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How can food processing achieve food and nutrition security?

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Abstract

In the agri-food chain, while the impact of producers and consumers on sustainability has been well studied, food processing has been less explored. This position paper aims to discuss the potential of food processing to address all food and nutrition security (FNS) outcomes in order to achieve improved food system sustainability. First, FNS dimensions and the four pillars of agro-food industry sustainability are defined, with a focus on ultra-processed foods. Second, the food matrix concept is developed as a new paradigm to holistically address all FNS. It is concluded that food processing should become more involved in circular food systems and bioeconomy, and that we need to relocate food production, processing, and consumption to be more aligned with regional food production specificities. For this, minimal processing to preserve food matrices should be preferred. Therefore, the strong current tendency to develop reductionist and siloed innovative solutions to improve the sustainability of food systems should be questioned.

KEYWORDS

food and nutrition securities, food matrix, food processing, minimal processing, sustainability, ultra-processed foods

1 | INTRODUCTION

Food should not be primarily an economic object: it should be something that helps to improve people's health and well-being while preserving environmental resources. Economic parameters, such as profitability, or revenue generation, should be secondary. Furthermore, we first eat food, not nutrients, and food belongs to a dietary pattern. For health and sustainability, we need to look at food in the context of dietary patterns, not nutrients; and we need to look at diets as a whole, particularly considering food synergies and interactions (Fardet & Rock, 2022a).

Dietary patterns represent an emergent outcome of food systems and need to become sustainable in all dimensions (FAO, 2018; SAPEA, 2023). According to some authors (and stakeholders), the global food system produces more food than is theoretically needed, with about 3000 Kcal/capita available daily (Wiseman et al., 2019). The same authors acknowledge that global diets have become increasingly poorer in quality since the 1960s onwards. The risk posed by such poor diets is an increase in cardiovascular diseases, early mortality, and morbidity that is now greater than the combined risk of practicing unsafe sex, abusing alcohol, drug and tobacco (GBD, 2019 Risk Factors Collaborators, 2020). In addition, the current mainstream food systems are seriously threatening the planetary boundaries that may ultimately determine human survival (IPCC, 2022; Kemp et al., 2022).

In the food system, which functions through several and interlinked agri-food chains, while the impact of producers and consumers on sustainability has been studied extensively, the impact of industries in the middle of the agri-food chain has been less studied and too often neglected (Axelos et al., 2020; Fardet & Rock, 2020). Yet, food processors can be a driver for improved quality of food products, further up the supply chain, and be essential for the quality of the food delivered to consumers further downstream. The food system approach is a relevant conceptual framework to systematically identify and discuss how food processing contributes to multiple food and nutrition security (FNS) outcomes (Augustin et al., 2016). It is also worth mentioning that, based on a food system's approach, FNS is also maintained and ensured when the system – of which food processing is a key component – is able to absorb and adapt to sudden shocks or stresses (Ingram, 2011). In summary, the question we address is: "How does food processing contribute to the different dimensions of FNS?"

Processing refers to many different practices and techniques involving different technologies. Thus, before the advent of ultra-processing after the Second World War, four main ways of producing foodstuffs were used for centuries, at both industrial and domestic levels (Fardet, 2018): (1) Thermal treatments (e.g., freezing, sterilization, UHT, drying, canning, smoking…); (2) Mechanical treatments (e.g., grinding, pressing, refining, skimming, peeling…); (3) Fermentative treatments (e.g., alcoholic, lactic, malolactic, acetic, etc.); and (4) Addition of culinary ingredients (e.g., salt, sugar, fat, etc.). In general, these four treatments have been used to preserve food on a small scale and also to improve the organoleptic properties of food. To the best of our knowledge, when the world population was less than two billion people before the Second World War, these four main food processes were not associated with such a high prevalence of chronic diseases (in fact, infectious diseases predominated) and food system led degradation (in terms of, i.e., environmental impacts and social implications).

Due to the historically strong focus on agriculture, the very broad heterogeneity of the technological processes applied and the difficulty of obtaining private data from the food industry (Barilla Foundation, 2020), the scientific literature on food processing and sustainability is not abundant, especially in the relation to the impact on greenhouse gas emissions, biodiversity, water footprint and overall environmental impact. Thus, a better identification of research gaps and necessary paradigm shifts motivated this work by an international and multidisciplinary consortium.

The objective and originality of this position paper is therefore to discuss how and to what extent food processing can contribute to the different dimensions of FNS, and what levers can be activated to achieve higher levels of sustainability at a systemic level. In addition to the four traditional food processes mentioned above, the paper will also focus on ultra-processed foods (UPFs), generally associated with degraded food systems and food matrices, thus emphasizing the importance of preserving the food matrix as much as possible to achieve better FNS.

2 | METHODS

In order to achieve our objective and reach a consensus on the topic of these position paper four steps were taken:

2.1 | The INRAE Syalsa metaprogramme

This position paper is an outcome of the French INRAE (National Research Institute for Agriculture, Food and the Environment) metaprogramme entitled: "Food systems and human health" (i.e., Syalsa acronym in French), and from the derived DURATRANSFO project (2021–2022) entitled: "Creation of an interdisciplinary consortium with an international vocation on the theme of Food processing and sustainability of food systems".

2.2 | Building of an international consortium

To build the international consortium around the topic of the DURATRANSFO project, more than 50 academic researchers worldwide were contacted to complement the initial limited French consortium of 11 researchers. They were selected based on their expertise and innovative research and publications at the interface between food processing and the various dimensions of sustainability. Finally, we reached a total of 19 non-French researchers from Australia, Asia, Europe and Africa with complementary expertise from 15 research institutions and universities, resulting in a multidisciplinary research team. Not all researchers contributed to this position paper, but all were involved in the overall and broader discussions.

2.3 | Identification of research gaps

Six online discussion sessions, with e-mail exchanges in between, were held (2021–2022) to identify the main research gaps and issues for the DURATRANSFO theme on "Food processing and food system sustainability". Four innovative and under-researched topics were jointly identified:

1. Reconnecting processing to local food systems: challenges and impacts.
2. Sustainability of food processing of animal products: what place?
3. How can food processing ensure food and nutrition security within a sustainable system?
4. Can the consumer influence the sustainability of food processing particularly with increased sustainable foods offer in the supply chain?

This paper is therefore the result of panel analyses around the third theme, which confirmed that the present food processing of industrialized countries does not ensure FNS while preserving the environment. Internal panel's discussions finally allowed conclusions and perspectives for future research, actions and prospects for an environment-friendly processing for FNS.

