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Food processing and sustainability: Exploring new multidisciplinary perspectives

Anthony Fardet[a,*], Mike Boland[b], Hoang Hong-Minh[c], Amélia Delgado[d], Rafia Halawany-Darson[e], Arnaud Germond[f], Claudiu Eduard Nedelciu[g], Nikolaos Kopsahelis[h], Arnaud Diemer[i], Virginie Baritaux[j], Francesca Galli[k], Edmond Rock[a]

[a] INRA, UMR 1019, UNH, CRNH Auvergne, F-63000 Clermont-Ferrand & Clermont Université, Université D'Auvergne, Unité de Nutrition Humaine, BP 10448, F-63000 Clermont-Ferrand, France
[b] Riddet Institute, Massey University, Palmerston North, New Zealand
[c] Université Paris-Saclay, INRAE, FRISE, Antony, 92761, France
[d] Mediterranean Institute for Agriculture, Environment and Development & Global Change and Sustainability Institute & Universidade Do Algarve, Campus de Gambelas 8005-139 Faro, Portugal
[e] Université Clermont Auvergne, INRAE, VetAgro Sup, UMRF, 63370 Lempdes, France
[f] QuaPA, INRAE, Centre Clermont-Auvergne Rhône Alpes, 63000 Clermont Ferrand, France
[g] System Dynamics Group, Faculty of Social Sciences, University of Bergen, 5007 Bergen, Norway
[h] Department of Food Science and Technology, Ionian University, Argostoli 28100, Kefalonia, Greece
[i] Centre D'Etudes et de Recherches sur le Développement International (UMR 6587), University of Clermont Auvergne, 63000 Clermont-Ferrand, France
[j] Université Clermont Auvergne, AgroParisTech, INRAE, VetAgro Sup, JRU Territoires, F-63000 Clermont-Ferrand, France
[k] Department of Agriculture, Food and Environment, University of Pisa, Via Del Borghetto 80, 56124, Pisa, Italy

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1. Context and objectives

The sustainability of food systems is defined by FAO as delivering "food security and nutrition for all in such a way that the economic, social and environmental bases to generate food security and nutrition for future generations are not compromised" (FAO, 2018). It can be improved by more sustainable production, processing, distribution, and consumption. Yet, today, food systems worldwide are being questioned by many actors who consider them to be unsustainable (Bock et al., 2022; Burlingame et al., 2022; Campi et al., 2021; Hoek et al., 2021; McGreevy et al., 2022), notably those dedicated to the production of cheap ingredients for formulating ultra-processed foods (UPFs) (Anastasiou et al., 2022; Fardet and Rock, 2020; Jonckheere and Neven, 2020; Kesse-Guyot et al., 2022). Otherwise, in terms of environmental impact, it has been recently reported that the whole agri-food-chain accounts for 34 % of greenhouse gas emissions (GHGE), with 24 % for food production, and only 10 % for food processing, food retail and consumers combined (Fig. 1) (Crippa et al., 2021).

A recent INRAe (French National Research Institute for Agriculture, Food and Environment) foresight report underlined that several analytical methods are available for estimating the sustainability of production and consumption of agricultural commodities; thereby, food processing, as a potential component of food system sustainability, is often omitted (Axelos et al., 2020). This means that the connection between food processing technologies and the health of ecosystems (including human health) on the one hand (downstream), and other

* Corresponding author. FARDET, INRA, UMR 1019, UNH, CRNH Auvergne, F-63000 CLERMONT-FERRAND & Clermont Université, Université d'Auvergne, Unité de Nutrition Humaine, BP 10448, F-63000 CLERMONT-FERRAND, France.
E-mail address: anthony.fardet@inrae.fr (A. Fardet).

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activities of food systems (upstream) on the other hand have been largely neglected. Therefore, the development of research has been driven by an objective of optimizing each component of the agri-food chain in isolation (i.e., siloed and reductionist solutions or innovations). This is misdirected, as all the food chain components are interconnected, in one way or another, implying, for example, that an improvement of a sustainability aspect of one component may have potential repercussions on the sustainability by other parts, e.g., GHGE. Therefore, as concluded by INRAe researchers, a "forward-looking thinking focused on the paths to follow in order to progress in a more integrated understanding of the relationships between the functioning of the food system (production-processing-consumption) and health issues (via food and environment), and the identification and analysis of the conditions for changes that could make it possible to respond better" is needed (Axelos et al., 2020).

Thus, until today, the main target for improving food system sustainability has been focused especially on farmers producing agriculture commodities (Campi et al., 2021; Dwivedi et al., 2017), and to a lesser extent on consumers and their behaviors (Bangsa and Schlegelmilch, 2019; Hoek et al., 2021), e.g., through sustainable food profiling models (Bunge et al., 2021). The role of food transformation - and also food distribution and retailing - have been less studied for their impact on food system sustainability, treated as a kind of black box, more specifically in academic research (Fig. 1). Yet, food processing impacts the quality of food from production upstream, and the health quality of foods marketed in food retail to the consumers. It also affects the whole production systems, e.g., the value-added sharing, consumption models and/or the food waste. As summarized by Knorr et al. (2020), "Current attention on food sustainability mainly concentrates on production agriculture and on nutrition, health, and well-being. Food processing, the necessary conversion of raw materials to edible, functional, and culturally acceptable food products, is an important link between production and consumption within the food value chain. Without increased attention to the role of food processing for a maintainable food supply, we are unlikely to succeed in addressing the mounting challenges in delivering sustainable diets for all people." (Knorr et al., 2020). Then, it becomes relevant to ask whether a more local food processing system and more aligned to consumer health would not stimulate more sustainable production upstream, reducing its contribution to less than 24 % of all GHGE (Crippa et al., 2021)?

Therefore, the main objective of this perspective paper is to discuss food processing as a relevant leverage point to improve food system sustainability as a whole, from producers to consumers. To address this issue, an international consortium has been built within the framework of an INRAe project entitled "Food systems and human health", and initially including twenty-nine researchers from fourteen countries in Europe, Oceania, Asia and Africa. For the present analysis, six online webinars, with more focused exchanges in between, were held (2021–2022) to identify the main research gaps and issues relative to food processing and sustainability (for details, see Fardet et al., 2024)

To achieve this, the aim of this perspective paper is structured as follows: 1) to briefly restate what comprises food processing, underlying why it is necessary to process foods; 2) to review what we know today about food processing and sustainability, addressing some recent reports questioning the whole sustainability of food processing, and 3) to explore pathways - through identification of research gaps - for improvements toward more sustainable food processing by 2050, based on the impacts identified at both upstream and downstream levels of processing; notably to contribute to the 2030 Agenda for Sustainable Development, adopted by all United Nations Member States in 2015 (Independent Group of Scientists appointed by the Secretary-General, 2019)

Finally, we intended to develop conceptual perspectives based on an umbrella review of previous works adopting different approaches on food processing and sustainability, rather than a *stricto sensu* data-driven approach, identifying gaps as avenues for future research, *e.g.*, do we need breakthrough changes or simply incremental changes in food processing based on the current food system? In addition, we have focused in section four on UPFs because UPFs is an important emerging issue since more than a decade, and among all food processes, it appears as one of the most threatening to global health (Fardet et al., 2024), not just human health (Lane et al., 2024).

2. A brief summary of why foods need to be processed

Humanity has consumed processed foods for a long time (Fardet, 2018). There are numerous benefits from transforming foods, including the destruction of microbes and toxins, improved bioavailability of some nutrients, extension of shelf life, and improved sensory characteristics and functional properties (van Boekel et al., 2010).

Fig. 1. Food processing in the agri-food chain: a black box? Abbreviation: GHGE: Greenhouse Gas Emissions.

Food processing began with the domestication of fire, more than one million years ago; then fermented foods (*e.g.*, breads, wines, cheeses) were developed since Neolithic times, in the context of securing and diversifying human foods (Toussaint-Samat, 2008). Breakthrough advances arose from about two hundred years ago, notably since the invention of canning in 1795 b y Nicolas Appert (1749–1841) to preserve food longer. There is no doubt that the transformation of food is necessary, to make it edible, digestible, safe and tasty, long-distance transportable and to make it last longer (Knorr and Watzke, 2019). This is becoming even more important with the exponential growth of the world population and the rise of large towns and megacities, requiring sophisticated food distribution systems and long shelf-lives. Food processing also should contribute to reducing fresh food wastes, and to the supply of safe and unspoiled foods to consumers. Foods need to be preserved because they are not produced all year round, but also depending on local climates. In some contexts, food needs to be distributed globally because of climatic constraints on some foods, and to overcome their seasonal availability, and preservation is subsequently required because of shipping times.

