rainfall consistently increases methylsulphinylbutyl-GL and methylsulphinylbutyl-isothiocyanate in most Brassica species, suggesting water scarcity stimulates their biosynthesis as a stress response (Ilahy et al. 2020).

Temperature fluctuations can influence GLS levels in plants. Elevated temperatures may lead to higher GLS content, although the timing of thermal stress during plant growth plays a critical role. Early exposure to high temperatures can increase GLS accumulation, whereas late-season heat stress may decrease GLS content (Kourani et al. 2022). In contrast, elevated CO_2 levels can lead to a reduction in GLS content in some plants, potentially due to alterations in internal resource allocation (La et al. 2009). Additionally, salinity stress has been reported to increase GLS accumulation, especially when stress levels exceed the plant's tolerance threshold (del Carmen Martínez-Ballesta et al. 2013). Finally, ultraviolet (UV) irradiation has recently emerged as a potential alternative to currently used post-harvest treatments. Although UV light has been shown to promote the production of certain flavonoids, vitamin C, and to increase antioxidant capacity and modify the activity of some peroxidases in some brassica vegetables (Darré et al. 2017; Neugart et al. 2014; Topcu et al. 2015), little is known about its effects on GLS and isothiocyanates. Most of the available evidence is focused on broccoli, showing an increase in GLSs following UV-B treatments (5–15 kJ/m^2), while knowledge on other crucifers is lacking.

Climate change and (micro)nutrient/bioactive bioavailability during the digestion-absorption process

The bioavailability of (micro)nutrients is influenced by multiple factors, with interactions between dietary components and with the food matrix playing a critical role. Consequently, new food choices or climate change-driven modifications in food composition could significantly impact the digestion, as well as the bioavailability and metabolism of macro- and micronutrients.

Amino acid bioavailability

The nutritional quality of dietary protein depends on 2 factors: its amino acid profile and its digestibility. A high-quality protein must provide a well-balanced profile of amino acids, especially the indispensable (essential) ones, and be efficiently digested and absorbed by the body. These 2 factors form the basis of widely used protein quality assessment methods. One such method, the Protein Digestibility-corrected Amino Acid Score (PDCAAS) was adopted in 1993 by both the United States Food and Drug Administration (US FDA) and the FAO/World Health Organization (WHO) as "the preferred" standard for evaluating protein quality (Boutrif 1991). However, recognizing limitations in PDCAAS, FAO proposed a more refined method in 2013: the Digestible Indispensable Amino Acid Score (DIAAS). The DIAAS calculates protein quality based on the amount of digestible essential amino acids (EAA) per g of dietary protein relative to an "ideal" reference protein. DIAAS offers a more accurate reflection of amino acid bioavailability and is increasingly considered a superior tool for assessing the nutritional value of proteins in bolth single and mixed sources.

A shift from an animal protein-based diet to a plant protein-based diet impacts amino acid bioavailability. Indeed, in the main cereal crops, lysine is the first limiting EAA, and the sulfur-containing amino acids (SAA: methionine and cysteine) are usually the first limiting EAA in the legume crops. Although there are exceptions where tryptophan (e.g., haricot beans, split yellow peas, chickpea, pinto beans) or lysine (black-eyed peas) is the first limiting EAA, it should be noted that plant proteins also have lower branched-chain amino acid (BCAA) (isoleucine, leucine, valine) and tryptophan scores than most animal proteins (Table 1).

DIAAS of several protein sources has been recently reviewed (Poutanen et al. 2022). Cereal grain proteins exhibited DIAAS ranging from 7 to 77, with lysine always being the limiting amino acid. Legumes were characterized by higher values (73–105 with SAA as the limiting ones), and animal proteins (from meat and milk) exhibited high values ranging from 99 to 141 (with valine, leucine, histidine, or SAA as limiting amino acids).

In addition to the content and profile of EAA, the quality and nutritional value of the protein is affected by the true ileal digestibility of the protein. Plant protein, in its natural form, generally has lower digestibility than animal protein (75–80% vs. 90–95%), due to stronger cell walls, seed-coats, and microstructural arrangement of the protein (e.g., protein cross-linking, secondary beta-conformation, and protein chain rigidity), antinutritional factors (e.g., protease inhibitors, lectins, glucosinolates, tannins, phytic acid), and a high non-protein component (e.g., insoluble dietary fiber and non-starch polysaccharides) (Almeida Sa et al. 2020; Gilani et al. 2012; Mongeau et al. 1989). However, prior to human consumption, most plant foods undergo some form of domestic or commercial processing—usually performed to increase shelf-life, palatability, and/or change some other functional properties of the food (e.g., solubility, binding capacity, texture, color) rather than to increase nutritional value (Almeida Sa et al. 2020). Nevertheless, processing methods can also be used to improve the digestibility, and thus, the quality and nutritional value of plant protein (Almeida Sa et al. 2020; Gilani et al. 2012).

Fat-soluble micronutrient bioavailability

Fat-soluble micronutrientbioavailability can be modulated by other food compounds. For instance, decreases in fat-soluble micronutrient transfer to mixed micelles during digestion (i.e., micronutrient bioaccessibility) and/or intestinal absorption have been documented in the presence of polyphenols (Reboul et al., 2007; Reboul et al., 2007; Goncalves et al. 2016), antinutrients including phytates and saponins or tannins (Margier et al. 2019; Antoine et al. 2021), phytosterols (Goncalves et al. 2011), fiber (Margier et al. 2019; Antoine et al. 2021), certain fatty acids (Goncalves et al. 2013), or other fat-soluble micronutrients (Tyssandier et al. 2002; During et al. 2002; Reboul et al. 2005; Reboul et al. 2006; Reboul et al. 2011; Goncalves et al. 2014; Goncalves et al. 2015; Wang et al. 2010). Increases in those compound contents can thus modulate fat-soluble micronutrient bioavailability.