2.4 | Bibliographic search

For each topic, and particularly the theme of this paper, a classic bibliographic search was carried out to identify what is already known, what is lacking and what can be improved. For this purpose, authors were assisted by two master's level students from the French agro-food engineer high-school VetAgro Sup (Lempdes, France).

As a result of the scientific meetings and the bibliographic analysis, two main issues have been identified in the following sections:

1. An assessment of the on-going situation: "Tensions between processing and food and nutrition security in global food systems";
2. A proposed paradigm shift: "The food matrix as a key paradigm for developing sustainable food processing and addressing food security".

3 | TENSIONS BETWEEN PROCESSING AND FOOD AND NUTRITION SECURITY IN GLOBAL FOOD SYSTEMS

3.1 | What is food and nutrition security?

Food security is undoubtedly a constantly evolving definition (Augustin et al., 2016). According to the FAO, "*Food security exists when all people, at all times, have physical, [social] and economic access to sufficient, safe and nutritious food which meets their dietary needs and food preferences for an active and healthy life*" (FAO, 2008; page 1). The term "Social" was added to the 1996 definition in 2002, and more recently the "Environmental" dimension. Today, six dimensions are distinguished and detailed as follows (HLPE/FAO, 2021):

1. Availability: "*Having a quantity and quality of food sufficient to satisfy the dietary needs of individuals, free from adverse substances and acceptable within a given culture, supplied through domestic production or imports*."
2. Access (economic, social, and physical): "*Having personal or household financial means to acquire food for an adequate diet at a level to ensure that satisfaction of other basic needs is not threatened or compromised; and that adequate food is accessible to everyone, including vulnerable individuals and groups*."
3. Utilization: "*Having an adequate diet, clean water, sanitation, and health care to reach a state of nutritional well-being where all physiological needs are met*."
4. Stability: "*Having the ability to ensure food security in the event of sudden shocks (e.g., an economic, health, conflict or climatic crisis) or cyclical events (e.g., seasonal food insecurity)*."
5. Agency: "*Individuals or groups having the capacity to act independently to make choices about what they eat, the foods they produce, how that food is produced, processed and distributed, and to engage in policy processes that shape food systems. The protection of agency requires socio-political systems that uphold governance structures that enable the achievement of FNS for all*." Indirectly, this may include sociological, religious, and/or cultural aspects, all participating in the independent food choices made by consumers. However, today, "Agency" has been largely co-opted by large multinationals with a great reliance on UPFs.
6. Sustainability: "*Food system practices that contribute to long-term regeneration of natural, social and economic systems, ensuring the food needs of the present generations are met without compromising the food needs of future generations*.". We should also add that food system practices should contribute to the preservation of agrobiodiversity.

With the prospect of healthy feeding nearly ten billion people by 2050, the food industry is facing a major challenge. To date, the widespread solution has been the global development of UPFs (Baker et al., 2020): they are "*formulations of ingredients, mostly of exclusive industrial use, that result from a series of industrial processes (hence 'ultra-processed')*." (Monteiro et al., 2019; page 937).

UPFs have clearly contributed to the access, stability, and safety dimensions of food security, but to the detriment of other dimensions, such as sustainability (Anastasiou et al., 2022; Fardet & Rock, 2020), agency and utilization, that is, nutrition/health securities (Askari et al., 2020; Barbosa et al., 2022; Chen et al., 2020; De Amicis et al., 2022; de Araújo et al., 2021; Delpino et al., 2021; Marti del Moral & Ishiyama, 2021; Pagliai et al., 2020). It cannot be denied that the older industrial processes, such as the canning of beans, or the pasteurization of milk, represented significant advances in promoting the availability and affordability of safe food on a global scale. Food safety hazards, meaning any biological, chemical, or physical characteristics that make food unsafe, have been addressed through the vulgarization of science-based methodologies such as HACCP, international bodies (e.g., Codex Alimentarius), regulations (e.g., European Food Law), alert mechanisms (RASFF) and law enforcement measures. The flagship of the companies marketing UPF is their superior food safety standards, even in regions where law enforcement is weak. However, recent food scandals, such as the high levels of ethylene oxide in food additives or the outbreak of foodborne pathogens in sweet snacks targeting children (Kobets et al., 2022), show that it is difficult to achieve 100% safety, even with UPF. And despite high levels of food safety, such massive UPF consumption also drives intensive and polluting monoculture and animal farming upstream (Fardet & Rock, 2020).

Fulfilling all securities appears to be challenging depending on the region, territory, or country considered. For example, in desert (sand or ice) countries, the year-round availability of food is impossible if it is sourced locally. Some countries, such as Egypt, do not have the necessary land area to produce the food needed to feed its own population. Food imports and interregional trade are therefore necessary in these circumstances. In addition, localized approaches, although more sustainable, may not produce enough food to supply large megacities or a defined region/territory. Foods will therefore need to be transported and exchanged, certainly. This raises the question of how to preserve food over long distances without compromising its health potential and safety. In addition to GHG emissions, transport facilitates the global spread of foodborne pathogens, including those equipped with multiple mechanisms of antimicrobial resistance (AMR). These so-called "superbugs" pose a serious threat, according to the World Health Organization (WHO), and include foodborne pathogens, such as *E. coli*, salmonellae, and others. Global food systems facilitate the spread of AMR along the chain and the transmission of infections between animals and humans, even when food safety control measures are implemented (Antimicrobial Resistance Collaborators, 2022). It is worth noting that in addition to infections, some foodborne pathogens also produce toxins that can persist in food (e.g., aflatoxins). If we consider that the generation time of microbes is expressed in minutes or hours, it is easy to understand how quickly they can adapt to a changing environment. Therefore, in the current scenario of long and complex food supply chains, different analytical capacities in different regions, heavy use of agrochemicals and food preservatives (as fungicides), then the risk of rapidly spreading outbreaks caused by AMR food-borne pathogens, including toxin producers (fungi, *E. coli*) should not be ignored. The above arguments clearly support the need to change food systems, with a specific focus on food processing.