However, now, food processing is at a crossroads (Knorr and Watzke, 2019): how can we deliver healthier foods while at the same time addressing better sustainability of food systems, considering both economic, social and environmental bases? Notably, the roundtables and discussion work conducted at INRAe led to two recently published perspective papers. One is a critical review of recent literature showing that global food processing does not address all food and nutrition securities, especially the UPF industry (Fardet et al., 2024). Another work focused on animal products and co-products, and showed they have the advantage to address the increasing demand for protein worldwide. However, the impact of these products (depending on product type) can rapidly increase with the food chain complexity and needs for refrigeration systems (Germond et al., 2024). In the end, the literature about the food processing industry and global sustainability is not as extensive as that, notably in comparison with food agricultural practices and production systems.

3. Food processing and sustainability: what does research tell us?

3.1. Optimizing food processing sustainability

The topic of food processing and sustainability has been the subject of several publications, in the form of reports, reviews, position papers, grey literature, and original articles. The position of some papers depends on the writers, either of academic or industry origin. As expected, review papers from industries generally underline the positive aspects of food processing for addressing food securities, with some advocating that ultra-processing could be a solution, among others, to nourish the predicted ten billion people worldwide by 2050, to valorize food by-products and/or to minimize food waste in a circular economy (Capozzi, 2022). However, these reviews are often based on the paradigm that food nutrients primarily matter for human health, and also for food system sustainability (*e.g.*, the focus on protein supply and human needs), whatever the quality of the whole food that contains these nutrients, *i.e.*, the food matrix or the degree of processing. Yet, this is not the case (Fardet and Rock, 2022), *e.g.*, the increasing development of ultra-processed plant-based alternatives or meat analogs (Fardet, 2024).

The most comprehensive review about food processing and food system sustainability is the one by Sovacool et al. (2021), who discusses different current and emerging options and practices for decarbonization of the food and beverage industry, "including energy and carbon savings, cost savings, and other co-benefits related to sustainability or health - as well as barriers across financial and economic, institutional and managerial, and behavioral and consumer dimensions" (Sovacool et al., 2021). Authors propose a less reductionist approach to this issue by taking into account environmental-associated costs of processing, but do not directly address the environmental cost of UPFs, notably involving food fractionation, chemical modifications, and/or enzymatic syntheses (involving numerous unit operations that are highly energy and water demanding) (Anastasiou et al., 2022; da Silva et al., 2020; Fardet and Rock, 2020; Anastasiou et al., 2023). More specifically, concerning the most GHGE-demanding and energy-intensive food processes, and according to Klemes and Perry (2008) (Klemes and Perry, 2008), the food and drink industry is a major user of energy in a large number of diverse applications, which include the provision of steam or hot water, drying, other separation processes such as evaporation and distillation, refrigeration, and baking.". These authors then list forty energy-intensive processes, including dehydration, freezing, extraction, filtration, evaporation, cooling and chilling, among others (Klemes and Perry, 2007). Notably, chilling and freezing use a monumental amount of energy. This was followed by grain and oilseed milling, dairy, fruit and vegetable preserving, and then sugar processing. Otherwise, in the USA a few years ago, animal slaughtering was the most energy-demanding process (i.e., of electricity and natural gas) mainly through boiling, cooling, and refrigeration (Germond et al., 2024). In the end, Sovacool et al. (2021) proposed decarbonization options, including automation and process optimization, thermal management and heat recovery, adoption of renewable electricity and heat/fuel switching, energy efficiency and sustainable packaging (Sovacool et al., 2021).

Beyond such an optimization, an alternative solution might be, at the same time, to decrease consumption of food products that are the most energy-demanding related to processing, and therefore the least sustainable. However, minimally-processed foods may also exhibit a high carbon footprint for their production, e.g., red meat (Tilman and Clark, 2014). In this way, to take account of this complexity of the agri-food chain sustainability, it has been proposed "to reduce the complexity of nutritional sustainability to a simplified outcome based on a common measurement model, which could be easily communicated throughout the whole agri-food chain, e.g., with a label or a trademark" (Bornkessel et al., 2019). Ultimately, this means an adaptation of eating habits for consumers, especially since foods with less environmental impact from processing (generally those that are less processed) are also generally better for health.

Along the same line of thinking, the review by Knorr et al. (2020) intended "to draw on multidisciplinary insights to demonstrate why food processing is integral to a future food supply" (Knorr et al., 2020), advocating for a consensus in developing essential, relevant sustainability indicators for food processors, e.g., Life Cycle Analyses of food processes and processed foods. Suggested recommendations for future resource-efficient and sustainable food processing could include resource management (e.g., water scarcity), sustainable, efficient, and responsible food packaging, storage and transportation, developing consumer trust (e.g., improved transparency), and development of a "precision" food chain. Within the agri-food chain, Knorr et al. also specifically proposed a move towards emerging solutions to improve the sustainability of food processing: thus, traditional chemical preservatives (e.g., salt, sugar and other chemicals) and thermal treatments could be progressively combined with newer processes, with ozone processing, cold plasma technology, high pressure processing, pulsed electric field, ultrasound, ohmic heating, and/or cavitation technologies (Knorr et al., 2020). Thus, replacement of conventional energy-intensive food processes with novel technologies may potentially reduce energy consumption, reduce production costs, and improve food production sustainability (Wang, 2013). However, we should be careful about rebound effects due to high electricity costs, and an increased dependence on complex information and automation systems in a context of inflation/scarcity.

Similar to the above-mentioned approaches to food processing and sustainability, van der Goot et al. (2016) suggested three main causes for inefficiencies in food production: 1) the increased use of products from animal origin, 2) the inefficient use of food products once produced, resulting in waste generation, and 3) the current set-up of food processes and processing chains. Their main conclusion deserves special attention since they advocated for using less pure ingredients coming from food fractionation and for not maintaining the current way of producing food products through the use of hyper-standardized ingredients (van der Goot et al., 2016). This implies "that the focus should be on creation of enriched fractions. The advantage of those enriched fractions is that they still possess part of the natural structure of the raw material, providing new opportunities for applications in food products. Preserving the natural structure might have a positive effect on the bioavailability of micronutrients" (van der Goot et al., 2016). This refocusing on the importance of minimally-processed food matrices for global health - that we also advocate for (Fardet et al., 2024) - goes against the widespread and massive globalization of refined, fractionated, and recombined ingredients used in UPFs (Monteiro et al., 2013; Dicken and Batterham, 2020) (see also Fig. 2 relative to the UPF water-energy-food nexus). Consequently, food process chains will require redesign, and "fractionation processes will be more specific, smaller and in the vicinity of the final application"; concluding that "this change in food production will become inevitable once natural resources become scarcer and more expensive" (van der Goot et al., 2016). Moreover, less refined and fractionated ingredients will lead to a healthier diet (van der Goot et al., 2016).

As previously suggested, beyond the impact of food processing on food system sustainability, there is also the issue of adequate metrics to use in measuring this impact. For example, the Food Foundation in the UK (Plating Up Progress project) recognizes "a lack of basic, transparent data within the food industry … currently hindering progress towards healthy, just, and sustainable food systems", and the need to establish clear metrics and/or criteria to drive faster progress (Food FoundationPlating Up Progress Policy Briefing, 2021). Among proposed holistic indicators for assessing the sustainability level of a food company, we can report the ITACA protocol (Barreca and Cardinali, 2019), the Four Pillar Framework for corporate alignment to the Sustainable Development Goals (SDGs), which identifies four dimensions of business activity that holistically and indivisibly impact society and the planet (Barilla FoundationUN Sustainable Development Solutions Network), and the sustainability checklist, including designing and adapting processing "in the food industry to clarify the potential hot spots in new process design and focused on environmental sustainability" (Woodhouse et al., 2018).

Another sustainable strategy within the food-processing sector might be "a waste-handling strategy that focuses simultaneously on waste prevention initiatives, opportunity for water reuse and optimization of wastewater management to develop sustainable treatment processes", the authors proposing ways of thinking to limit waste, e.g., water reuse in processes that do not affect food hygiene, resulting in lower wastewater volumes for treatment (Fagbohungbe et al., 2021). This approach of reducing food, energy and/or water wastes has also been previously proposed (Augustin et al., 2016; Wang, 2013; Woodhouse et al., 2018).