Antinutrients

A study showed that under water stress (i.e., restriction of the water supply till 25% field capacity is reached), phytate content in lentil was increased by 32% (Bansal et al. 2023). Among all the different stresses that can be caused by climate change (elevated CO_2, heat, drought, salinity), a review confirmed that heat stress and drought stress were the most impactful in terms of increasing phytate content in wheat (Zahra et al. 2023). However, the impact of climate change on phytate content likely depends on the crop genotypes. For instance, in sorghum, the growth temperature could lead to either an increase or decrease in phytate content depending on the genotype studied (Wu et al. 2016).

Table 1. Amino acid content in selected protein sources.

	Content in g/100 g protein					
	SCP Saccharomyces cerevisiae	Insects Acheta domesticus	Algae Arthrospira platensis	Potato	Beef	FAO pattern
Histidine	0.79	3.13	1.13	2.20	4.06	1.50
Isoleucine	2.12	3.93	3.64	5.47	4.30	3.00
Leucine	4.35	6.31	6.17	9.97	8.21	5.90
Lysine	3.14	5.71	3.40	7.72	9.07	4.50
Methionine	1.31	1.87	1.71	2.22	1.68	1.60
Phenylalanine	3.21	3.17	3.33	6.02	4.17	3.80
Threonine	2.49	3.85	3.31	5.38	4.71	2.30
Valine	3.83	5.20	4.21	6.23	4.60	3.90
Tryptophan	2.75	0.85	0.85	1.43	ND	0.50

From A. Grden & B.G. Sołowiej (2022)(288).

Fiber

Fiber content in crops is highly sensitive to agro-climatic conditions, as shown by a study performed on potatoes (Thomas et al. 2021). Azam and colleagues showed that elevated atmospheric CO_2 led to an increase in fiber content of root vegetables (carrot, radish, and turnip) (Azam et al. 2013). A 50% decrease in nitrogen fertilization level, which can be a strategy to mitigate the impact of crop production on climate change, also induced an increase in crude fiber content in wheat (Wroblewitz et al. 2013). Conversely, a review highlighted that salinity stress was only moderately linked to crop fiber content (Zahra et al. 2023).

The negative effects of foods rich in antinutrients or fiber may be offset by strategies aimed at increasing the bioavailability of fat-soluble micronutrients . This can be achieved by adding food compounds that can positively influence micronutrient bioavailability, such as fat (specific fatty acids, phospholipids), as shown for vitamin E (Reboul 2017). Moreover, although plant-based products can decrease fat-soluble micronutrient bioavailability due to their contents in fiber and antinutrients (Margier et al. 2019; Antoine et al. 2021), recent data suggest that they can also protect fat-soluble micronutrients such as vitamin D from degradation during the digestion process (Antoine et al. 2021; Antoine et al. 2023).

Finally, some new matrices, such as edible insects, appear promising for carotenoid delivery: β-carotene accumulated in black soldier fly larvae was bioavailable in gerbils and capable of improving their vitamin A status (Morand-Laffargue et al. 2023).

Mineral bioavailability

Mineral bioavailability depends on diet composition, food matrix, and food mineral content. A critical aspect of understanding how climate change affects mineral bioavailability also involves examining the climate change impact on food contents in phytates, tannins, and fiber, which are known to significantly influence mineral bioavailability, as previously mentioned.

Antinutrients

Phytate or phytic acid is a negatively charged molecule that binds to positively charged minerals like Zn, Fe, Mg, Ca, K, and Mn (Choukri et al. 2022; Samtiya et al. 2020). This chelating property, mainly driven by inositol pentaphosphate and inositol hexaphosphate, leads to the formation of complexes that reduce minerals' absorption and, consequently, their bioavailability (Wu et al. 2016; Perera et al. 2018). Given the observed increases in phytate content under environmental stress conditions (as discussed above), there is a growing concern about the nutritional implications. For example, wheat exposed to heat and drought stress showed elevated phytate levels, potentially decreasing the bioavailability of essential minerals (Zahra et al. 2023). Similarly, in lentils, phytate content increased by 0.1% under heat stress, adversely affecting the bioavailability of Fe and Zn (Choukri et al. 2022).

While the phytate content in field peas, soybeans, and maize showed no significant change under elevated CO_2, wheat exhibited a notable decrease of 4.2%. Conversely, rice and sorghum experienced increases of 1.2% and 12.8%, respectively, under elevated CO_2 conditions (Myers et al. 2014). These findings suggest that the response to climate change variables can be species-specific and complex.

Similarly to phytic acid, tannins can (also) bind to positively charged cations, lowering their bioavailability. Wu and colleagues studied the impact of high temperature on the tannin content in six different sorghum genotypes. High temperatures significantly reduced the tannin content in all genotypes. These authors also explored the *in vitro* Fe availability and observed that in five out of six sorghum genotypes, the availability of Fe decreased significantly under high temperature conditions, meaning that factors other than tannin content reduced Fe availability (Wu et al. 2016).