3.2 | The contribution of food processing to food and nutrition security outcomes

Industrial food processing, contributes to FNS outcomes in different ways, which also leads to tradeoffs between the different FNS dimensions. Food processing generally leads to an increase in food "availability", extending food preservation across seasons, geographical areas, and time, thus enabling food to be supplied in sufficient quantities to the greatest number of people worldwide. However, if industrial foods are generally very safe and free from harmful substances (mainly foodborne pathogens and their toxins and dangerous microorganisms), UPFs, even when authorized, may contain a wide variety of xenobiotics, even if authorized, such as synthetic compounds (e.g., some additives and ultra-processed nutrients, such as invert sugar, hydrolyzed proteins, hydrogenated oils), potentially toxic compounds migrating from packaging, pesticide residues with unknown long-term health effects, and potential additive cocktail effects. In addition, although highly standardized convenience foods can be adapted to a particular culture (e.g., the sugar content of sodas and yogurts varies from country to country), they are increasingly replacing traditional foods in some countries, especially among the youngest, for example, the increasing development of fast food restaurants.

Food processing facilitates "access", especially in huge megacities, and at reasonable costs, particularly for vulnerable individuals and groups. Famine in some parts of the world would probably be worse without processed foods. But again, the preference has often been for convenience and UPFs, which are cheap calories for most people, especially the poorest in Western countries. In addition, the prevalence of these foods in emerging and developing countries contributes to the triple burden of malnutrition, with the recent emergence of chronic diseases such as obesity and type 2 diabetes in countries that are generally malnourished or undernourished, not overnourished.

Food processing can promote a healthy and sustainable "use" of food (e.g., through processing that limits nutrient degradation, preserves the nutritional value, or even increases it, as in the case of fermentation). Nor should the importance of cultural aspects of food use be underestimated, and the enormous patrimony of diverse processing techniques worldwide that needs to be valorized, rediscovered, and/or promoted, for example, fermented foods (Mensi & Udenigwe, 2021). Under certain conditions, food upgrading through the addition of micronutrients such as vitamins, iron, and zinc (sometimes referred to as "food fortification") can help meet the nutritional needs of deprived people. This has been showcased by a social business (called "Shokti Doi") in rural Bangladesh, which takes a localized approach to source milk, producing fortified yogurt in micro-factories, and selling it to the poor people in the surrounding area (Reiner et al., 2015). However, UPFs do not address nutritional well-being (where all physiological needs are met with lower risk of non-communicable diseases). They are associated with increased prevalence of chronic diseases and early mortality worldwide (Barbosa et al., 2022; Cascaes et al., 2022; De Amicis et al., 2022; de Araújo et al., 2021; Delpino et al., 2021; Marti del Moral & Ishiyama, 2021; Mazloomi et al., 2022; Moradi et al., 2021; Oliveira et al., 2022; Pagliai et al., 2020; Taneri et al., 2022); many are still fortified with micronutrients (i.e., fiber, vitamins, minerals, antioxidants, etc.) to prevent deficiencies, but meeting nutritional requirements is not enough to prevent the development of chronic diseases if the food matrix quality is too degraded and/or too artificial (Fardet & Rock, 2022a). For example, in China (Fardet et al., 2021) and India (Fardet et al., 2022), improvements in nutritional requirements have been observed during the last 30 years of the food transition. However, an exponential increase in the prevalence of chronic diseases is correlated with increased consumption of industrial foods and animal products, suggesting that the quality of calories appears to be more important than simply providing sufficient nutrients and calories.

Food processing contributes to the "stability" of food security in the event of sudden shocks or cyclical events, because it allows food to be preserved and stored in large quantities worldwide. Such buffer stocks of food and clean water can be used in the event of food shortages, for example to feed victims of humanitarian disasters, such as earthquakes or floods. Also, cooking natural foods at home may not be sufficient in all regions due to climate and other constraints. In addition, there may be disasters where people cannot prepare food themselves because they have lost their homes. Giedelmann-L et al. (2022) highlight that most humanitarian food supply chains cannot handle perishable products due to their high demands on logistics operations (Giedelmann-L et al., 2022). Limitations also apply to the provision of food and nutrition in refugee camps (Seifert et al., 2018), which mostly rely on food supplies from outside the camp (Seifert et al., 2023).

Food processing may address "Agency" in a certain way. However, in the case of UPFs, it is difficult (but not impossible) for consumers to act independently to make enlightened choices about what they eat, mainly because of their very wide availability everywhere, especially in food deserts of fresh produce, and UPFs are often marketed as healthy when they are not. Moreover, the aggressive marketing of these foods to vulnerable and uninformed children and other (disadvantaged) populations shows that food choices are not made on the basis of full awareness (Pulker et al., 2018; Santana et al., 2020). Furthermore, it is not easy nowadays for consumers to engage in the policy processes that shape food systems. It is, therefore, likely that changes will come first through changes in consumer food behavior, and from there, eventually through food education, although public authorities should set an example by regulating UPF marketing.

Food processing on a global scale does not address "Sustainability" (i.e., long-term regeneration of natural, social, and economic systems), especially UPFs (Anastasiou et al., 2022; Fardet & Rock, 2020; Fellegger Garzillo et al., 2022; Kesse-Guyot et al., 2022). As regards to UPFs (economies of scale as an industrial paradigm), they drive upstream intensive and polluting large monocultures and livestock farms, which do not allow long-term regeneration of natural, social, and economic systems (Fardet & Rock, 2020). However, food processing may add value to raw materials/inputs, but at a cost. Therefore, environmental sustainability is a critical parameter for the coming years, that is, developing food processing innovations while maintaining the resilience of food systems.

All these FNS dimensions are interlinked, and we need to recognize and address trade-offs and lock-ins. For example, processing can extend shelf-life, which can be good for reducing waste. Still, it may also have an environmental impact (e.g., freezing or freeze-drying), leading to economic costs (electricity), or a reduction in nutritional value (e.g., fewer vitamins in fruits/vegetables). As an example of lock-in, the industrial processing of wheat for bread and pasta requires specific wheat varieties that contain enough protein to withstand continuous (and rapid) industrial processing (Galli et al., 2015). This leads to the purchase and cultivation of only a few varieties, reducing agrobiodiversity (and ultimately making agriculture less resilient to the threats of climate change).

It is therefore not easy for the food processing agribusiness to achieve the combination of all six dimensions of FNS. Thus, while food processing can contribute to FNS, the ultra-processing solution is neither sufficient nor satisfactory, especially for human health and food system sustainability. This underlines the need for innovation in food processing (Gruchmann et al., 2021) that simultaneously considers the six dimensions of FSN rather than just a few of them individually.