Otherwise, researchers from General Mills have advocated for a broad coalition among academia, government, and the food industry to "ensure that the food supply concurrently prioritizes sustainability and nutrient density in the framework of consumer-preferred foods. The coalition can also help to ensure sustainable diets are broadly adopted by consumers" (Miller et al., 2021), adding that industrially processed foods may be one of the solutions to supply affordable and convenient, but still nutrient-dense and sustainable foods. Perhaps, but provided these are not mainly micronutrient-enriched UPFs. They conclude that the food industry "has the scale and influence to make significant changes to what and how we eat, especially regarding consumers who may not have the resources or interest to pursue 'sustainable' foods independently." (Miller et al., 2021). Such a conclusion may seem acceptable, but how can we make sure that industrial goals align with consumers' interests in terms of nutrition, reasonable food prices, and environmental concerns? Arguably, manufacturers have financial necessities or profit-maximizing interests; which may be counter to the above objectives. Hence, there is the possibility that to reach food sustainability will require profound changes in industry governance models. Decentralized governance typical of a circular economy may address this gap.

3.2. *Towards food processing and upcycling in a more circular economy*

Several authors agree on a key issue: the circular economy should become a reality in the food industry (Stillitano et al., 2021; Teixeira, 2018). Notably, as reported, "this demands more efficient and environmentally friendly food processing technologies and process integration together with waste minimization and recovery and incorporation

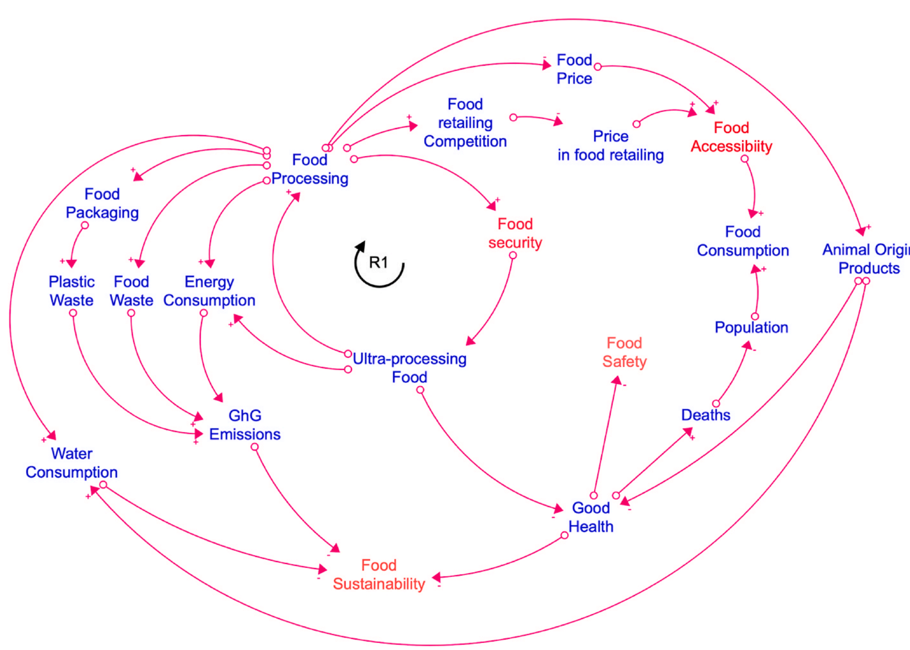

Fig. 2. A Causal Loops Diagram (CLD), including positive and negative polarity in the food processing system, that introduces all the complexity of the water-energy-food nexus.

of food by-products in the food processing chain" (Teixeira, 2018).

An important issue of food processing sustainability is food waste and the potential to upcycle it into new foods. The issue has been extensively and previously addressed (Thorsen et al., 2022, 2023; Anastasiou et al., 2022; Capozzi, 2022). In summary, despite all authors recognizing that the valorization of by-products could be exploited to develop nutrient-rich ingredients at lower economic and environmental costs, different conclusions about this issue have been reported. Thus, some defend the position that one can add nutritional value to UPFs by using by-products or new ingredients derived from food waste (Capozzi, 2022). However, such a position is mainly based on a reductionist view of UPF and human health that relies on the nutri-centered approach, i.e., healthy foods are nutritionally-balanced ones, and that UPF reformulation may be a solution to address human health and nutritional needs. Other researchers disagree with this approach, having a more holistic approach of food health potential and food processing (Fardet and Rock, 2022; Scrinis and Monteiro, 2018), emphasizing that a siloed approach to food processing sustainability may lead only to greenwashing. A more holistic view is also reported and defended by Thorsen et al. (2023) emphasizing that "many of the currently available upcycled foods are considered discretionary foods, such as biscuits, crackers, and other snack foods, that are not an essential part of healthy dietary patterns and should only be eaten sometimes and in small amounts" and that "many of these manufactured foods could also be UPFs as some of their ingredients have undergone industrial processes such as fractioning, hydrolysis, hydrogenation, or chemical modifications. In addition, to make them more appealing to consumers, high levels of sugar, fats, and salt are frequently added." Therefore, with a broader view, upcycled foods should address together the three pillars of sustainability that are environmental, social, and economic dimensions (Thorsen et al., 2023).

4. A focus on ultra-processing and sustainability

Ultra-processed foods are briefly defined as "formulations of ingredients, mostly of exclusive industrial use, that result from a series of industrial processes (hence 'ultra-processed')" (Monteiro et al., 2019). To say it differently, they are characterized in their formulation by the addition of cosmetic ingredients and/or additives (i.e., markers of ultra-processing) for mainly industrial use - and having undergone excessive processing - to imitate, exacerbate, mask or restore sensory properties (aroma, texture, taste and color); and their processing can also involve very denaturing technological processes (cooking-extrusion, blowing, etc.).

For around sixty years, the massive development of UPFs in Western countries, and more recently in emerging and developing countries (Baker et al., 2020), has tended to drive upstream unsustainable agricultural production systems characterized in particular by intensive large monocultures and animal farms, and downstream through supplying to food retailers and consumers unhealthy foods and negative impacts of over-packaging (Fardet and Rock, 2020). Ultra-processed foods are pushed to the globalized market by their wide availability, convenience, hyper-palatability and intensive marketing practices (including 'glocalisation' with offers meeting local tastes). These products are today associated, when consumed in excess, with many increased risks of chronic disease and early mortality (Askari et al., 2020; Cascaes et al., 2022; Delpino et al., 2021; Martini et al., 2021; Mazloomi et al., 2022; Moradi et al., 2021, 2022; Pagliai et al., 2020; Suksatan et al., 2022; Wang et al., 2022; Yuan et al., 2023; Taneri et al., 2022). Price competition in food retail is not unlinked to this situation, as to achieve very low food prices, the industry is almost obliged to produce UPFs, in particular by replacing natural foods with very cheap ingredients of ultra-processing (*e.g.*, flavoring/aroma instead of real fruit) (Davidou et al., 2021). Beyond price competition, social, economic and political drivers are also involved, interconnected and associated to transformations all along the supply chain, *e.g.*, the expansion and growing market and political power of transnational food and beverage corporations as a driver of UPF development (Baker et al., 2020). Also, by definition, these UPFs are produced at large scale, to achieve economies of scale, with chemical preservatives to expand the shelf life, and are then very accessible through global value chains and big retailers/stores. The latter have become the dominant distribution channel to access food (a formal, very organized one) together with many other food system options (less formalized) available to the consumer today. More specifically, while UPFs well address food availability, ensuring food security and supplying cheap calories, and food safety, this is achieved to the detriment of food system sustainability, human health, and socio-economics (Fardet and Rock, 2020), and they also significantly contribute to GHGE (Fardet et al., 2024), *e.g.*, in France they contributed 24 % to the diet's GHGE, 23 % to water use, and 23 % to land use (Kesse-Guyot et al., 2022), and they account for 50 % of the total climate change and land use impacts in Belgium (Dénos et al., 2024).

Worldwide safe food availability during the whole year has therefore been achieved through industrial UPFs (Baker et al., 2020). The advent of ultra-processing may be considered as the last nutritional food transition, which began just after the Second World War with the development of new processing technologies, notably including food fractionation, purified ingredient syntheses, and drastic modern processes such as puffing, hydrogenation and extrusion-cooking. However, plant and animal-based UPFs have been more and more consensually associated with unsustainable food system outcomes (Anastasiou et al., 2022; da Silva et al., 2021; Kesse-Guyot et al., 2022; Lawrence, 2022; Northcott et al., 2023).

More generally, the reduction of consumption of useless excess calories, generally driven by UPFs (da Silva et al., 2021) or discretionary/non-core foods, without replacing them by alternative foods, appears to be a simple means of reducing the carbon footprint of our diet (Sundin et al., 2021). Of note, obesity has been reported to account for around 1.6 % of GHGE worldwide (Magkos et al., 2020).

