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A B S T R A C T

Food systems are composed of interrelated activities that transform agricultural products into food. Their operations need to meet several food security, food safety, and sustainability requirements. Therefore, risk assessment of food systems must be multidisciplinary and include food safety, nutrition, environmental, economics, and social criteria. However, combining these criteria to assess multiple impacts remains a challenge in complex and multi-stakeholder systems. Until now, only a few holistic assessments, whether domain-oriented or generic and with different levels of quantification, have covered all criteria and the whole food systems. We reviewed and presented the various assessment methods and their applications in food systems, highlighting their advantages and disadvantages. Recommendations were made for a tiered approach combining different holistic assessment methods.

1. Introduction

Assessing the impacts of food systems encompasses the evaluation of the effects of its different elements and activities related to food production, processing, distribution, preparation, and consumption, from an economic, safety, health, social, and environmental perspective (IFPRI, 2023; OECD, 2023; Willett et al., 2019). The complexity of assessing food systems based on these several criteria results in increased complexity in regulatory decision-making. Focusing on single benefits for each of these criteria could lead to a multitude of conflicting goals as these criteria are also of interest to different stakeholders within the decision-making process. For instance, one may want to control microbiological risks (safety goal) by applying more stringent thermal treatments which in return increase the energy demand (conflicting with the environment goal) and also may generate neo-formed contaminants (conflicting with the safety goal).

Several recent attempts to assess food systems exist, although often domain-oriented and independent of each other, they address a broad range of criteria. For instance, Willett et al. (2019) examined the nutrition and environmental aspects of food systems. Fardet & Rock (2020) considered health and nutrition in a broader assessment including environmental and socio-economic factors but without quantifying the latter. Ritchie et al. (2018) introduced the concept of a "field-to-fork" assessment of nutritional intakes, proposing a food system assessment from a nutritional perspective. These clearly show the desire to move towards holistic assessments of food systems but also highlight its challenges. Firstly, studying a food system in a holistic manner means taking on a very broad scope, which may require considerable resources to be conducted properly in a reasonable timeframe. Secondly, it requires a multidisciplinary team, sharing the same vocabulary and objective, which is not immediate in a scientific landscape often organized by disciplines. Thirdly, there is the need to go beyond the description of the different criteria and provide quantitative or semi-quantitative outputs for making evidence-based decisions in a transparent manner. This will increase the confidence of risk managers and ensure sound recommendations from senior policymakers (FAO, 2017).

In this perspective paper, we have built on our collective expertise on risk-benefit assessment, willingness-to-pay, cost-utility analysis, and other multi-criteria methods, to identify the advantages and disadvantages of methods currently used in holistic risk assessment, in order to provide a basis on which food systems can be assessed. Therefore, this paper aims to provide guidance on methods to assess food systems now and in the near future due to for instance new policy measures, emergent consumer habits, or, global economic crisis. We particularly fostered solutions that maximise co-benefits for human health (nutrition and

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food safety), the environment and the economy. This was done by evaluating the extent to which the current methods assess the food systems holistically. Next, the benefits and drawbacks of holistic approaches versus domain-based methods were addressed before concluding with recommendations for risk assessors and risk managers.

2. Methods for assessing food systems

2.1. Domain-oriented approaches

2.1.1. Life cycle assessments

Life Cycle Assessment (LCA) allows to assess the environmental impacts of goods and services across its life cycle, e.g., for a food including the production of its raw commodities, transportation, distribution, consumption and any food loss and waste occurring along these phases. Among its advantages, is its wide-scope (e.g., cradle-to-grave) that accounts for all the inputs within the food systems even from indirect processes (e.g., packaging manufacture) and its established methodology (e.g., ISO14040 and ISO 14044), Product Environmental Footprints (PEFCR) of the EU). The environmental impact is evaluated using several methodologies (e.g., ReCiPe, IMPACT, 2002+) expressing results as midpoint (e.g., greenhouse gas emissions, fresh water use, biodiversity loss, eutrophication, land use, etc.) or endpoint categories (e.g., damage to human health) (Rosenbaum et al., 2018). Midpoint categories allow the translation of relevant emissions or resource extractions before reaching the population or protected entities (e.g., human, animal, natural environment). The midpoint categories are seen as more relevant for decision-making and less uncertain due to the proximity of the event to the receiving population; in addition substances associated with several direct and indirect impacts are not captured at the endpoint stage (Dekker et al., 2020).