3.3 | The four pillars of agro-food industry sustainability

A way to improve the sustainability of food processing in the agro-food industry can be found in the holistic framework proposed by the Barilla Center for Food & Nutrition through the four pillars of food company sustainability (Barilla Foundation, 2020). Indeed, these Four Pillar Framework identified four dimensions of business activity that have a holistic and indivisible impact on society and the planet, as described below (Barilla Foundation et al., 2020; pages 12–13) (Figure 1):

1. Beneficial products and strategies: "This Pillar addresses the impact of a company's products, services, and strategies on human well-being and the planet's sustainability. For the food sector, this Pillar focuses on business contributions to healthy and sustainable dietary patterns through their products and strategies. This includes whether product lines are healthful and whether product use is conducive to well-being and supports improved living standards and consumers' life goals."
2. Sustainable business operations and internal processes: "This Pillar considers the environmental and social impacts of business operations, including resource use (land, water, energy) and emissions, respect for human rights, diversity and inclusion, and decent work conditions that improve the livelihoods of employees and their families. It also assesses whether a company encourages and rewards conduct that strives to internalize externalities."
3. Sustainable supply and value chains: "This Pillar reflects the company's role in and responsibility for the broader ecosystem of which it is part, including its interaction with its supply chain and value chain, producers, clients, consumers, and the industry in which it operates. This Pillar focuses on whether the company supports the realization of the Sustainable Development Goals (SDGs) through these interactions and whether it collaborates to promote, incentivize, and ensure more sustainable practices and better livelihoods within its own value chain as well as within the relevant industries or sectors that its operations influence."
4. Good corporate citizenship: "Pillar refers to how companies engage externally and seek to influence the rules that govern them. It assesses whether companies avoid strategies that would diminish social goods or societal well-being and whether companies value and do not undermine the crafting and effective deployment of law and policy that advances sustainable development."

The report concludes: "*A more sustainable food system requires greater and more focused commitments by businesses; a more comprehensive and coherent framework to align corporate practice, measurement, and reporting to the SDGs; and the creation of more precise SDG-aligned metrics*." (Barilla Foundation et al., 2020; page 90).

In addition, based on the Four Pillars, the authors also conducted a manual content analysis of the sustainability reports of the 100 largest publicly listed global agri-food and beverage companies published in 2020, and related to 2018 and 2019. These companies represent 70% of the total global market value. Most companies (Engida et al., 2018) are defined as "food producers." There are 25 drug and grocery companies and 23 companies that produce and sell beverages. The countries (77 OECD and 23 non-OECD) most represented by companies are the United States (26), Japan (9), and China (8). The main findings were that (1) companies are little inclined to describe strategic goals for each of the Pillar 1 topics, (2) companies are more likely to set strategic goals for topics such as 'Sustainable Food Production and Sourcing,' 'Waste production,' and 'Securing Sustainable Water Supply for Human Use and Ecosystem' than for the other Pillar 2 topics, with percentages ranging from 25% to 30%, (3) companies are little inclined to set strategic goals

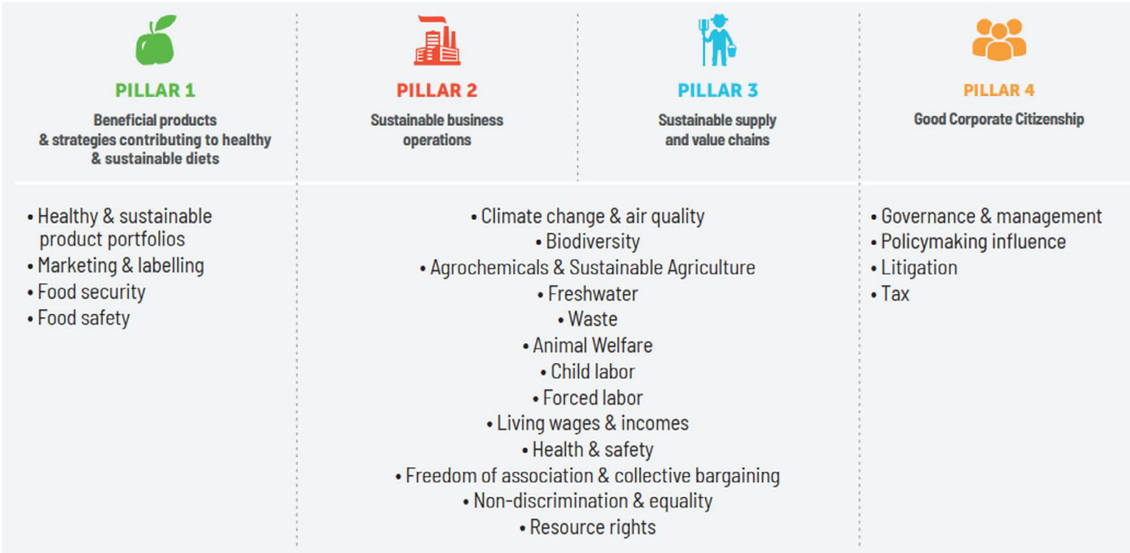

FIGURE 1 The four pillars of agro-food industry sustainability (From Barilla Foundation (Barilla Foundation et al., 2020)).

for Pillar 3 topics, and (4) companies do not define strategic goals regarding Corporate Taxation and Resource Rights topics (references to Community Engagement and Anti-Corruption activities are also very rare in companies' strategic planning) (Barilla Foundation et al., 2020). More generally, the authors observed that: "*companies stress those key performance indicators and metrics that are financially material and can have a benefit in terms of investment and marketing attraction. How companies contribute to overall sustainable development is still not clear, lacking key pieces of information within sustainability reports, as demonstrated by the gaps identified in Pillars 2, 3, and 4… In particular, most of the scrutinized companies share the risk that climate change can negatively affect business production and the risk of having unhealthy products*" (Barilla Foundation et al., 2020; page 42).

3.4 | The case of ultra-processing and food and nutrition securities

As suggested above (in section 1.2.), UPFs and UPFs supply chain/system clearly do not address all six dimensions of FNS at the same time (Anastasiou et al., 2022; da Silva et al., 2020; Fardet & Rock, 2020; Monteiro et al., 2021) (Figure 2). Therefore, there is a need to question ultra-processing and to define more sustainable food processing. In addition, UPFs are heavily marketed (Baldwin et al., 2018; Kelly et al., 2016; Sina et al., 2022). Most of the time, the labeling mentions nutrients but not 'how much' processing has been done. Information about the environmental impact is often missing or misleading; yet this is also a key policy message to consider for labeling. Regulatory authorities need to monitor and control the marketing of highly processed foods or clearly label them for consumers on the front of the pack. The message to consumers should be clear, especially in developed and developing economies where the UPFs are readily available and consumed.