5. Perspectives to food processing and sustainability: four emerging issues to address for the future?

Based on the above-mentioned considerations, reflections were carried out by our international and multidisciplinary consortium related to "food processing and food system sustainability". The consortium identified and discussed four emerging research topics - areas insufficiently addressed by research - related to food processing and sustainability. The intent here is not to discussed in depth these four topics, but to report the consortium's conclusions and perspectives.

5.1. How can food processing achieve together food and nutrition securities for enhanced sustainability?

This first topic is a global question, which also includes the three more specific sub-topics as described below in 5.2, 5.3 and 5.4. Food technologists are today challenged to develop products addressing all food and nutrition securities: Availability, Access (economic, social and physical), Utilization, Stability, Agency and Sustainability (HLPE/FAO, 2021; Fardet et al., 2024). As previously mentioned, UPFs are cheap calories available globally to as many people as possible, but to the detriment of human health, socioeconomics and environmental sustainability. The challenge now is also to include the other neglected dimensions with the approaching objective of feeding nine to ten billion people at horizon 2050. Thus, there is a real need to develop new and modern technologies to process foods to allow food availability for all, notably in countries where food self-sufficiency is impossible (*e.g.*, desert countries) while preserving human and environmental health. To address this issue, we must come back to the need for a clear definition of what is a "healthy food", notably based on a preserved "food matrix effect" (Fardet and Rock, 2022), to better inform food technologists in addressing the global health issue.

5.2. Re-connecting processing to local food systems? Issues and impacts

As reported by Baker and Friel (2016): “Traditional food systems are generally characterized by “short" supply chains involving the local production, distribution and consumption of unprocessed or minimally processed staple foods; while modern food systems are characterized by complex and globalized networks of many actors involved in the different stages of “long" supply chains, oriented towards maximum efficiency in order to reduce costs and increase production of a wider variety of food types” (Baker and Friel, 2016). Therefore, UPFs being massively and widely distributed by large multinational agri-food industries, first in Western countries, and more recently in emerging and developing countries (Wood et al., 2023), we may question whether it would not be preferable, for sustainability, to shift from the model of big international food industries to more relocated food processing industries directly connected to local production, notably to avoid ultra-processing, which is necessarily adapted to very long distances and long storage times. This leads us to the issue of short supply chains that might be adopted to relocate food transformations.

Thus, the dominant conventional food system - characterized by concentration of firms and value chains, globalization, specialization and financialization (Baker et al., 2020) - has led to the “disconnection” and the geographical and relational distancing between food producers and the final consumers. In social debates and scientific literature, special attention is paid to a wide variety of “alternative” initiatives that have developed to “re-connect” consumers with the place of production, the production methods and/or the people who produce food (Barham, 2003; Forssell, 2017; Ilbery et al., 2005; Renting et al., 2003). Over the last decades, the focus on short food supply chains, involving a reduced number of intermediaries between producers and consumers, has led to limited attention on intermediaries in general, and processors in particular (Chiffoleau and Dourian, 2020; Kneafsey et al., 2013). However, the issues associated with processing and the role of processors in local food systems are increasingly considered in different works, *e.g.*, the impact of processing technologies in terms of nutrition and health quality in short food supply chains (Chiffoleau and Dourian, 2020), the role of processors in supporting farmers’ market integration and development of local food systems (Hernández et al., 2021), the efficient and sustainable scale of processing units (De Vries et al., 2018), the inclusion of conventional players and avoiding “local-wash” (Cleveland et al., 2015), the adaptation of the processing technologies to less “industrialized” agriculture (smaller quantities, seasonal production, heterogeneous qualities) (Chiffoleau and Dourian, 2020), the inclusion of processors in local food policies, and what policies should be designed to support local reindustrialization (Chiffoleau et al., 2021).

5.3. Animal-based food processing and sustainability

Intensive animal-based food production has long been pointed out to contribute the most to GHGE and environment degradation. However, there has been little focus on animal-based food transformation and sustainability (Germond et al., 2024). Notably, intensive livestock production is generally devoted to supplying cheap animal-based products and ingredients, often in ultra-processed ready-to-eat meals. Beyond just the reduction of consumption of animal-based food, concomitant with the consumption of animal-based foods of higher quality (*i.e.*, Demitarian or flexitarian diets), one should question the transformation and sustainability of animal-based food, in particular the new sources of animal proteins such as insects and cultured meats, while keeping in mind the cultural dietary habits and environmental impacts as well. There is also the issue linked to the globalization of the food chain system in animal processing or by-products, *e.g.*, concerning fish processing, ten companies have 40 % of the market share, and crustaceans are transported all around the globe for processing (European Environment Agency, 2016).

Otherwise, through a relocation of food transformation, how should animal products be processed for better food systems, qualitatively regarding animals’ well-being, and quantitatively considering the nutrition balance with plant foods? This also raises the question of the slaughter of animals, especially those reared extensively. Another issue is that of sustainability when extracting and isolating nutrients from by-products of animal-based food through fractionation, *e.g.*, protein isolates, collagen and lactose.

5.4. The offer and the demand: can consumers influence the sustainability of food processing?

The current consumer mindset, encouraged by economical constraints (*e.g.*, conventional and intensive marketing practices), is one of the drivers of negative environmental impacts (White et al., 2019) and health impacts (unhealthy foods displace healthy alternatives). This is reinforced by the fact that in current food systems, the costs of harmful foods are externalized (*i.e.*, not reflected in market prices), and the benefits of healthy foods are not appreciated (FAO, 2023). These externalities often make sustainable and healthy foods less affordable to consumers. Major brands and companies claim that they capitalize on the high demand for processed foods for the general public over the years. Indeed, the agri-food industry is mainly reactive, not proactive, and adapts according to the *apparent* demands/needs of consumers, often driven by intensive promotion by retailers. Food habits followed by the community ostensibly seem to govern the demand for food (Coronado-Apodaca et al., 2023). However, studies showed that the UPFs are in the first instance created to support an economic gain rather than being a true demand from the consumer (Wood et al., 2023). It should also be mentioned that, worldwide, the supermarkets and fast food chains (a hegemony of a few multinationals with vested interests in the *status quo*) generally control what foods are available to the populations of big cities, accelerating the loss of culinary traditions.

Consumers are generally unaware of the extent to which their food choices impact the environment, however their food choices could participate in the shift to more sustainable diets. Mehrabi et al. (2022) highlight the important role of citizens in the transition to sustainable food systems, and consider that it is necessary to re-connect food consumers and food providers (Mehrabi et al., 2022). For this, it would appear mandatory to inform and educate consumers about what is happening behind the “*black box*" of processing, what are the choices they have to do, and what are the impacts of these choices; and, finally, to engage them towards sustainable diets as a key strategy for reducing global environmental impacts of the agricultural and food sectors (Petersson et al., 2021). This can be supported by a multilevel carbon and water footprint dataset of food commodities (Petersson et al., 2021).

Therefore, the main issue is to analyze how consumers can drive more sustainable food transformation, knowing that they have little education and information about this topic, implying that it is important to reduce complexity of diffused information. Consumers have significant influence over the trends and directions of food and agriculture systems. However, since they have little information on transformation/processing, and more on production/agriculture, they demand changes at the farm level specifically (*i.e.*, food crop production; this is the mainstream in mass media). Therefore, there is a need to go beyond influencing individual’s choices (Elliott et al., 2024; Potter et al., 2021). Clearly, there are numerous actors involved in food systems; and each of these stakeholders has their part of responsibility in this immensely complex path to food system change towards sustainability and transparency. Notably, as proposed by Koler and Levy (1971), companies in the agri-food sector need to adopt sustainable business models that consider, beyond economic aspects, major social and environmental sides. This means putting sustainability at the core of the value proposition. In this regard, demarketing should continue to draw attention of academicians, industrials and policymakers since it seems to be an effective strategy that promises to contribute to sustainability across all the three dimensions (Koler and Levy, 1971).

Hence, beyond unsustainable UPFs with enhanced sensory properties, how can we propose less processed and tasty foods without resorting to cosmetic agents? How can we change consumers' habits related to food choices and consumption? For the cost, how can externalities criteria be included in the current market price of those foods (Pieper et al., 2020), but without excluding vulnerable population groups? Thus, improving the food system will require deep transformations, in symbiosis with individual and collective actions.