Fiber

Concerning dietary fiber, the lower mineral absorption might be related to a decrease in their migration rate to the intestinal lumen due to the thickening property of viscous fiber. Nevertheless, dietary fiber, particularly non-digestible oligosaccharides, is also known to promote the production of vitamins and short-chain fatty acids by the intestinal microbiota, which may enhance mineral absorption (Baye et al. 2017).

Polyphenol bioavailability

Polyphenol bioavailability can be influenced by macro- and/or micronutrients in the food matrix or when simultaneously consumed. Proteins, in particular, generally reduce polyphenol bioavailability (Zhang et al. 2014). A well-known example is milk consumption with tea or coffee, a Western habit that is reported to reduce the health-promoting activity of polyphenols due to their binding to caseins (Serafini et al. 1996; Sharma et al. 2008; Tagliazucchi et al. 2012). A similar effect was also reported for soy proteins (Rawel et al. 2002; Sengul et al. 2014) and should be considered when switching to milk substitutes (*e.g.*, rice, oat, soy, and almond drinks).

Similarly, polyphenol binding with food fiber, which is expected to rise in crops in a climate change scenario (Thomas et al. 2021; Azam et al. 2013), is reported to have detrimental effects on polyphenol bioavailability (Bohn 2014). Conversely, carbohydrates, which are expected to generally increase in plants exposed to abiotic stresses (Du et al. 2020), may enhance polyphenol absorption, improving their bioavailability (Zhang et al. 2014; Bohn 2014; Gonzales et al. 2015).

Glucosinolate bioavailability

High temperatures can degrade vitamin C, which stabilizes myrosinase activity (Bones and Rossiter 2006), potentially influencing GLS absorption and metabolism (Frandsen et al.

2019). Myrosinase stability is also influenced by factors such as temperature and pH, by affecting its effectiveness in converting GLSs into isothiocyanates (Mikkelsen et al. 2000). Low soil pH levels, often exacerbated by acid rain, enhance Fe availability in the plant tissues (Aripin and Surugau 2016). However, elevated Fe concentrations can disrupt GLS bioavailability by shifting hydrolysis toward the production of nitriles instead of isothiocyanates.

Elevated temperatures and extended growing seasons can lead to increased fiber content in Brassicaceae, likely as a defense response (Saleem et al. 2023). Dietary fiber may disrupt bacterial GLS metabolism in the cecum, as observed in gnotobiotic rats with human-like gut microbiota (Rungapamestry et al. 2007). Chronic consumption of non-starch polysaccharides leads to cecal acidification, potentially affecting bacterial myrosinase activity and GLS derivatives. Moreover, insoluble dietary fiber can obstruct enzymatic access to GLS, reducing hydrolysis efficiency and consequently lowering the bioavailability of GLS breakdown products (Zhao et al. 2022).

The growing use of organic fertilizers as an alternative to conventional ones has also been shown to influence GLS bioaccessibility (Martínez-Castro et al. 2023; He et al. 2023; Kitamura et al. 2021). Indeed, isothiocyanate bioaccessibility in cruciferous seeds was found to be extremely low, while the bioaccessibility of total GLSs in the green tissues of the plants was high, with average values exceeding 50% of the initial GLS content, for both cultivation systems.

Finally, the ratio of individual GLSs within plants can modulate their bioavailability. Preconditioning plants to drought could confer them a degree of resilience against subsequent heat and drought stress during later stages of development (Abellán et al. 2021). The distinct responses of aliphatic and indole GLS to various treatments may be attributed to disparities in their biosynthetic pathways. Notably, indole GLS and indole-3-acetic acid share a common intermediate, potentially rendering them competitive in terms of biosynthesis (Kambona et al. 2023).

Undoubtedly, plants possess the capacity to adjust both their primary and secondary metabolic pathways in response to individual or combined stress factors. This metabolic flexibility enables them to redirect energy and resources away from growth and reproduction toward mechanisms that support stress tolerance, which is vital for their survival (Lyu et al. 2021).

Impact of sustainable processing on nutrient and micronutrient/bioactive bioavailability

Most processing methods (milling, soaking, cooking, as well as ancestral techniques like fermentation or germination) are able to improve plant protein digestibility (Almeida Sa et al. 2020; Nagra and Bhatty 2007), as well as the bioaccessibility and bioavailability of carotenoids (Reboul 2019), minerals (Samtiya et al. 2020; Hefnawy 2011; Lestienne et al. 2005), and GLSs (Jones et al. 2010; Cieslik et al. 2007). These beneficial effects are either due to a disruption of the food matrix or a partial removal of antinutritional factors that can hamper digestion. Conversely, food processing can greatly reduce food polyphenol content (Ficco et al. 2020) as polyphenols can be degraded, lost in water, or removed with by-products (skin, bran…).

The food industry is under increasing pressure to develop processing technologies that preserve food nutritional quality and safety, while being environmentally friendly and meeting consumers' demands in terms of sensory properties (Barba et al. 2019). Several conservation or cooking techniques have emerged during the past decades, including microwaves, pulsed electric fields (PEF), high-pressure homogenization (HPH), high-pressure processing (HPP), and ultrasounds (US). These techniques allow processing vegetables without an important increase in the product temperature, avoiding an excessive deterioration of the product. Fermentation and sprouting have gained renewed attention due to their ability to improve food nutritional quality and shelf-life at low cost.