3.5 | Food securities in developed, emerging, and developing countries: Different scenarios?

Western countries (especially Anglo-Saxon ones) have high levels of UPF consumption (high in added salt, sugar, and fat, additives, and other xenobiotics and makers of ultr-a-processing, i.e., MUPs) combined with a reasonably good nutritional adequacy. However, the prevalence of chronic diseases is highest in these countries. This suggests that meeting all nutritional needs is not enough to stay healthy (Fardet & Rock, 2022a). There are also socioeconomic strata for UPF consumption, with the poorest consuming them the most.

In developing and emerging countries, there is a lower level of UPF consumption combined with a lower level of nutritional adequacy, that is, a more monotonous diet, but still a lower level of chronic disease prevalence. Therefore, things do not get better by providing cheap UPFs, as evidenced by the increase in chronic diseases in these countries when UPFs penetrate the market (the triple burden of malnutrition is now emerging) (Baker & Friel, 2016; Popkin et al., 2021; Popkin & Ng, 2021), for example in China (Fardet et al., 2021), Brazil (Monteiro et al., 2015) and India (Fardet et al., 2022). In countries such as Brazil, for example, the increase in UPF contributed to approximately 20% of the total diet-related ecological footprint over the last 30 years (da Silva et al., 2021). Notably, this trajectory has been associated with environmental degradation, as deforestation in the Amazon's rainforest threatens the equilibrium of the global climate (Maeda et al., 2021; Zalles et al., 2019). UPFs have also been linked to health concerns as both the food matrix and composition are degraded, leading to

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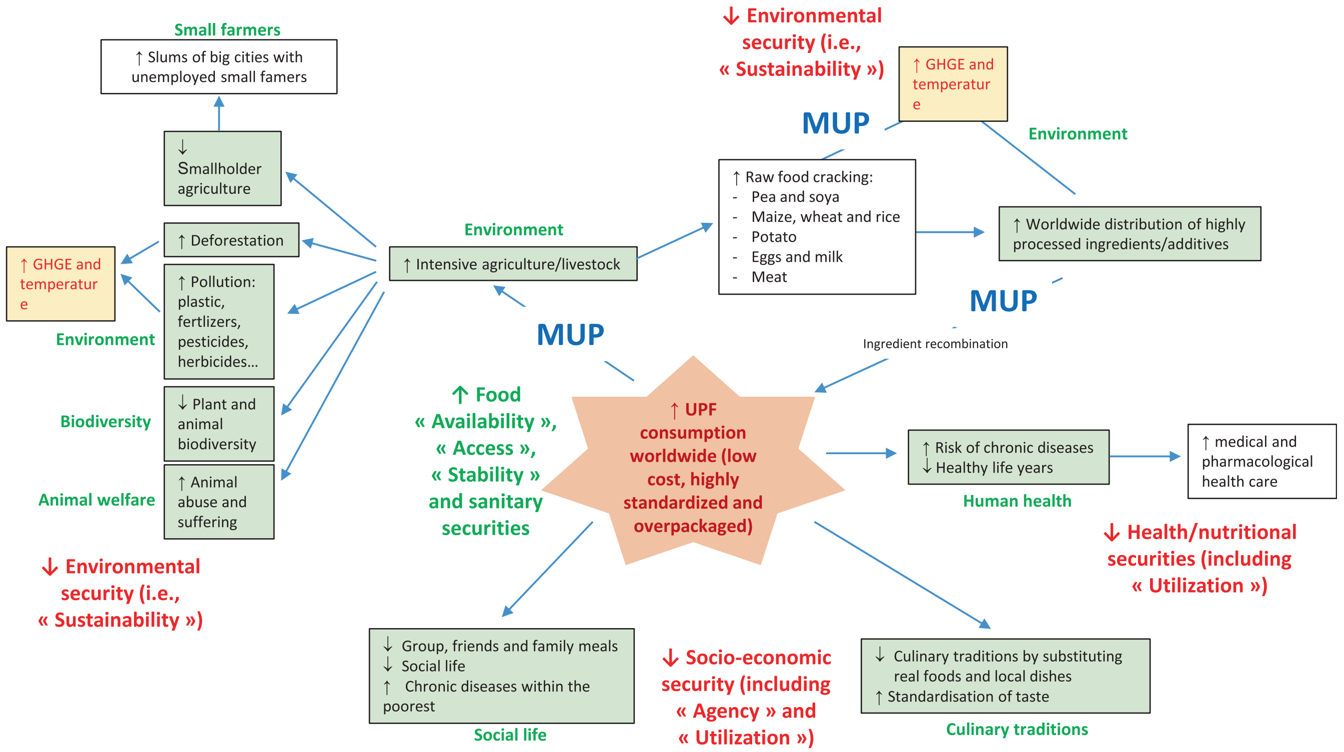

FIGURE 2 Ultra-processing and FNS (adapted from Fardet & Rock (Fardet & Rock, 2020)). While UPFs well address some food securities (in green), this is to the detriment of environmental, socio-economic, and health sustainability (in red). Based on scientific evidence, this figure is a synthesis of the interlinks between the massive consumption of UPFs worldwide and the different FNS: for environmental sustainability, we notably started from the definition of a UPF which contains at least one marker of ultra-processing (MUP), and we went back to their productions upstream.

diseases, such as diabetes and obesity. Moreover, chemical preservatives (e.g., in cured meat products, such as nitrites and nitrates), along with the use of high processing temperatures, may contribute to the formation of potentially carcinogenic compounds. As emerging economies continue to grow, the offer for UPFs is increasing.

Therefore, one main question seems to emerge from these analyses: "How to find solutions for healthy diets in these countries without taking the step of large-scale food industrialization?". In general terms, the food industry has been inspired by the manufacturing industry – and perhaps also by the pharmaceutical industry for the formulation-type products, where the quality of ingredients is constant throughout the year, which is not in line with the laws of nature. And perhaps this is one of the main problems of the food industry. So the main challenges for the food industry that need to be addressed are: how does the food industry adapt to the raw product that is available locally? And how to develop food processing capabilities that can adapt? To address the issue of FNS relative to food processing, should we analyze according to regions and cultures or according to the level of the country's development? Considering the specific aspects of different countries, there are leading priorities for each country. For example, price is the primary constraint in Senegal, which needs affordable food/nutrition to be close to the consumer. An ideal approach would be to transition towards a system where market incentives drive down the price of the healthiest and most sustainable products, with different incentives for different countries.