6. Conclusions and perspectives

The emerging issue of food processing and sustainability is a huge challenge ahead (see also "The SWOT matrix of food processing and sustainability" in Table 1). In the near future, two scientific approaches/scenarios can be followed concerning food processing: it can be addressed either 1) in a reductionist way, e.g., through optimizing food processes, reducing energy demand and food waste and/or reformulating UPFs with upcycled ingredients, or 2) with a more holistic approach as proposed by the Four Pillars Framework for corporate alignment to the Sustainable Development Goals (Barilla FoundationUN Sustainable Development Solutions Network,). Certainly, food processing sustainability should include not only optimization of processes (i.e., a siloed approach) but also external factors linked to the food industry, such as providing a healthy and affordable diet for consumers, reorganizing food systems at more local scale, and reducing the negative ecological impact of animal and crop farming. As we previously concluded: "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." (Fardet et al., 2024).

Table 1
SWOT matrix of food processing and sustainability.

Strengths	Weaknesses
• A high level of sanitary security; • A high level of food availability; • A diversified food offering due to international fluxes.	• Too much ultra-processed foods associated with degraded food systems and energy-demanding processes; • Development of siloed and reductionist solutions (*i.e.*, greenwashing); • Depending too much on highly standardized ingredients all the year; • Most of the time reactive, and not proactive in the face of the challenges of current changes; • Legal or political measures that are not binding enough for increasing food processing sustainability.
Opportunities	**Threats**
• Evolution of food choices and expectations by consumers, *i.e.*, shorter list of ingredients, less processed foods and more naturalness; • Relocating food transformation, adapted to local production; • Revegetation of the plate due to climate chansge.	• Culinary traditions replaced by ultra-processed foods; • Degraded human health (increase chronic diseases) and reducing healthy life years; • Environment, including GHGE, deforestation, loss of biodiversity, reducing small farmers and small processors.

However, at the global level, there are undoubtedly very different geographies, socio-economic, environmental and/or agri-food industrial environments. These specificities, also included in the recent food sovereignty concept, need to be taken into consideration for future foresight food processing scenarios, notably for desert countries where often available agricultural areas to feed the whole population are insufficient, leading to inevitable importations of industrially processed foods. Thus, relocating food processing may not be the only solution for better sustainability. The main challenge here appears to be the quality of the imported processed foods, *i.e.*, coming from sustainable food processing in the country of origin, and not linked to deforestation imports.

Another concluding point concerns consumers' education on sustainable food processing and their awareness of food waste to lead to an increase of sustainable foods. Besides, this educational approach should encompass the transition to traditional diets and food products. In this case, it will be potentially possible to develop food processing schemes that comply with the pillars of bio-economy at a local level, motivating food industries to develop innovative and resilient food products (Kopsahelis and Kachrimanidou, 2019). The shift of consumers could also associate with ESG (environmental, social and governance) investing, that has been extensively prompted by numerous objectives, including SDGs. Bio-economy could facilitate the stimulation of ESG through the production of bio-based and value-added products, to comply with the emerging consumers demands. On top of that, the ESG criteria could be mentioned as an approach that food industries should comply with, driven by consumers' demand for sustainable food products. It should be noted that this approach refers to developed countries, as food industries have established processes, and consumers have secured access to food, and the target is to increase the resilience of food systems. Therefore, bio-economy can subsidize economic, environmental and social development, but still should be assessed on particular and provisional grounds, as different populations and areas demonstrate diversified priorities and needs.

In the end, one of the biggest challenges in the current Anthropocentric Age would be to develop both healthy, safe, tasty, and accessible processed foods for nearly ten billion people in 2050 while staying within planetary boundaries. For this, it appears that incremental and reductionist innovations will not be sufficient. More holistic breakthrough innovations are needed, and interventions need to be targeted at changing the values, assumptions and goals of the processed foods system. This means that any changes should be co-created with other actors of the agri-food chain, and recognize the interdependence of the actors of the whole system. The complex nature of food systems requires targeting multiple components simultaneously and a strong role for policy intervention. According to Baker et al. (2020), many frameworks exist to guide these cross-cutting changes: actions targeting food supplies (subsidies, reformulation …), food environments (advertising, promotion, labeling …), and behavior change communication (food--based dietary guidelines, mass-media campaigns, nutrition education in schools …) (Baker et al., 2020). Recently, the WHO reports that worldwide policy responses and regulatory actions are currently inadequate and weak (WHO, 2020). Therefore, it seems that the holistic position, notably through a relocation of food processing to avoid food waste and ultra-processing, and to regenerate food systems, is the most suitable for a global perspective (Fardet et al., 2024). Avoiding ultra-processing should stimulate more sustainable agri-food systems upstream and healthier foods downstream.

CRediT authorship contribution statement

Anthony Fardet: Writing – review & editing, Writing – original draft, Validation, Supervision, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Mike Boland:** Writing – original draft, Validation, Conceptualization. **Hoang Hong-Minh:** Writing –

original draft, Validation, Conceptualization. **Amélia Delgado:** Writing – original draft, Validation, Conceptualization. **Rafia Halawany-Darson:** Writing – original draft, Validation, Conceptualization. **Arnaud Germond:** Writing – original draft, Validation, Conceptualization. **Claudiu Eduard Nedelciu:** Writing – original draft, Validation, Conceptualization. **Nikolaos Kopsahelis:** Writing – original draft, Validation, Conceptualization. **Arnaud Diemer:** Writing – original draft, Validation, Conceptualization. **Virginie Baritaux:** Writing – original draft, Validation, Conceptualization. **Francesca Galli:** Writing – original draft, Validation, Conceptualization. **Edmond Rock:** Writing – original draft, Validation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

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Data availability

No data was used for the research described in the article.

References

Anastasiou, K., Baker, P., Hadjikakou, M., Hendrie, G.A., Lawrence, M., 2022. A conceptual framework for understanding the environmental impacts of ultra-processed foods and implications for sustainable food systems. J. Clean. Prod., 133155 https://doi.org/10.1016/j.jclepro.2022.

Anastasiou, K., Baker, P., Hendrie, G.A., Hadjikakou, M., Boylan, S., Chaudhary, A., Clark, M., DeClerck, F., Fanzo, J., Fardet, A., Marrocos Leite, F.-H., Mason-D`Croz, D., Percival, R., Reynolds, C., Lawrence, M., 2023. Conceptualising the drivers of ultra-processed food production and consumption and their environmental impacts: a group model-building exercise. Global Food Secur. 37, 100688. https://doi.org/10.1016/j.gfs.2023.100688.

Askari, M., Heshmati, J., Shahinfar, H., Tripathi, N., Daneshzad, E., 2020. Ultra-processed food and the risk of overweight and obesity: a systematic review and meta-analysis of observational studies. Int. J. Obes. 44 (10), 2080–2091. https://doi.org/10.1038/s41366-020-00650-z.

Augustin, M.A., Riley, M., Stockmann, R., Bennett, L., Kahl, A., Lockett, T., Osmond, M., Sanguansri, P., Stonehouse, W., Zajac, I., Cobiac, L., 2016. Role of food processing in food and nutrition security. Trends Food Sci. Technol. 56, 115–125. https://doi.org/10.1016/j.tifs.2016.08.005.

Axelos, M., Soler, L.G., Dallongeville, A., Thomas, A., Akermann, G.B.A., Antignac, J.-P., Benoit, P., Le Bizec, B., Bertin, N., Causse, M., Chakir, R., Chiffoleau, Y., Cravedi, J. P., Darmon, N., Denaix, L., Doré, A., Dubuisson-Quellier, S., Duru, M., Etilé, F., Fortané, N., Garric, J., Gésan-Guiziou, G., Hannachi, M., Jeuffroy, M.-H., Lamine, C., Lescourret, F., Libois, F., Marette, S., Martin - Laurent, F., Mougin, C., Oswald, I., Peyraud, J.L., Plantard, O., Prache, S., Rault, A., 2020. Nexus Santé: entre Agriculture – Alimentation – Environnement. Réflexion Prospective Pluridisciplinaire. Rapport de Synthèse. INRAe. France.

Baker, P., Friel, S., 2016. Food systems transformations, ultra-processed food markets and the nutrition transition in Asia. Glob. Health 12 (1), 80. https://doi.org/10.1186/s12992-016-0223-3.

Baker, P., Machado, P., Santos, T., Sievert, K., Backholer, K., Hadjikakou, M., Russell, C., Huse, O., Bell, C., Scrinis, G., Worsley, A., Friel, S., Lawrence, M., 2020. Ultra-processed foods and the nutrition transition: global, regional and national trends, food systems transformations and political economy drivers. Obes. Rev. 21 (12), e13126. https://doi.org/10.1111/obr.13126.

Bangsa, A.B., Schlegelmilch, B.B., 2019. Linking sustainable product attributes and consumer decision-making: insights from a systematic review. J. Clean. Prod., 118902 https://doi.org/10.1016/j.jclepro.2019.118902.

Barham, E., 2003. Translating terroir: the global challenge of French AOC labeling. J. Rural Stud. 19 (1), 127–138. https://doi.org/10.1016/S0743-0167(02)00052-9.