Protein bioavailability

Bioprocessing technologies like germination, malting, or fermentation have been shown to improve the proteins, amino acids and bioactive compounds profiles of quinoa, as well as decreae the content of antinutritional compounds (Vicente-Sánchez et al. 2024). Other industrial processing methods (e.g., milling, microfiltration, alkali-solubilization, acid precipitation, centrifugation, flocculation, fractionation, enzymatic-hydrolysis, ultra-heat treatment, and spray-drying) can increase protein digestibility of peas and other plants up to 97%. The effect of different processes on pulse *in vitro* protein digestibility has been recently reviewed by (Bessada et al. 2019) and is summarized in Table 2.

The way peptides and free amino acids can be released from the food microstructure influences digestibility and nutritional value. For plant protein, complete elimination of the microstructure and the non-protein components (insoluble dietary fiber and non-starch polysaccharides) appears to enhance digestibility and protein quality (Rutherfurd et al. 2015). Therefore, the role of the food structure, the nutritional value of the non-protein components, and their interaction with protein must be considered (collectively termed the food matrix effect) (Turgeon and Rioux 2011). The food matrix effects can be synergistic or antagonistic, defined by the desired outcome of the diet. For example, dietary fiber and antinutritional factors contained in plant-based foods generally reduce digestibility and protein quality (Gilani et al. 2012; Mongeau et al. 1989). However, dietary fiber is considered beneficial for other health-related aspects (e.g., gastrointestinal function, immune function, lipid and glucose metabolism)(Almeida Sa et al. 2020). Plant antinutritional factors such as glucosinolates, tannins, and phytic acid act in a similar manner. They can interfere with the absorption and utilization of proteins, yet they also exhibit beneficial properties, including antioxidant, anti-inflammatory, and antibacterial effects (Gilani et al. 2012). With the appearance of new alternative proteins on the market, the design of protein blends will bring new research challenges as the interactions and the structure formation modulated by proteins

Table 2. Crude protein and IVPD (*in vitro* protein digestibility) in raw and processed pulses.

Pulse	Crude protein (%)	IVPD (%) raw	IVPD (%) processed
Bean	24.75%–28.12%	70.53%–78.04%	Soaking: 75.96%–83.20% Boiling: 87.36%–94.15% Roasting: 64.92%–72.97% Autoclaving: 78.95%–86.10% Microwave: 81.66%–88.63% Fermentation: 73.43%–80.85% Micronization: 67.90%–75.51%
Pea	21%–23.3%	78.40%–80.12%	Soaking: 83.74%–85.46% Boiling: 94.33%–95.78% Roasting: 73.06%–74.96% Autoclaving: 86.55%–88.27% Microwave: 89.08%–90.89% Fermentation: 81.39%–82.93% Micronization: 75.96%–77.86%
Chickpea	17%–22% 25.3%–28.9% (dehulled)	34%–76% 83.61% (flour)	Boiling: 88.52% Autoclaving: 89.96% Microwave cooking: 89.40%
Lentil	23.86%–29.2%	75.90%–77.05% 85% (flour)	Soaked flours: 85.5% Soaked and cooked flours: 91.7% Soaked, cooked and dehydrated flours: 95.5% Germinated seed: 75.1% Dehulled germinated seed: 78.8%
Faba bean	26.6%	73.28%–80.1%	Dehulling: 73.86% – 75,42% Soaking (12, 24, 36, 48 h): 73.88%, 74.21%, 74.22%, 74.31% Microwave: 74.56%–75.80% Cooking: 74.10%–78.65% Cooking, soaking, dehulling: 80.21% Autoclaving: 76.30%–78.55%
Lupin	29.33%–39.71%	68.26%–89%	Boiling: 68%
Cowpea	22%–30%	72.2%–74.8%	Soaking: 82%–85% Cooking: 88%–92% Autoclaving: 91%–95%

From Bessada et al. (2019).

are unknown and specific to each matrix composition and the process used. How these protein structures will be hydrolyzed by digestive enzymes in the gastrointestinal tract remains unknown, as well as the consequences of the release of amino acids during digestion.

A very active field of research focuses on the creation of viable meat protein analogues, which requires the formation of fibrous structures from alternative proteins through processing. Methods such as electrospinning, selective precipitation, or extrusion can create anisotropic protein structures (Mattice and Marangoni 2020). During extrusion, proteins are treated at high concentrations, together with other components, and subjected to denaturation and aggregation by the concurrent effect of heat and shear (Dekkers et al. 2018). Extrusion technologies have proven effective in improving nutritional properties of plant-based foods by decreasing the activity of antinutritional factors in complex matrices containing peas, faba, kidney beans, and sorghum (Corredig et al. 2020). This process may also improve protein digestibility through both the inactivation of these antinutritional factors and the modifications of protein structures. The development of new ingredients from alternative protein sources will require processing technologies adapted to the raw material characteristics and the level of purity expected. Dry separation or cold pressing technologies have been proposed as sustainable solutions to obtain protein concentrates. They result in less-refined ingredients in which the original cellular structure of the raw materials is to some extent maintained, creating some challenges. Pretreatments or post-treatments such as soaking, fermentation, or enzymatic hydrolysis, electrostatic separation, and superfine powder production can decrease the presence of antinutritional factors, the amount of insoluble fiber, and improve functionalities such as dispersibility or flavor (Adjei-Fremah et al. 2019; Barakat et al. 2015; Primozic et al. 2018). Nevertheless, new research will be needed to determine whether these less refined ingredients exhibit the same digestibility compared to more purified protein isolates. A whole systems approach requires enhanced attention to these aspects, to be able to suggest choices of protein sources for future value.