4 | HOW TO LINK HEALTHY AND SUSTAINABLE FOOD? THE FOOD MATRIX AS A KEY PARADIGM FOR DEVELOPING SUSTAINABLE FOOD PROCESSING AND ADDRESSING FOOD SECURITIES

4.1 | What is food health potential?

To address all dimensions of FSN and develop more sustainable food processing, it appears fundamental to define first what "a healthy food is" (Figure 3). It is not sensu stricto a nutritionally balanced food because it does not exist except breast milk, hence the recommendation 'to eat varied'. A healthy food is the least processed one to be both edible, safe, and tasty with the best matrix quality, just because the food matrix governs the metabolic fate of nutrients (Fardet & Rock, 2022a, 2022b) (Figure 4a,b). Therefore, the challenge for the food industry would be to develop less processed foods with a good matrix quality without adding MUPs, and not to reformulate UPFs (Scrinis & Monteiro, 2018).

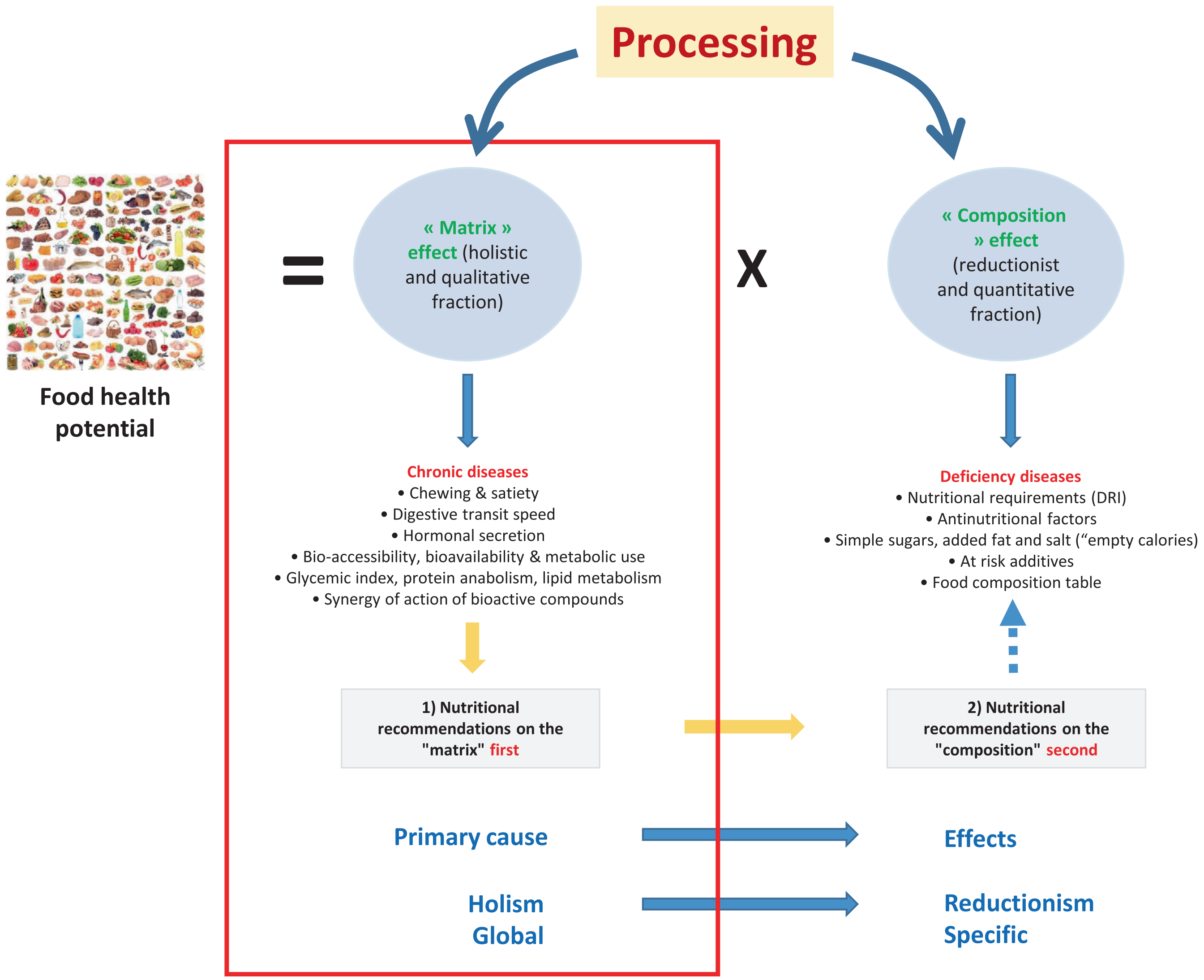

FIGURE 3 Food health potential based on a holistic-reductionist approach, including "matrix" (first) and "composition" (second) effects (adapted from Fardet & Rock (Fardet & Rock, 2022b)).

What is a food matrix? It has been recently defined as follows in food science: "*the food matrix is a part of the microstructure of foods, usually corresponding to a physical and spatial domain, that contains, interacts directly and/or gives a particular functionality to a constituent (e.g., a nutrient) or element of the food (e.g., starch granules, microorganisms). A first deduction from this concept is that the food matrix is component-specific, that is, different components (or structural elements) in the same food may "see" or interact with different matrices*" (Aguilera, 2019; page 3613). Put differently, and more pragmatically, the food matrix effect can also be defined as follows: two foods of similar composition, but with different matrix or tridimensional architecture do not have the same metabolic, physiological and health effects, for example, whole versus finely ground almonds (Fardet & Rock, 2022a).

Therefore, processing should preserve food matrices as much as possible while at the same time making it possible to value food diversity upstream, that is, agro-biodiversity. Beyond ultra-processing, new food, processes are therefore needed: we can distinguish between incremental innovations based on reductionist technological solutions and more holistic breakthrough innovations based on already existing foods but involving the development of new technologies to preserve foods for longer periods of time.