Barilla Foundation, UN Sustainable Development Solutions Network (UN SDSN), Columbia center on sustainable investment (CCSI), columbia center on sustainable investment (CCSI), 2020. Fixing the business of food - how to align the agri-food sector with the SDGs. Barilla Center for Food & Nutrition, Italy.

Barreca, F., Cardinali, G.D., 2019. ITACAFood: a model to certificate the sustainability of food processing facilities. Sustainability 11 (17), 4601. https://doi.org/10.3390/su11174601.

Bock, A.K., Bontoux, L., Rudkin, J., 2022. Concepts for a sustainable EU food system. In: Publications Office of the European Union (Ed.) EUR 30894 EN. European Commission, Luxembourg.

Bornkessel, S., Smetana, S., Heinz, V., 2019. Nutritional sustainability inside–marketing sustainability as an inherent ingredient. Front. Nutr. 6 (6), 84. https://doi.org/10.3389/fnut.2019.00084.

Bunge, A.C., Wickramasinghe, K., Renzella, J., Clark, M., Rayner, M., Rippin, H., Halloran, A., Roberts, N., Breda, J., 2021. Sustainable food profiling models to inform the development of food labels that account for nutrition and the environment: a systematic review. Lancet Planet. Health 5 (11), e818–e826. https://doi.org/10.1016/S2542-5196(21)00231-X.

Burlingame, B., Lawrence, M., Macdiarmid, J., Dernini, S., Oenema, S., 2022. IUNS task force on sustainable diets - linking nutrition and food systems. Trends Food Sci. Technol. 130, 42–50. https://doi.org/10.1016/j.tifs.2022.09.007.

Campi, M., Dueñas, M., Fagiolo, G., 2021. Specialization in food production affects global food security and food systems sustainability. World Dev. 141, 105411. https://doi.org/10.1016/j.worlddev.2021.

Capozzi, F., 2022. Food innovation in the frame of circular economy by designing ultra-processed foods optimized for sustainable nutrition. Front. Nutr. 3 (9), 886220. https://doi.org/10.3389/fnut.2022.886220.

Cascaes, A.M., Ribeiro Jorge da Silva, N., dos Santos Fernandez, M., Bomfim, R.A., Vaz, J.d.S., 2022. Ultra-processed foods consumption and dental caries in children and adolescents: a systematic review and meta-analysis. Brit. J. Nutr. https://doi.org/10.1017/S0007114522002409. Online ahead of print.

Chiffoleau, Y., Dourian, T., 2020. Sustainable food supply chains: is shortening the answer? A literature review for a research and innovation Agenda. Sustainability 12 (23), 9831. https://www.mdpi.com/2071-1050/12/23/9831.

Chiffoleau, Y., Echchatbi, A., Rod, J., Gey, L., Akermann, G., Desclaux, D., Jard, G., Kessari, M., Moinet, K., Peres, J., Robin, M.-H., Samson, M.-F., 2021. Quand l'innovation sociale réoriente l'innovation technologique dans les systèmes agroalimentaires : le cas des chaînes locales autour des blés. Innovations 64 (1), 41–63. https://doi.org/10.3917/inno.pr2.0095.

Cleveland, D.A., Carruth, A., Mazaroli, D.N., 2015. Operationalizing local food: goals, actions, and indicators for alternative food systems. Agric. Hum. Val. 32 (2), 281–297. https://doi.org/10.1007/s10460-014-9556-9.

Coronado-Apodaca, K.G., Martínez-Ruiz, M., Iqbal, H.M.N., Sosa-Hernandez, J.E., Parra-Saldívar, R., 2023. Agro-food sustainability transitions: new Frontiers for food security. Curr. Opin. Environ. Sci. Health 31, 100412. https://doi.org/10.1016/j.coesh.2022.

Crippa, M., Solazzo, E., Guizzardi, D., Monforti-Ferrario, F., Tubiello, F.N., Leip, A., 2021. Food systems are responsible for a third of global anthropogenic GHG emissions. Nature Food 2 (3), 198–209. https://doi.org/10.1038/s43016-021-00225-9.

da Silva, J.T., da Cruz, G.L., Rauber, F., Louzada, M.L., Kluczkovski, A.R.G., Frankowska, A., Schmidt, X., Reynolds, C., Bridle, S., Levy, R.B., 2020. The impact of ultra-processed food on carbon, water and ecological footprints of food in Brazil. Eur. J. Publ. Health 30 (Suppl. 5). https://doi.org/10.1093/eurpub/ckaa165.433.

da Silva, J.T., Garzillo, J.M.F., Rauber, F., Kluczkovski, A., Rivera, X.S., da Cruz, G.L., Frankowska, A., Martins, C.A., da Costa Louzada, M.L., Monteiro, C.A., Reynolds, C., Bridle, S., Levy, R.B., 2021. Greenhouse gas emissions, water footprint, and ecological footprint of food purchases according to their degree of processing in Brazilian metropolitan areas: a time-series study from 1987 to 2018. Lancet Planet. Health 5 (11), e775–e785. https://doi.org/10.1016/S2542-5196(21)00254-0.

Davidou, S., Christodoulou, A., Frank, K., Fardet, A., 2021. A study of ultra-processing marker profiles in 22,028 packaged ultra-processed foods using the Siga classification. J. Food Compos. Anal. 99, 103848. https://doi.org/10.1016/j.jfca.2021.103848.

De Vries, H., Mikolajczak, M., Salmon, J.-M., Abecassis, J., Chaunier, L., Guessasma, S., Lourdin, D., Belhabib, S., Leroy, E., Trystram, G., 2018. Small-scale food process engineering — challenges and perspectives. Innov. Food Sci. Emerg. Technol. 46, 122–130. https://doi.org/10.1016/j.ifset.2017.09.009.

Delpino, F.M., Figueiredo, L.M., Bielemann, R.M., da Silva, B.G.C., Dos Santos, F.S., Mintem, G.C., Flores, T.R., Arcêncio, R.A., Nunes, B.P., 2021. Ultra-processed food and risk of type 2 diabetes: a systematic review and meta-analysis of longitudinal studies. Int. J. Epidemiol. 51 (4), 1120–1141. https://doi.org/10.1093/ije/dyab247.

Dénos, C., Vandevijvere, S., Boone, L., Cooreman-Algoed, M., De Bauw, M., Achten, W.M. J., Dewulf, J., 2024. Contribution of ultra-processed food and animal-plant protein intake ratio to the environmental impact of Belgian diets. Sustain. Prod. Consum. 51, 584–598. https://doi.org/10.1016/j.spc.2024.10.008.

Dicken, S.J., Batterham, R.L., 2020. Ultra-processed food: a global problem requiring a global solution. Lancet Diab. Endocrinol. 10 (10), 691–694. https://doi.org/10.1016/S2213-8587(22)00248-0.

Dwivedi, S.L., Lammerts van Bueren, E.T., Ceccarelli, S., Grando, S., Upadhyaya, H.D., Ortiz, R., 2017. Diversifying food systems in the pursuit of sustainable food production and healthy diets. Trends Plant Sci. 22 (10), 842–856. https://doi.org/10.1016/j.tplants.2017.06.011.

Elliott, P.S., Devine, L.D., Gibney, E.R., O'Sullivan, A.M., 2024. What factors influence sustainable and healthy diet consumption? A review and synthesis of literature within the university setting and beyond. Nutr. Res. 126, 23–45. https://doi.org/10.1016/j.nutres.2024.03.004.

European Environment Agency, 2016. Seafood in Europe - A Food System Approach for Sustainability. Publications Office of the European Union.

Fagbohungbe, M.O., Hursthouse, A.S., Miller, J., Morrison, G., Stockwell, M., McLellan, I., 2021. Sustainable strategies for improved regulatory compliance within the food-processing sector. Proc. Ins. Civil Eng. - Waste Resour. Manag. 174 (2), 47–58. https://doi.org/10.1680/jwarm.20.00027.

FAO, 2018. Sustainable Food Systems - Concept and Framework. Rome, Italy.

FAO, 2023. The State of Food and Agriculture - Revealing the True Cost of Food to Transform Agrifood Systems. Rome, Italy.

Fardet, A., 2018. Chapter 3 - characterization of the degree of food processing in relation with its health potential and effects. Adv. Food Nutr. Res. 85, 79–121. https://doi.org/10.1016/bs.afnr.2018.02.002.

Fardet, A., 2024. Ultra-processing should be understood as a holistic issue, from food matrix, to dietary patterns, food scoring and food systems. J. Food Sci. 89 (7), 4563–4573. https://doi.org/10.1111/1750-3841.17139.