Fat-soluble micronutrient bioavailability

A recent study showed that HPP did not significantly increase kale vitamin E bioaccessibility (Schmidt et al. 2021). Furthermore, several publications showed that PEF could either increase or decrease selected carotenoid bioaccessibility depending on the PEF intensity (González-Casado et al. 2018; Bot et al. 2018; Jayathunge et al. 2017; Zhong et al. 2019). HPH of mandarin (Sentandreu et al. 2020) or tomato juice and pulp (Zhang et al. 2019) also led to conflicting results. US of tomato pulp led to a decrease in lycopene bioaccessibility (Anese et al. 2013), although this may depend on the presence of oil (Anese et al. 2015). In contrast, it led to an increase in carotenoid bioaccessibility in mango byproducts (Mercado-Mercado et al. 2018). Overall, it is impossible to draw generalizable conclusions for such processes, as their specific effects on carotenoid bioaccessibility should be evaluated for each food matrix considered (see for review (López-Gámez et al. 2021)).

All the processes aiming at decreasing the antinutritional content of foods such as pulses may also promote fat-soluble micronutrient bioavailability. Among these processes, the most common are soaking, blanching, cooking, as well as sprouting the grains. However, previous results showed that even though optimizing these different steps can lead to significant reductions in antinutrient levels, this was insufficient to restore vitamin D bioaccessibility (Antoine et al. 2022). Conversely, germination of sesame seeds showed that this process could increase both the conversion of γ-tocopherol to α-tocopherol and tocopherol bioaccessibility (Li et al., 2020).

Finally, fermentation may be of interest as it is characterized by moist, warm, and acidic conditions. This creates an optimal environment for enzyme activation and fermentation is thus a recognized strategy to decrease antinutrient levels (Samtiya et al. 2020). A clinical study in 7 healthy volunteers showed that the ingestion of a product obtained following the alcoholic fermentation of orange juice led to an increase in β-cryptoxanthin absorption (Hornero-Méndez et al. 2018), likely in relation to the modification of the food matrix. Such an effect is probably not limited to the fermentation of the micronutrient source, as a recent clinical trial showed that exopolysaccharides from milk fermented by lactic acid bacteria enhanced dietary carotenoid bioavailability in humans in a randomized crossover trial and in rats (Morifuji et al. 2020).

Mineral bioavailability

The impact of different processing methods on the mineral composition and antinutritional factors in lentils was reviewed in (Hefnawy 2011). The findings revealed that microwave cooking resulted in a lesser reduction in the values of Ca, Mg, K, Na, P, Fe, and Cu compared to boiling and autoclaving, recommending microwave cooking as a preferable method for preparing lentils, as it not only enhances the nutritional quality but also reduces the cooking time. The use of the novel processing technique of sonication significantly increased the mineral contents (Na, K, Ca, P, Mg, Cu, and Zn) of apple juice (Abid et al. 2014). Finally, HP processing of milk and soy smoothies showed no significant changes in mineral contents (Na, K, Ca, Mg, Fe, Cu, Zn and Mn) after the treatments and storage (Andrés et al. 2016).

Phenolic compound bioavailability

Alternative milling methods, such as micronization and microfluidization, can help preserve polyphenol content in flours (Kasote et al. 2021; Mert 2020). Additionally, methods like debranning/pearling and air-classification can select bran fractions rich in polyphenols (Ficco et al. 2018). Microfluidization increases the specific surface area more effectively than traditional grinding (Raghavendra et al. 2006). During microfluidization, suspended particles undergo high shear stress, impact force, and hydrodynamic cavitation, leading to size reduction. The subsequent particle expansion creates pores or cavities, which increase the bioaccessibility of polyphenols bound to or entrapped in the bran matrix, thus potentially improving their bioavailability (Wang et al. 2013; Wang et al. 2014).

Furthermore, high hydrostatic pressure was found to preserve polyphenols in tomato purees (Patras et al. 2009) and to increase their content and bioaccessibility in chili pepper when combined with a mild thermal treatment (Andrés et al. 2016), thus indicating that, by using reduced heat and/or shorter processing times, the loss of polyphenols during processing may be reduced, preserving their bioavailability.

Supercritical carbon dioxide (SCCD) is a promising alternative to thermal heating for fruit juice preparation, being a safe (*i.e.,* nontoxic and non-flammable) and inexpensive method of food preservation. SCCD inhibits juice browning by inactivating polyphenol oxidase or peroxidase, which are tissue enzymes released during fruit processing. SCDD improves the stability of vitamin C, total anthocyanins, and antioxidant capacity of blackcurrant juice before *in vitro* digestion. It also increases the bioaccessibility of anthocyanins (i.e., delphinidin 3-O-glycosides) and antioxidant capacity upon *in vitro* digestion compared to thermal treatment at 45 °C and pasteurization at 85 °C (Trych et al. 2022).