4.2 | Innovative, incremental, and reductionist technological solutions for food securities

New food alternatives are being developed to meet the SDGs, such as insects, UPF reformulation, plant-based meat analogs, or in vitro meat. These are generally reductionist innovations that correct imbalances in the previous food system, but do not challenge it in depth and try to solve problems one by one in a siloed way. But are they really sustainable (IPES-Food, 2023)? Do we really need new foods? Are "ancient/traditional" foods already suitable and sufficient in quantity,

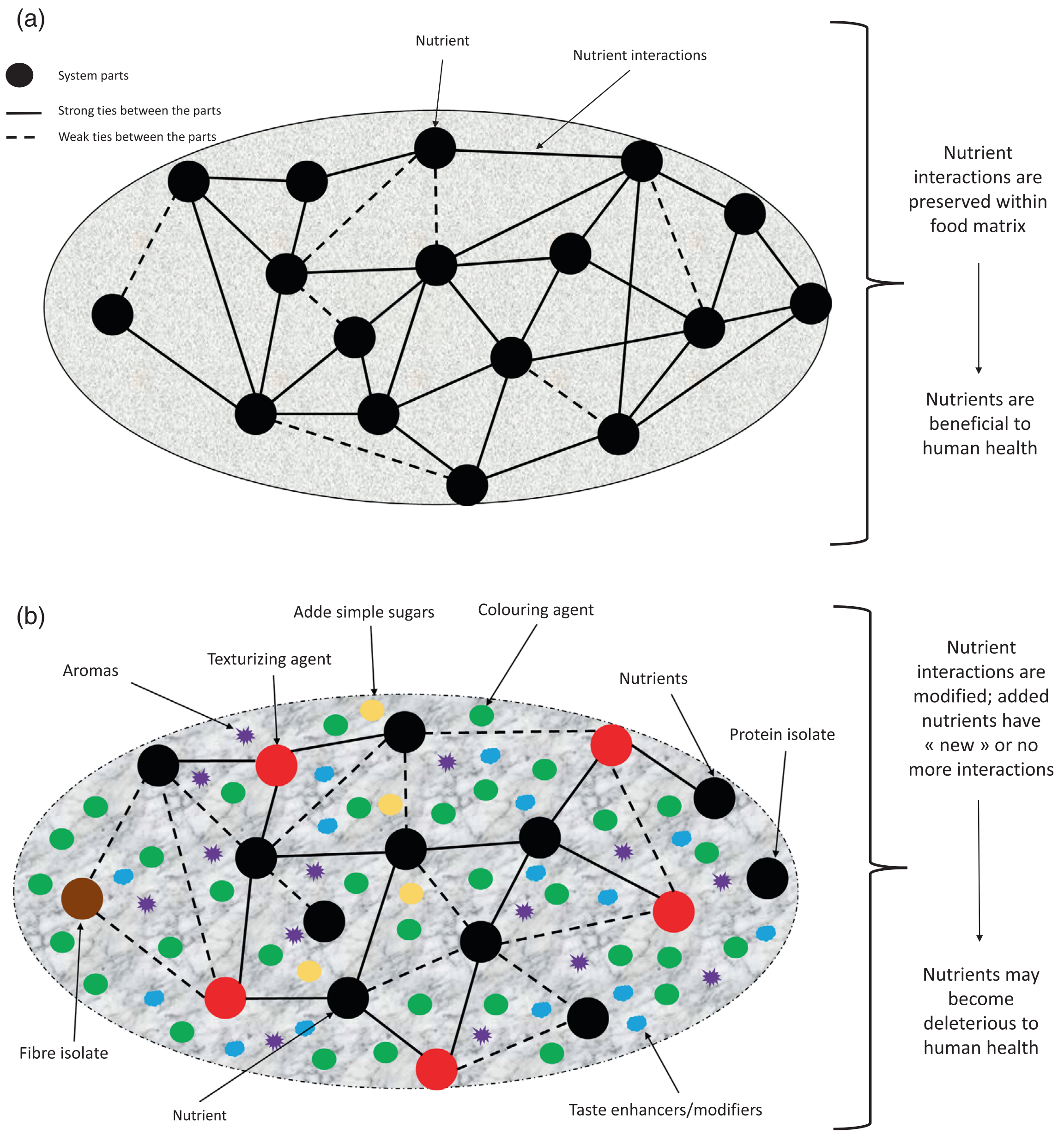

FIGURE 4 Food matrix governs and regulates the metabolic fate of nutrients: (a) Preserved food matrix (un−/minimally-processed foods); and (b) Degraded and artificialized food matrix (ultra-processed foods) (from (Fardet & Rock, 2022a) with permission of Spinger ©).

but should they be processed in a different way while rebalancing our diet, for example, with less animal-based foods and UPFs?

Busy lifestyles demand ready-to-eat (RTE) foods, which has led to a surge in the consumption of industrially processed foods and UPFs. At the same time, consumer awareness and guidance on healthy eating is motivating them to find healthier versions of RTE foods. Red meat, especially beef, has a high carbon footprint (Tilman & Clark, 2014), but ultra-processed meat products such as some industrial sausages among the UPFs have a high footprint as well (Fellegger Garzillo et al., 2022). Does this suggest a need for our food industry to develop versions of these products with low environmental footprints, providing consumers with similar sensorial experiences as the conventional products? Today, the solution chosen is that of highly ultra-processed meat analogs and substitutes, rather than encouraging people to return to real minimally-processed plant-based foods and to keep sustainable meat consumed in low amounts. The need for a not-too-brutal transition is invoked to justify the development of these animal-based food analogs. However, these new UPFs are not associated with a lower risk of chronic diseases and optimal sustainability of the food system (IPES-Food, 2023), even though it is true that, based on life cycle assessment, ultra-processed plant-based food meat analogs are less environmentally costly than red meat (Saget et al., 2021; Singh et al., 2021); but this is far from being the best solution in the long term.

Indeed, the new categories of foods, plant protein/fungi/fermentation-based animal food analogs, insect-based food, or in vitro meat, are generally considered to partially solve the problem of food security while achieving sustainability. Techniques for growing meat in vitro are still at a very early stage and would require further research for more rapid turnover. Proteins from legumes, such as pea protein, have a lower environmental impact than other types of plant protein. Full or partial replacement of a conventional protein with a lower environmental impact (pea/mycoprotein) can reduce the overall environmental impact of processed foods or UPF. Although proteins must first be isolated from legume grains and this process can contribute to the product's overall carbon (and environmental) footprint, it is still well below the impact of animal protein-based products. Product techno-functionality and sensorial quality still need to be optimized (Nette et al., 2016). However, protein isolates are MUPs, and their long-term health effects as isolated compounds are unlikely to be the same as those naturally present in minimally-processed plant-based food matrices. This may be the case for gluten isolates, which are massively added to UPFs and are probably no stranger to the increasing prevalence of non-celiac gluten sensitivity (Fardet, 2015). In other words, the effect of the food matrix matters.