Fardet, A., Rock, E., 2020. Ultra-processed foods and food system sustainability: what are the links? Sustainability 12 (15), 6280. https://doi.org/10.3390/su12156280.

Fardet, A., Rock, E., 2022. Chronic diseases are first associated with the degradation and artificialization of food matrices rather than with food composition: calorie quality matters more than calorie quantity. Eur. J. Nutr. 62, 2239–2253. https://doi.org/10.1007/s00394-021-02786-8.

Fardet, A., Gold, S., Delgado, A., Kopsahelis, N., Kachrimanidou, V., Kaur, L., Galli, F., Rock, E., 2024. How can food processing achieve food and nutrition security? Sustain. Dev. 32 (4), 4172–4185. https://doi.org/10.1002/sd.2899.

Food Foundation, Plating Up Progress Policy Briefing, 2021. Mandatory Business Reporting to Accelerate the Food Industry's Transition to Healthy and Sustainable Food. Food Foundation, London, UK [UK].

Forssell, S., 2017. Perspectives on the Sustainability Promise of Alternative Food Networks, Department of Economics and Management. University of Helsinki, Faculty of Agriculture and Forestry, Helsinki, Finland.

Germond, A., Fardet, A., Álvarez Garcia, C., Boland, M., Ming Hoang, H., Mullen, A.-M., Kaur, L., 2024. Analyzing the complexity of animal products' processing and its impact on sustainability. Front. Sustain. Food Syst. 8, 1424282. https://doi.org/10.3389/fsufs.2024.1424282.

Hernández, P.A., Galli, F., Prosperi, P., Šūmane, S., Duckett, D., Almaas, H.E., 2021. Do small food businesses enable small farms to connect to regional food systems? Evidence from 9 European regions. Global Food Secur. 29, 100505. https://doi.org/10.1016/j.gfs.2021.100505.

HLPE/FAO, 2021. Report on Food Security and Nutrition: Building a Global Narrative towards 2030. HLPE/FAO, Rome, Italy.

Hoek, A.C., Malekpour, S., Raven, R., Court, E., Byrne, E., 2021. Towards environmentally sustainable food systems: decision-making factors in sustainable food production and consumption. Sustain. Prod. Consum. 26, 610–626. https://doi.org/10.1016/j.spc.2020.12.009.

Ilbery, B., Morris, C., Buller, H., Maye, D., Kneafsey, M., 2005. Product, process and place:an examination of food marketing and labelling schemes in Europe and north America. Eur. Urban Reg. Stud. 12 (2), 116–132. https://doi.org/10.1177/0969776405048499.

Independent Group of Scientists appointed by the Secretary-General, 2019. The Future Is Now: Science for Achieving Sustainable Development (GSDR 2019). United Nations, New York, USA.

Jonckheere, J., Neven, L., 2020. Implications of food processing: the role of ultraprocessed foods in a healthy and sustainable diet - health Impact. Environmental Iimpact, and Behavioral Aspects. Flemish Institute of Healthy Living, Laken (Brussels), Belgium.

Kesse-Guyot, E., Allès, B., Brunin, J., Fouillet, H., Dussiot, A., Berthy, F., Perraud, E., Hercberg, S., Julia, C., Mariotti, F., Deschasaux-Tanguy, M., Srour, B., Lairon, D., Pointereau, P., Baudry, J., Touvier, M., 2022. Environmental impacts along the value chain from the consumption of ultra-processed foods. Nat. Sustain. 6, 192–202. https://doi.org/10.1038/s41893-022-01013-4.

Klemes, J., Perry, S., 2007. Process Optimisation to Minimise Energy Use in Food Processing, Handbook of Waste Management and Co-product Recovery in Food Processing, ume 1. Woodhead publishing, pp. 59–89.

Klemes, J., Perry, S., 2008. Methods to Minimise Energy Use in Food Processing, Handbook of Water and Energy Management in Food Processing. Woodhead publishing, pp. 136–199.

Kneafsey, M.V.L., Schmutz, U., Balasz, B., Trenchard, L., Eyden-Wood, T., Bos, E., Sutton, G., Blackett, M., authors Santini, F., Gomez, Y., Paloma, S., 2013. Short food supply chains and local food systems in the eu. A state of play of their socio-economic characteristics. In: Office of the European Union. Luxembourg (Luxembourg).

Knorr, D., Watzke, H., 2019. Food processing at a crossroad. Front. Nutr. 6, 85. https://doi.org/10.3389/fnut.2019.00085.

Knorr, D., Augustin, M.A., Tiwari, B., 2020. Advancing the role of food processing for improved integration in sustainable food chains. Front. Nutr. 7 (34). https://doi.org/10.3389/fnut.2020.00034.

Koler, P., Levy, S.J., 1971. Demarketing, yes, demarketing. Harv. Bus. Rev. 79, 74–80.

Kopsahelis, N., Kachrimanidou, V., 2019. Advances in food and byproducts processing towards a sustainable bioeconomy. Foods 8 (9), 425. https://doi.org/10.3390/foods8090425.

Lane, M.M., Gamage, E., Du, S., Ashtree, D.N., McGuinness, A.J., Gauci, S., Baker, P., Lawrence, M., Rebholz, C.M., Srour, B., Touvier, M., Jacka, F.N., O'Neil, A., Segasby, T., Marx, W., 2024. Ultra-processed food exposure and adverse health outcomes: an umbrella review of epidemiological meta-analyses. BMJ 384, e077310. https://doi.org/10.20944/preprints202308.1407.v1.

Lawrence, M., 2022. Ultra-processed foods: a fit-for-purpose concept for nutrition policy activities to tackle unhealthy and unsustainable diets. Public Health Nutr. 1–5. https://doi.org/10.1017/S1368980022002117.

Magkos, F., Tetens, I., Bügel, S.G., Felby, C., Schacht, S.R., Hill, J.O., Ravussin, E., Astrup, A., 2020. The environmental foodprint of obesity. Obesity 28 (1), 73–79. https://doi.org/10.1002/oby.22657.

Martini, D., Godos, J., Bonaccio, M., Vitaglione, P., Grosso, G., 2021. Ultra-processed foods and nutritional dietary profile: a meta-analysis of nationally representative samples. Nutrients 13 (10), 3390. https://doi.org/10.3390/nu13103390.

Mazloomi, S.N., Talebi, S., Mehrabani, S., Bagheri, R., Ghavami, A., Zarpoosh, M., Mohammadi, H., Wong, A., Nordvall, M., Kermani, M.A.H., Moradi, S., 2022. The association of ultra-processed food consumption with adult mental health disorders: a systematic review and dose-response meta-analysis of 260,385 participants. Nutr. Neurosci. 1–19. https://doi.org/10.1080/1028415X.2022.2110188. Online ahead of print.

McGreevy, S.R., Rupprecht, C.D.D., Niles, D., Wiek, A., Carolan, M., Kallis, G., Kantamaturapoj, K., Mangnus, A., Jehlička, P., Taherzadeh, O., Sahakian, M., Chabay, I., Colby, A., Vivero-Pol, J.-L., Chaudhuri, R., Spiegelberg, M., Kobayashi, M., Balázs, B., Tsuchiya, K., Nicholls, C., Tanaka, K., Vervoort, J., Akitsu, M., Mallee, H., Ota, K., Shinkai, R., Khadse, A., Tamura, N., Abe, K.-i., Altieri, M., Sato, Y.-I., Tachikawa, M., 2022. Sustainable agrifood systems for a post-growth world. Nat. Sustain. 5, 1011–1017. https://doi.org/10.1038/s41893-022-00933-5.

Mehrabi, S., Perez-Mesa, J.C., Giagnocavo, C., 2022. The role of consumer-citizens and connectedness to nature in the sustainable transition to agroecological food systems: the mediation of innovative business models and a multi-level perspective. Agriculture 12 (2), 203. https://www.mdpi.com/2077-0472/12/2/203.

Miller, K.B., Eckberg, J.O., Decker, E.A., Marinangeli, C.P.F., 2021. Role of food industry in promoting healthy and sustainable diets. Nutrients 13 (8), 2740. https://www.mdpi.com/2072-6643/13/8/2740.

Monteiro, C.A., Moubarac, J.C., Cannon, G., Ng, S.W., Popkin, B., 2013. Ultra-processed products are becoming dominant in the global food system. Obes. Rev. 14 (Suppl. 2), 21–28. https://doi.org/10.1111/obr.12107.