During the fermentation process, microbial strains belonging to *Lactobacillus* spp. and *Saccharomyces* spp. can improve polyphenol bioaccessibility (Shiferaw Terefe and Augustin 2020). Thank to hydrolytic activities (e.g., cellulase, amylase, lipase, esterase, tannase and glucosidase), beneficial microorganisms are potentially able to break matrix-bound components, enhancing polyphenol bioaccessibility and consequently polyphenol bioavailability (Rodríguez et al. 2009). In addition, the fermentation process may enhance the biological properties of the final fermented matrix by stabilizing polyphenols or releasing free and simpler polyphenol-derived compounds with improved health-beneficial properties. As an example, fermentation of broccoli puree determined the hydrolysis of chlorogenic acid into caffeic acid, which is better absorbed than chlorogenic acid itself (Filannino et al. 2015; Olthof et al. 2001). Furthermore, fermentation of cherry juice by *L. plantarum* converted caffeic acid into dihydrocaffeic acid, which had a higher antioxidant capacity compared to caffeic acid (Filannino et al. 2015).

Finally, sprouting and germination of grains and seeds can enhance polyphenol bioavailability by activating enzymes that may increase their synthesis and release (Geng et al. 2022; Rastogi et al. 2022). A slight enhancement of polyphenols and flavonoids was observed during the first 4 days of germination in mung bean sprouts (Świeca and Gawlik-Dziki 2015) and in different *Brassicaceae* sprouts (Šamec et al. 2018). Sprouting and roasting increased the bioaccessibility of phenolics from pearl and finger millets (Hithamani and Srinivasan 2014). Being climate-resilient crops, flours prepared from sprouted sorghum, tapioca, and cowpea have been proposed as partial alternatives to wholewheat flour, and to produce composite flours to develop high-quality flatbreads for low-income countries. Indeed, these flatbreads showed a higher content of resistant starch than whole wheat bread and were also richer in phenolic compounds (Marchini et al. 2023).

Glucosinolate bioavailability

GLS bioavailability varies depending on the food matrix, cooking process, vegetable variety and the specific GLS class (Lafarga et al. 2018). Myrosinase, the enzyme responsible for GLS hydrolysis, is temperature-sensitive and is easily inactivated during conventional thermal processing, preventing the formation of more bioavailable and bioactive derivative products. Microwave treatments in some cruciferous vegetables (e.g., red cabbage) showed that low to intermediate microwave powers (e.g., 8–24 min at 180–540 W) retained substantial myrosinase activity, whereas high power microwave cooking (5 min at 900 W) resulted in its complete inactivation (Lafarga et al. 2018; Verkerk and Dekker 2004).

Steaming, by contrast, can increase GLS content by 20–30% by favoring the formation of isothiocyanates over nitriles (Oliviero et al. 2018), and is considered the most effective thermal method for preserving GLSs and myrosinase activity compared to blanching, boiling, or microwaving.

Non-thermal processing technologies like HPP, HPH, and PEF offer promising and sustainable alternative strategies for minimizing the degradation of GLSs during processing. Myrosinase activity was retained following treatments with HPP at 100–600 MPa, though higher pressures reduced activity. At 600 MPa, maximum degradation/conversion of GLSs in cruciferous vegetables was observed. For example, Westphal and colleagues reported that processing broccoli sprouts at 600 MPa resulted in an increase of iberin, sulforaphane, and erucin contents compared to fresh sprouts (Westphal et al. 2017). Similarly, Wu and colleagues showed that HPP at 600 MPa induced irregular crushing damage to kale leaves, enhancing conversion in the myrosinase–GLS–isothiocyanate system (Wu et al. 2022).

Some studies reported that PEF processing may represent a suitable method to promote GLS production in broccoli (Aguiló-Aguayo et al. 2015); however, results are inconsistent, and further research is mandatory. The impact of HPH on GLSs has been evaluated in one published study, which found that sulforaphane extraction from raw broccoli seeds increased with decreasing particle size. However, excessive size reduction did not necessarily result in an increase in sulforaphane content. The highest yield was obtained with HPH at 5000 psi and 5 passes extraction, resulting in a sulforaphane concentration three times higher than the control (Xing et al. 2019).

Fermentation is also widely used to process Brassica vegetables, with sauerkraut from cabbage being the most common product. During fermentation certain lactic acid bacteria strains completely hydrolyze GLSs, leaving only their breakdown products (Šalić and Šamec 2022). Glucobrassicin, one of the most studied GLSs given its potential beneficial properties, is hydrolyzed into indole-3-carbinol and indole-3-acetonitrile (Palani et al. 2016). In the presence of ascorbic acid, indole-3-carbinol can be converted into ascorbigen, the major GLS-derived compound in fermented cabbage (Ciska et al. 2021). At low pH, indole-3-carbinol is unstable and can be converted into 3,3′-diindolylmethane, which, together with ascorbigen, is considered the most potent bioactive compound in cruciferous vegetables (Wagner and Rimbach 2009).

Limitations of the review

The literature search relied on keyword-based queries across selected databases. This approach has several inherent limitations. First, the choice of keywords may not encompass all relevant terms, particularly in interdisciplinary research where terminology can vary. In particular, keywords may miss relevant studies if the terminology is not standardized or if abstracts do not reflect the full content of the studies. Second, the selection of databases may exclude pertinent studies. Additionally, the search was restricted to English-language studies, potentially overlooking valuable research published in other languages. Lastly, publication bias favors studies with positive or significant results, which may skew the overall conclusions drawn from the available literature.

Besides, the heterogeneity of the experimental conditions among the different studies makes a generalization of the results difficult. Moreover, other factors, including soils, agronomic practices, and cultivars, can also highly impact crop composition. In some cases, the selected studies were designed to investigate mechanisms to enhance the quality of crops or to explore exposure-resistant varieties, and in these cases, the environmental exposure levels were not always realistic representations of environmental changes.