The tendency to develop reductionist and siloed innovative solutions can therefore be questioned. Is it really necessary to keep increasing food production? Would it not be better to improve access to, availability and affordability of some other existing real foods, and to simplify and optimize food systems, namely at post-harvest losses and conservation through better managed cold-chain, so that less food is wasted?

4.3 | Towards new sustainable food processes for addressing food and nutrition securities while preserving food matrices

The issues here are how to develop more sustainable and nutrient-dense minimally processed foods (more sustainable than isolating plant proteins, fiber, etc.), how to improve processing to preserve the overall health potential of foods, and how to develop new technologies (minimal processing) to preserve fresh and local produce for long periods of time. For example, the massive use of additives can be questioned in relation to the use of other healthier techniques, especially for preserving food over long distances.

It is not possible here to describe all the innovations in food processing based on minimal processing, given the large number of studies (Sovacool et al., 2021). However, research has shown that food technologists can develop such innovations which should allow less degradation of the food matrix and/or composition while preserving food in the long term, for example, ultra-high pressure for fruit juices instead of heat treatments (Chakraborty et al., 2014) or pulsed electric field for plant foods (Sánchez-Moreno et al., 2009), improved by using renewable energy. Similarly, companies can develop dynamic management capabilities to implement related changes in technology and supply chain management that promote more sustainable food production (Gruchmann et al., 2021).

5 | CONCLUSIONS, PERSPECTIVES & IMPLICATIONS

Scientific-sound evidence shows that the increasing massive production and consumption of UPFs worldwide does not allow all FNS targets to be met simultaneously. The main conclusion is that to achieve global sustainability of food processing – while addressing all FNS together – it is necessary to adopt a holistic picture of all dimensions of sustainability of the agro-food industry, such as the one proposed by The Four Pillars of sustainability of the food industry, and to avoid greenwashing to contain the massive and increasing production of UPFs worldwide. Therefore, we need to elude siloed and reductionist solutions, particularly the ones offered in the form of reformulated UPFs. As people first eat complex food matrices, not nutrients, we also need a paradigm shift and reconsider the definition of a healthy and sustainable food, which is not a nutritionally balanced one, but the less processed one, according to a holistic view of its health potential, not a reductionist one. Consequently, efforts should be directed, first of all, towards developing appropriate sustainable agricultural food systems and then adjusting food processing 'downwards', with a territorial/regionalized perspective, that is, depending on the geography and pedo-climatic conditions of the country. This means that agricultural practices should not adapt to the constraints of the globalized food industry system, which leads to conventional, intensive practices for the supply of raw materials that support economies of scale.

From these analyses, a key question emerges: how can we move from a food system that is increasingly geared towards the production of UPFs to a food system that is dedicated to healthy and sustainable minimally processed food? As far as food businesses are concerned, it is worth noting that in Europe (and probably in the world), the vast majority of food businesses are small and medium-sized enterprises (SMEs), which account for half of the value added and turnover in the sector, while providing more jobs than multinational companies. Agri-food SMEs are also at the forefront of preserving biodiversity and promoting traditional foods. Therefore, in order to counter the massive development of very large agro-food industries (i.e., Big Food), it is necessary to rebalance and re-localize food transformation and to ask how more SMEs can guarantee FNS worldwide. Industries may then enter into a concept of "balanced cropping for balanced dietary pattern" by adapting processing to local, climate-smart and nutrition-adapted diversified productions. However, such a reflection should be carried out only country by country, and taking into account its own agronomic, cultural, and pedo-climatic specificities of the different country regions. Food processing could be adapted to the seasonal availability of food by country to stimulate upstream biodiversity rather than large monocultures. This leads to another important question, that is: "To what extent can this lead to food sovereignty of countries"?

Ultimately, the food industry needs a revolution to move towards a more balanced food transformation and food matrix preservation. This could address more sustainable production and consumption (SDG n°12: "Establishing sustainable consumption and production patterns") due to its impact on society while being profitable for the food industry. In order to achieve this, consumer education appears to be the first most important step, leading to healthier food choices, for example, reducing the consumption of UPF, and potentially promoting more virtuous food processes. Second, the large food retailers also have a vital role to play as the price wars, associated with competition, have strongly stimulated the development of UPF to achieve ever lower food prices and the use of massively cheap MUP instead of real and noble food ingredients. There is a conscious need of a change in the paradigm of producing and consuming food (SDG n°2, 3, 12). In particular, food should no more make people ill, and in contributing to that, UPFs – that are cheaper, convenient and available worldwide all year round – are damaging public health (obesity and malnutrition, including in children).

In terms of research gaps or future work, our analyses highlighted the need to further study and quantify the impact of ultra-processing on the sustainability of food systems, and to compare it with that of local minimally-processed foods. This requires a holistic approach, taking into account, not only Life Cycle Assessment (LCA) and emissions, but all sustainability aspects including social aspects such as child labor or workers' salaries as proposed by the Barilla Center for Food & Nutrition through the four pillars of food company sustainability (Barilla Foundation, 2020). In addition, good practices for waste and by-product valorization have become imperative and should be enforced if we really intend to consider FNS and sustainability.

Likewise, despite the fact that we have entered the bio-economy era, which has been proposed as the most promising and legitimate option to build sustainable food systems, several actions should still be taken to accelerate the transition towards circularity and sustainability. Indeed, in line with the European Commission's "Farm to Fork" strategy, Member States should be strongly encouraged to promote the transition to sustainable food systems, starting with agro-ecology practices at the farm levels. This will promote the development of products with zero environmental impact, the mitigation of climate change and the improvement of access to nutritious, affordable and sustainable food. Functional foods are constantly being developed, but the majority of them are not green-labeled (Alexandri et al., 2022). A siloed approach will only lead to false conclusions, and will not benefit economics, society nor the environment as a whole in the long run: the promotion of access to healthy and sustainable foods should be on top of policy makers' agendas and national as well as at global levels. Notably, one implication for management and policy perspectives could be to tax foods with the highest negative environmental and health impacts, while promoting easier access to healthy and sustainable foods.

AUTHOR CONTRIBUTIONS

Anthony Fardet wrote the first draft of the manuscript. Stefan Gold, Amélia Delgado, Francesca Galli, Lovedeep Kaur, Vasiliki Kachrimanidou, Nikolaos Kopsahelis and Edmond Rock wrote some sections and critically revised the manuscript. All authors have read and agreed to the submitted version of the manuscript.

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CONFLICT OF INTEREST STATEMENT

A.F. had been scientific expert for Siga© society between 2017 and 2022. Other authors: none.

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