Due to its utility, LCA has been extended to assess social (s-LCA) and nutritional impact (n-LCA) (McLaren et al., 2021; UNEP, 2021), which moves the methodology towards a multi-domain approach. The s-LCA assesses the potential or actual social impact of products and processes on different stakeholders namely workers, consumers, the local community, society, value chain actors, and children (UNEP, 2021; Mármol et al., 2023). These social impacts on different stakeholders are assessed based on the guidelines set by the United Nations Environment Programme while a variety of tools can be used across the food supply chain (Desiderio et al., 2022; UNEP, 2021). Meanwhile, n-LCA has been developed for food systems to translate to nutritional impact of food products or diets throughout the lifecycle of the product from production until consumption ("cradle to plate").

The utility of LCA as a tool in holistic assessments can be through decision-making processes by identifying which part of the supply chain to focus on. This is exemplified in the hotspots identified across the different supply chains such as the production of milk (Guzmán-Luna et al., 2022), butter (Flysjö, 2011), canned sardines (Almeida et al., 2015), recipes (Cambeses-Franco et al., 2023), and different dairy farms (Mazzetto et al., 2022). Furthermore, n-LCA is a tool to account for nutritional quality of food products and novel foods while doing environmental impact assessment (Fardet and Rock, 2020; Mazac et al., 2023; McAuliffe et al., 2020). One of the advantages of using LCA is its cradle-to-grave scope allowing it to account for the impacts generated from various locations. Another development in LCA is to combine the indicators into one score (Jolliet, 2022; Röös et al., 2015) or visual representation (e.g. traffic light system) (Stylianou et al., 2021). Although, this raises the question of how weighting individual indicators was performed.

The use of LCA with other assessment methods is, however, not straightforward due to differences in scope, functional units and data used (Feliciano et al., 2022). This comparison difficulty can also be seen in n-LCA where nutrition database values, functional unit applied, and the availability of data on consumer practices often differ per study. Meanwhile, among the difficulties in s-LCA are the complexity of social issues and its impact pathways especially in industrial settings (Mármol et al., 2023; Pollok et al., 2021). Overall, these differences between studies add challenges when aggregating and comparing results published in the literature. Besides, as LCA is constrained by the current system data, it cannot be used to assess alternative (e.g., optimized) food systems that deviate largely from the current food system (Notarnicola et al., 2017).

2.1.2. Human health assessment

The societal burden of foodborne diseases or diet-related illnesses are expressed as population health metrics (e.g., incidence and mortality), or composite indicators that combine morbidity and mortality (i.e., disability adjusted life years, DALY and quality adjusted life years, QALY). The DALY is a popular metric used in public health research and officially adopted by the WHO and a key measure for Global Burden of Disease (GBD) studies (GBD 2017 Risk Factor Collaborators, 2018 Risk Factor Collaborators, 2018; WHO, 2020). It is also the metric of choice for several health risk-benefit assessments (RBAs) (Membré et al., 2021; Verhagen et al., 2021). RBAs quantify the health impacts of diets, foods, or food components by integrating knowledge on nutrition, toxicology, microbiology, and epidemiology to assess risks and benefits (Boué et al., 2022; De Oliveira Mota et al., 2021; Thomsen et al., 2019). These can include beneficial effects associated with the intake of nutrients or foods, as well as adverse effects associated with dietary risk factors, nutritional status (e.g., undernutrition), chemicals (e.g. pesticides), and foodborne hazards.

The QALY is a health gain measure and calculated based on the utility weight of the health state that is multiplied by the duration spent in health state (Gold et al., 2002). QALY became the standard metric in health economic evaluations and cost-utility analyses. Using QALY instead of DALY is preferred by some because the QALY utility weights are population based and country specific, while DALY weights are based on expert judgement (Hoffmann et al., 2012).

These methodologies have the advantage of integrating morbidity and mortality in one single number; being applicable to measure various health outcomes and allow for comparisons of these health outcomes across countries. Yet, these metrics have been applied with the focus on consumer health, and not with the perspective of whole food systems on human health impacts (Assunção et al., 2019). For example, health of farmers and industry workers exposed to chemical substances have not often been included in RBAs, as RBAs typically target health outcomes based on exposure levels of the general population (Nauta et al., 2018), whereas occupational exposure and related risks are often addressed in separated assessments that supports regulation of safe working environments (Vinsonneau and Lyapcheva, 2024). Other disadvantages include challenges that are inherent to communicating composite metrics: suitable for a population-level decision but not easily interpreted by an individual.