Monteiro, C.A., Cannon, G., Levy, R.B., Moubarac, J.-C., Louzada, M.L.C., Rauber, F., Khandpur, N., Cediel, G., Neri, D., Martinez-Steele, E., Baraldi, L.G., Jaime, P.C., 2019. Ultra-processed foods: what they are and how to identify them? Public Health Nutr. 22 (5), 936–941. https://doi.org/10.1017/S1368980018003762.

Moradi, S., Hojjati Kermani, M.a., Bagheri, R., Mohammadi, H., Jayedi, A., Lane, M.M., Asbaghi, O., Mehrabani, S., Suzuki, K., 2021. Ultra-processed food consumption and adult diabetes risk: a systematic review and dose-response meta-analysis. Nutrients 13 (12), 4410. https://www.mdpi.com/2072-6643/13/12/4410.

Moradi, S., Entezari, M.H., Mohammadi, H., Jayedi, A., Lazaridi, A.V., Kermani, M.A.H., Miraghajani, M., 2022. Ultra-processed food consumption and adult obesity risk: a systematic review and dose-response meta-analysis. Crit. Rev. Food Sci. Nutr. 63 (2), 249–260. https://doi.org/10.1080/10408398.2021.1946005.

Northcott, T., Lawrence, M., Parker, C., Baker, P., 2023. Ecological regulation for healthy and sustainable food systems: responding to the global rise of ultra-processed foods. Agric. and Hum. Values. Ahead of print. https://doi.org/10.1007/s10460-022-10412-4.

Pagliai, G., Dinu, M., Madarena, M.P., Bonaccio, M., Iacoviello, L., Sofi, F., 2020. Consumption of ultra-processed foods and health status: a systematic review and meta-analysis. Brit. J. Nutr. 125 (3), 308–318. https://doi.org/10.1017/S0007114520002688.

Petersson, T., Secondi, L., Magnani, A., Antonelli, M., Dembska, K., Valentini, R., Varotto, A., Castaldi, S., 2021. A multilevel carbon and water footprint dataset of food commodities. Sci. Data 8 (1), 127. https://doi.org/10.1038/s41597-021-00909-8.

Pieper, M., Michalke, A., Gaugler, T., 2020. Calculation of external climate costs for food highlights inadequate pricing of animal products. Nat. Commun. 11 (1), 6117. https://doi.org/10.1038/s41467-020-19474-6.

Potter, C., Bastounis, A., Hartmann-Boyce, J., Stewart, C., Frie, K., Tudor, K., Bianchi, F., Cartwright, E., Cook, B., Rayner, M., Jebb, S.A., 2021. The effects of environmental sustainability labels on selection, purchase, and consumption of food and drink products: a systematic review. Environ. Behav. 53 (8), 1–35. https://doi.org/10.1177/0013916521995473.

Renting, H., Marsden, T.K., Banks, J., 2003. Understanding alternative food networks: exploring the role of short food supply chains in rural development. Environ. Plann.: Econ. Space 35 (3), 393–411. https://doi.org/10.1068/a3510.

Scrinis, G., Monteiro, C.A., 2018. Ultra-processed foods and the limits of product reformulation. Public Health Nutr. 21 (1), 247–252. https://doi.org/10.1017/s1368980017001392.

Sovacool, B.K., Bazilian, M., Griffiths, S., Kim, J., Foley, A., Rooney, D., 2021. Decarbonizing the food and beverages industry: a critical and systematic review of developments, sociotechnical systems and policy options. Renew. Sustain. Energy Rev. 143, 110856. https://doi.org/10.1016/j.rser.2021.110856.

Stillitano, T., Spada, E., Iofrida, N., Falcone, G., De Luca, A.I., 2021. Sustainable agri-food processes and circular economy pathways in a life Cycle perspective: state of the art of applicative research. Sustainability 13 (5), 2472. https://doi.org/10.3390/su13052472.

Suksatan, W., Moradi, S., Naeini, F., Bagheri, R., Mohammadi, H., Talebi, S., Mehrabani, S., Kermani, M.A.H., Suzuki, K., 2022. Ultra-processed food consumption and adult mortality risk: a systematic review and dose-response meta-analysis of 207,291 participants. Nutrients 14 (1), 174. https://doi.org/10.3390/nu14010174.

Sundin, N., Rosell, M., Eriksson, M., Jensen, C., Bianchi, M., 2021. The climate impact of excess food intake - an avoidable environmental burden. Resour. Conserv. Recycl. 174, 105777. https://doi.org/10.1016/j.resconrec.2021.105777.

Taneri, P.E., Wehrli, F., Roa Diaz, Z.M., Itodo, O.A., Salvador, D., Raeisi-Dehkordi, H., Bally, L., Minder, B., Kiefte-de Jong, J.C., Carmelli, J.L., Bano, A., Glisic, M., Muka, T., 2022. Association Between Ultra-Processed Food İntake and All-Cause Mortality: A Systematic Review and Meta-Analysis. Am. J. Epidemiol 191 (7), 1323–1335. https://doi.org/10.1093/aje/kwac039. July 2022.

Teixeira, J.A., 2018. Grand challenges in sustainable food processing. Front. Sustain. Food Syst. 2, 19. https://doi.org/10.3389/fsufs.2018.00019.

Thorsen, M., Skeaff, S., Goodman-Smith, F., Thong, B., Bremer, P., Mirosa, M., 2022. Upcycled foods: a nudge toward nutrition. Front. Nutr. 9, 1071829. https://doi.org/10.3389/fnut.2022.1071829.

Thorsen, M., Mirosa, M., Skeaff, S., Goodman-Smith, F., Bremer, P., 2023. Upcycled food: how does it support the three pillars of sustainability? Trends Food Sci. Technol. 143, 104269. https://doi.org/10.1016/j.tifs.2023.104269.

Tilman, D., Clark, M., 2014. Global diets link environmental sustainability and human health. Nature 515 (7528), 518–522. https://doi.org/10.1038/nature13959.

Toussaint-Samat, M., 2008. A History of Food. Wiley-Blackwell; 2nd, New and Expanded Edition, Oxford, UK.

van Boekel, M., Fogliano, V., Pellegrini, N., Stanton, C., Scholz, G., Lalljie, S., Somoza, V., Knorr, D., Jasti, P.R., Eisenbrand, G., 2010. A review on the beneficial aspects of food processing. Mol. Nutr. Food Res. 54 (9), 1215–1247. https://doi.org/10.1002/mnfr.200900608.

van der Goot, A.J., Pelgrom, P.J.M., Berghout, J.A.M., Geerts, M.E.J., Jankowiak, L., Hardt, N.A., Keijer, J., Schutyser, M.A.I., Nikiforidis, C.V., Boom, R.M., 2016. Concepts for further sustainable production of foods. J. Food Eng. 168, 42–51. https://doi.org/10.1016/j.jfoodeng.2015.07.010.

Wang, L., 2013. Energy consumption and reduction strategies in food processing. In: Tiwari, K., Norton, Tomas, Holden, Nicholas M. (Eds.), Sustainable Food Processing. Brijesh, pp. 377–400. https://doi.org/10.1002/9781118634301.ch16.

Wang, M., Du, X.Y., Huang, W., Xu, Y., 2022. Ultra-processed foods consumption increases the risk of hypertension in adults: a systematic review and meta-analysis. Am. J. Hypertens. 35 (10), 892–901. https://doi.org/10.1093/ajh/hpac069.

White, K., Habib, R., Hardisty, D.J., 2019. How to shift consumer behaviors to be more sustainable: a literature review and guiding framework. J. Mark. 83 (3), 22–49. https://doi.org/10.1177/0022242919825649.

WHO, 2020. Assessing National Capacity for the Prevention and Control of Noncommunicable Diseases: Report of the 2019 Global Survey. Geneva, Switzerland.

Wood, B., Williams, O., Baker, P., Sacks, G., 2023. Behind the 'creative destruction' of human diets: an analysis of the structure and market dynamics of the ultra-processed food manufacturing industry and implications for public health. J. Agrar. Change. https://doi.org/10.1111/joac.12545. Ahead of print.

Woodhouse, A., Davis, J., Penicaud, C., Ostergren, K., 2018. Sustainability checklist in support of the design of food processing. Sustain. Prod. Consum. 16, 110–120. https://doi.org/10.1016/j.spc.2018.06.008.

Yuan, L., Hu, H., Li, T., Zhang, J., Feng, Y., Yang, X., Li, Y., Wu, Y., Li, X., Huang, h., Hu, F., Chen, C., Zhang, M., Zhao, Y., Hu, d., 2023. Dose–response meta-analysis of ultra-processed food with risk of cardiovascular events and all-cause mortality: evidence from prospective cohort studies. Food Funct. 14, 2586–2596. https://doi.org/10.1039/D2FO02628G.