It remains difficult to predict which crops will be able to adapt to climate change, as this largely depends on the intensity of the change. As far as proteins are concerned, most research has focused on the link between climate change and the protein content in crops, but beyond quantity, it is vital to understand how climate change will affect protein composition, as this will have a huge impact on the plant's nutritional properties (amino acid profile, digestibility) and its behavior during food processing.

An overview of climate change expected impact on micronutrient content and bioavailability is given in Figure 1. However, strict guidelines to improve (micro)nutrient bioaccessibility/bioavailability cannot be provided since these are dependent on the type and conditions of processing, and of the food matrix composition and structure.

Perspectives of research

The ability of plants to dynamically reprogram their metabolism in response to environmental stress is a cornerstone of their survival strategy. However, this metabolic flexibility—while beneficial for stress acclimation—can have unintended consequences for human nutrition. Shifts in primary and secondary metabolism may lead to increased synthesis of antinutritional factors such as phytates, tannins, and fiber, which in turn impair the bioavailability of essential nutrients including amino acids, minerals, and fat-soluble bioactives. The impact of these changes is also highly context-dependent, varying with crop species, genotype, and the nature of the stress factor. As climate change continues to reshape agro-ecological conditions, understanding these interactions becomes essential. Future strategies must therefore balance plant resilience with nutritional quality. The need for

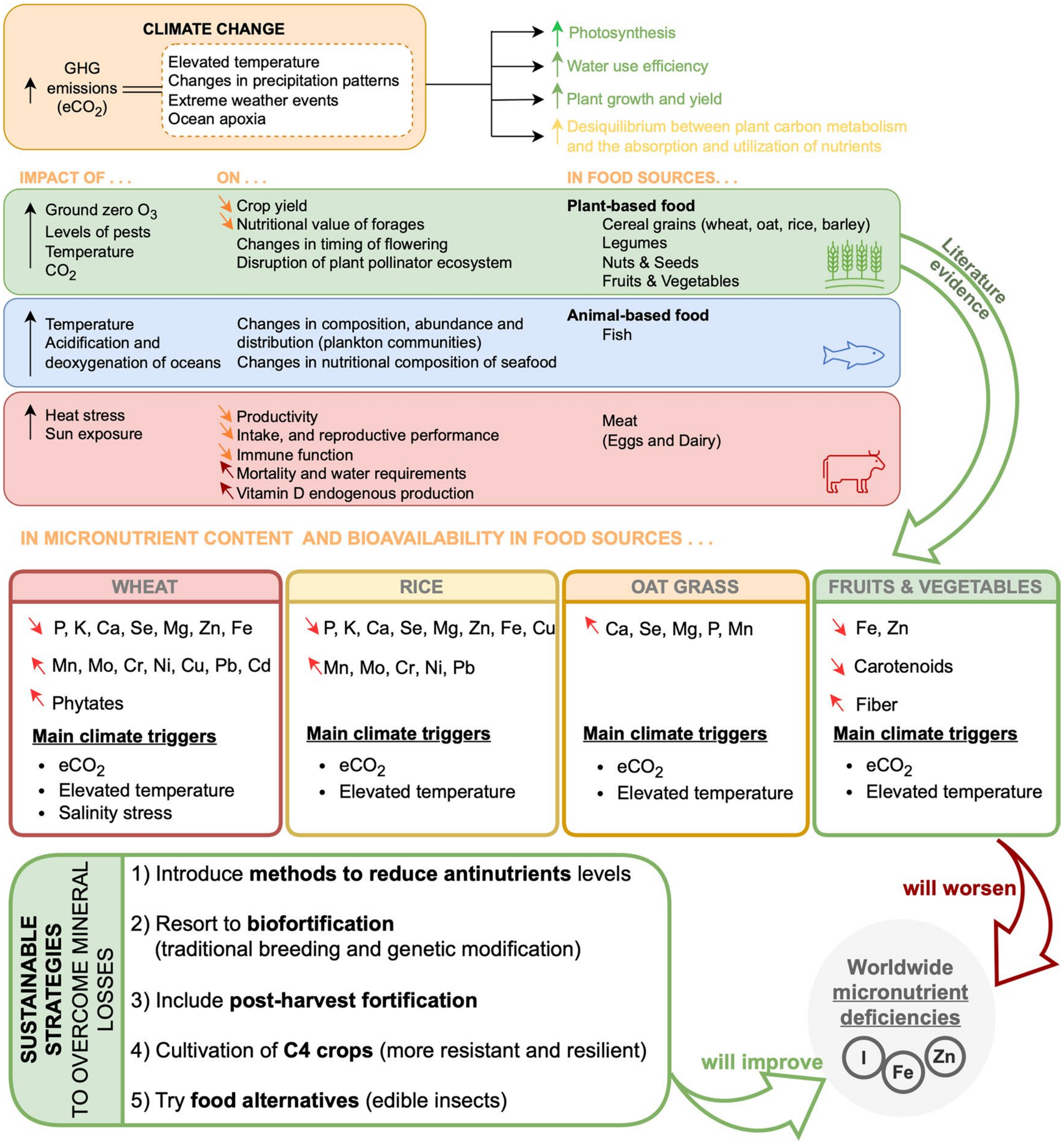

Figure 1. Conceptual framework illustrating the influence of climate change drivers on plant- and animal-based food sources, impacting micronutrient composition and bioavailability, and proposed sustainable mitigation strategies.