2.1.3. Economics-oriented assessments

Cost of illness (CoI) studies estimate the economic burden of diseases accounting direct health costs (e.g. drugs, hospitalization), direct non-health (e.g. transport) and indirect non-health costs (e.g. absence from work) for a given period of time. Originally, CoI did not include pain and suffering, but were recently included in some authors (Devleesschauwer et al., 2018). Cost-effectiveness (CEA) and cost-utility analyses (CUA), on the other hand, mainly focuses on cost associated with health losses (Focker and van der Fels-Klerx, 2020; Pitter et al., 2015).

Inversely, the cost-benefit analysis (CBA) relies on the welfare economics accounting from gains and losses of all agents related to private and/or public choices for improving safety and/or environment. The CBA is based on (i) the microeconomic theory determining consumers' surplus/demands and producers' profits/supplies along the supply chain, and (ii) the empirical measure for one or several improved characteristics expressed in terms of willingness to pay (WTP) or willingness to accept (WTA) (Foster and Just, 1989; Freeman et al., 2014).

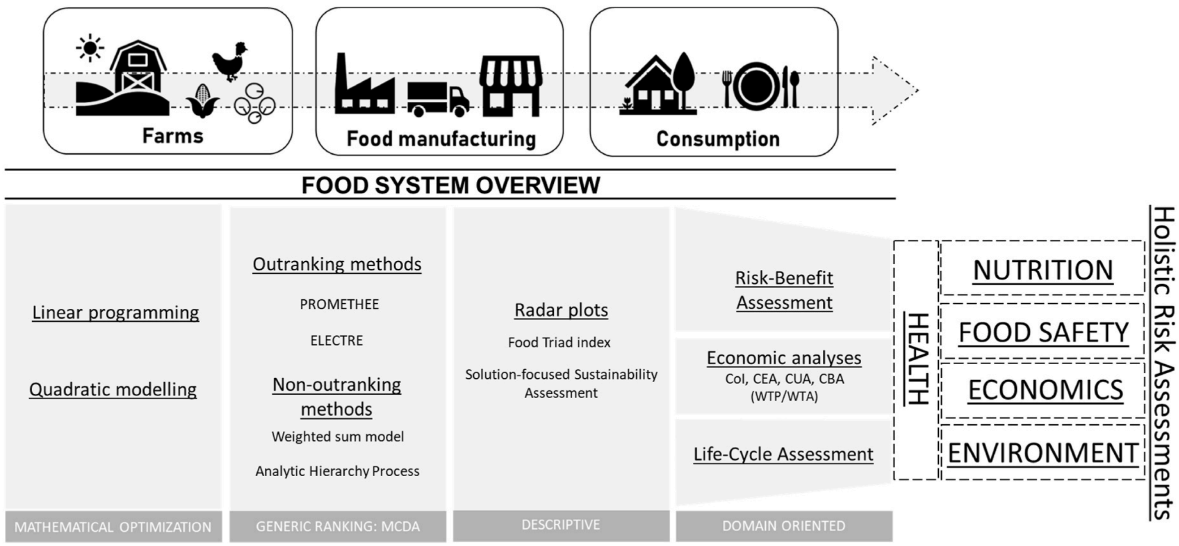

Fig. 1. The holistic risk assessment and existing approaches for integration. Note that the four criteria include elements of health assessment. Acronym: Cost of Illness studies (CoI), Cost-Effectiveness Analysis (CEA), Cost-Utility Analysis (CUA), Cost-Benefit Analysis (CBA), Willingness-To-Pay (WTP), and Willingness-To-Accept (WTA).

The CBA framework with WTP/WTA can measure market adjustments following quality improvements related to safety, health and/or environmental characteristics, evaluated with a common-monetary metric. With the CBA, the impact of regulatory in norms and standards, subsidies and/or taxes or labels and recommendations can be evaluated via a partial equilibrium model that focuses on one specific product, integrating farmers, supply chain, imports and exports, consumers and third parties like dwellers valuing environmental damages (Disdier and Marette, 2012). To characterize food systems, the method can be extended to general-equilibrium approaches seeking to understand how changes and/or policies may affect productions across different categories of markets and foods.