Climate change drivers—including elevated atmospheric CO_2, rising temperatures, altered precipitation patterns, and ocean acidification—will impact both plant- and animal-based food systems. These drivers disrupt photosynthesis, water-use efficiency, crop yields, and animal productivity, resulting in changes to the micronutrient composition and bioavailability in cereals, legumes, fruits, vegetables, and animal-based foods (fish, meat, eggs, and dairy). This will likely exacerbate worldwide micronutrient deficiencies. Sustainable strategies to mitigate these micronutrient losses include reducing antinutrients, biofortification, post-harvest fortification, cultivating resilient C_4 crops, and exploring alternative food sources such as edible insects.

GHG: Greenhouse gases; eCO_2: CO2 emissions; O3: ozone; P: phosphorus; K: potassium; Ca = calcium; Se: Selenium; Mg: Magnesium; Zn: zinc; Fe: Iron; Mn: manganese; Mo: molybdenum; Cr: chromium; Ni: nickel, Pb: lead; Cu: copper; Cd: cadmium; I: iodine.

adaptive agricultural practices is crucial as farmers aim to maintain crops amid changing climates. Selective breeding for stress-resistant varieties, adjusting planting schedules, and employing sustainable water management practices are essential strategies. Furthermore, integrating traditional agricultural knowledge with modern science can enhance resilience.

A range of adaptive strategies—from traditional breeding to genome-editing techniques—have been proposed to preserve or improve the bioavailability of micronutrients in foods. Key approaches include biofortifying staple foods (Kumar et al. 2025), improving nutrient absorption by reducing antinutritional factors (Cominelli et al. 2022), and introducing new metabolic pathways to enable plants to produce nutrients they wouldn't normally synthesize such as omega-3 fatty acids (Venegas-Calerón et al. 2010). Biofortification has seen successful applications in various crops like beans, pearl millet, maize, rice, and wheat, each tailored to enhance specific micronutrients like Fe and Zn (Semba et al. 2022; Bouis et al. 2019) or provitamin A carotenoids (Giuliano 2017; Li et al. 2024). However, while many biofortified crops are nearing commercialization, challenges remain in ensuring genetic stability, public acceptance, and regulatory approval.

Within the genetic modification strategy, the development of staple crops tolerant to abiotic stress factors such as drought, elevated CO_2, elevated temperature, and increased soil salinity is also part of the sustainable practices' agenda, and more efforts should be encouraged (Banerjee et al. 2023; Esmaeili et al. 2022; Parmar et al. 2025). Rodriguez and colleagues focused their research on advancements and available resources in genomics to improve nutrient availability in five minor crops and pseudocereals, including finger millet, foxtail millet, quinoa, amaranth, and buckwheat. Through this research work, the authors aimed to increase knowledge about resilient but neglected crops, which have the potential to contribute to food and nutritional security through sustainable agriculture in marginal areas (Rodríguez et al. 2020).

Interventions such as post-harvest fortification and national micronutrient supplementation programs have also shown beneficial impacts on public health. These strategies, potentially more immediate and less resource-intensive than biofortification, are vital in the global effort to improve nutrient intake (Semba et al. 2022; Owino et al. 2022).

The decline in micronutrients under varying climate change scenarios poses significant challenges, especially for C3 plants. Understanding these complex interactions is crucial for developing resilient agricultural practices and ensuring food security in the face of climate change. Toward greater food diversity, one approach is the cultivation of C4 crops rather than C3 crops, to minimize mineral loss in more sensitive crops (Ujiie et al. 2019). Pulses also offer a sustainable alternative, providing a rich source of protein and minerals. These crops use nitrogen from the air, fixing it in the soil, thereby reducing the dependence on synthetic nitrogen fertilizers and contributing to a decrease in greenhouse gas emissions (Kumar et al. 2022). Increasing the cultivation of pulses and incorporating them into crop rotations might enhance not only crop yields but also food and nutrition diversity (Kumar et al. 2022). Polyculture can also improve soil health and reduce vulnerability to climatic extremes (Singh and Singh 2017).

Further research is deeply needed to determine the metabolism and bioavailability of (micro)nutrients and bioactives from new food sources, such as millet and sorghum grains, to finely evaluate the benefits of the introduction of such cereals in modern Western diets (Bhatt et al. 2023).

Additionally, further research on food transformation processes will likely help us to characterize and select the most potential and sustainable processes that will be associated with better results in terms of (micro)nutrient bioavailability.

Finally, climate change may also modify our requirements for specific nutrients. For instance, a recent study conducted with 13406 Germans showed that hot and dry summers in Germany since the start of modern climate recordings had a measurable positive effect on 25(OH)D plasma levels of the examined population (Kraus et al. 2020). Conversely, heat waves can potentiate inflammatory responses (Mora et al. Mora et al. 2017) and thus increase our need for anti-inflammatory micronutrients such as vitamin D (Dey et al. 2024) or carotenoids (Rubin et al. 2017). This should be carefully explored to anticipate climate change effects on population health.

All these research gaps need to be filled to enable a transition to more sustainable diets, which should be characterized by a variety of plant foods rich in bioavailable nutrients, capable of covering the dietary needs of different population groups despite climate change.

Author contributions

ER was involved in the conception of the paper; ER, AMG, KP, PR and DD were involved in the design of the paper; all authors collected and interpreted the data, drafted the paper and approved the final version to be published. All authors agree to be accountable for all aspects of the work.

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ORCID

Emmanuelle Reboul http://orcid.org/0000-0002-4576-1992

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