One major limitation of CBA is the fragility of WTP/WTA elicitation, with the focus on one specific characteristic or food, while consumers are generally concerned by a basket of options encompassing several foods. Another disadvantage of economic-oriented metrics is its acceptability from all stakeholders, including the general public: e.g., converting biodiversity or human life into one currency could make public debates very controversial (Roosen and Marette, 2011).

2.2. *Methods combining multiple criteria*

2.2.1. *Descriptive approach: "radar plots"*

Radar plots illustrate multiple criteria on a single graphic in the form of closed polygonal profiles of definite size, position, and shape, like a probability distribution function, where each property is represented by an axis of the chart (Porter and Niksiar, 2018). Radar plots make it possible to identify similarities and potential trade-offs between criteria. However, since these charts are multidimensional, results cannot be expressed in a single value. Radar plots have been used by Hollander et al. (2019) for different fish production and consumption scenarios, evaluating their sustainability, nutritional impact and food safety aspects based on the Solution-focused Sustainability Assessment (SfSA) framework. Another example is the Food-triad index, calculated by ranking multiple features from the nutritional, health and environmental criteria for food products (de Almeida Sampaio Guido et al., 2020). These approaches are not integrative with the advantage of being easily interpretable and transparent. However, these are not designed to balance the value of each criterion nor to identify best alternatives among several options.

2.2.2. *Mathematical optimization*

Mathematical optimization tools such as linear programming or quadratic modelling are useful in translating nutritional needs into food choices with food safety, bioavailability, budget for food, consumption habits and environmental impact (Gazan et al., 2018). Mathematical optimization models can generate a specific solution that fulfil several constrain simultaneously. In the context of the diet, they are useful to identify optimal food intakes that minimize adverse health effects (van Dooren, 2018). Improvement of the nutritional profile of diets and food baskets without cost increases has been investigated (Gurmu et al., 2019; Maillot et al., 2017). In addition, optimization methods have the advantage of being able to consider the main criteria of sustainability: health, environment, economy and cultural acceptability (Burlingame and Dernini, 2012). Studies accounting for these four criteria were conducted to optimize food supplies in educational settings (Eustachio Colombo et al., 2019). Masino et al. (2023) applied a similar analysis targeting omnivores and diets with a reduced amount of animal products. Mathematical optimization is also used in a broader context of circular food systems with different sectors and activities to assess the possible reinvention of food systems in the future (van Zanten et al., 2023). They have implemented it using a broadscale biophysical data-driven model comprised of interconnected modules of farming (crop, farm animal system, fisheries), residual streams, transportation, and GHG emissions.

However, due to the heterogeneity of the different criteria and the diversity of their metrics (e.g., intake of nutrients in grams per day, prices in monetary units, environmental indicators in greenhouse gas emissions), their integration into one model is complex (Gazan et al., 2018). This generates a lack of transparency and endorsement by decision-makers. These models require also large amounts of data and the applicability of the results relies on the availability and quality of data, reason why uncertainty has to be explicitly accounted to make this quantitative approach relevant for end-users. Sensitivity analysis following a deterministic or probabilistic approach, Bayesian frameworks, fuzzy set theory, or grey theory are among other techniques to evaluate the uncertainty impact on the assessment outputs (Broekhuizen et al., 2015).

2.2.3. *Generic ranking based on multi-criteria decision analysis*

Multi-criteria decision analysis (MCDA) includes a broad category of generic methods suitable for integrating the different aspects of

Table 1
Overview of holistic methods with their advantages and disadvantages.

Assessment method	Characteristics	
	Advantages	Disadvantages
Domain-oriented approaches		
Human health: RBA	A quantitative method that expresses the result in a single value (DALY, QALY) to make the decision, in theory, straightforward.	Lack of transparency when not able to include all health effects associated with an exposure. Challenging to communicate.
Environment: LCA	Captures the broad range of impact of an emission on the environment and different populations. Recently, possibility to account beyond environmental impacts, for societal (s-LCA) or nutritional (n-LCA) impacts.	Difficult to achieve consensus between stakeholders on the boundary of the system on which assessment is performed. Requires substantial amount of both qualitative and quantitative data originating from heterogeneous databases. This adds constraint when aggregating different studies. Based on the current food system and can therefore not be used to assess alternative (optimized) food systems that deviate largely from the current food system.
Economics: Costs-Benefits Analysis, Willingness to Pay, Cost of Illness	Adapted to the risks and benefits incurred by the consumer. Cost Benefit and Cost of Illness are quantitative methods which express the results in single monetary value. Consumer behaviours, profits along the supply chain, cost of illness, and impacts of regulation are taken into account with WTP (micro-economy). Besides, WTP may be adapted to assess safety and environment.	There are difficulties to get information about the production costs along the supply chain and how regulation impacts these costs. Translating health into monetary values might not be easily acceptable to some stakeholders. WTP might be seen as subjective when applied to a complex food system with multiple operational steps that consumers do not know well. There are many potential biases regarding the WTP elicitation.
Methods combining multiple criteria		
Radar plots	Transparent and easy to communicate.	Does not provide an aggregation, then not easy to use for decision-making.
Mathematical optimizations	Quantitative, in theory easy to make a decision based on its outputs	Mechanistic representation of the values is not fully explainable.
MCDA	Flexible: It is possible to integrate indicators of a different nature and not necessarily quantitative (ordered values are enough). Relatively easy to communicate (as intuitive).	Need stakeholders for providing weights, which might be seen as subjective.

decision-making. MCDA is typically applied to problems with multiple, often conflicting criteria that needs evaluation across domains. The outranking methods (e.g. PROMETHEE, ELECTRE) have been advocated by Wątróbski et al. (2019) and Van der Fels-Klerx et al. (2018) when dealing with semi-quantitative ordered criteria from different nature. They could manage weak or strict preferences between alternatives but also indifference or even incomparability. Likewise, utility-based MCDA methods allows to aggregate the utilities of alternatives on each selected criterion (Greco et al., 2016; Henson et al., 2007).

MCDA methods are flexible, provide transparency during criteria weighting before aggregating into a final ranking score. This depends on the group of assessors as different sets of weights may be given by different groups of stakeholders (e.g., regulators, citizens, food business operators). The FAO (2017) demonstrated the utility of outranking methods in comparing different interventions to reduce risks caused by aflatoxins in maize. The quantitative criteria DALY reduction due to lower occurrences of liver cancer and costs while feasibility, food accessibility and effect on childhood stunting were qualitative, ordered criteria. This illustrates an advantage of outranking methods: they do not require a full quantification of the criteria. Another advantage is they can relate different parts of the food system as the interventions evaluated were either upstream or downstream chain (from pre-harvest option up to dietary modification). Meanwhile, the algorithm behind the ranking might be difficult to communicate as well as outcomes generated through a given weighting system that, albeit transparent might be controversial.

3. Conclusion and recommendations

Holistic assessments are necessary to integrate various crucial criteria associated with food systems (Fig. 1). They allow for a science-based approach by incorporating specialized scientific expertise (e.g., predictive microbiology models, LCA tools, socioeconomics) within the assessments. They are also essential to address the additional burden of emerging food safety and security issues due to climate change and others which require compromises (e.g., increase water use to reduce microbial load in produce). Decision-making within food systems will evolve as regulatory authorities are constantly challenged to find solutions that incorporate various criteria related to sustainability (Marette and Réquillart, 2020; Tribaldos and Kortetmäki, 2022).

Hence, risk managers need to consult and evaluate various types of evidence to account for multiple factors when making decisions that are structured, coherent, and transparent (FAO 2017). Generally, the problem formulation surrounding a risk assessment issue is often framed within a discipline-specific approach. Scientific advice is then delivered to risk managers through the lens of the requested domain(s). This domain-segregated approach may pose difficulties in providing transparency on how the different sources of evidence were interpreted and considered during policy formulation (FAO, 2017; Rideout and Kosatsky, 2017).

The methodology chosen to perform a holistic assessment of a food system therefore cannot be totally separated from the decision-maker who will be involved in the management phase. That is definitely a first drawback. The second was illustrated in the previous section: we pointed out that all holistic methods, although they have their strengths, face intrinsic limitations and bottlenecks (complexity, lack of transparency, difficulty in encompassing the full extent of the food system, etc.) (Table 1). Besides, each method requires specific data that can be very costly to produce or collect, as well as highly specialized analytical expertise; this is not necessarily feasible in the context of evaluation, which also has its own time and resource constraints. Finally, the methods share a final drawback: the impacts of the different criteria included in the assessment have a different time scale (e.g., loss of biodiversity has a longer impact than contamination by food-borne pathogens), which highlights the necessary trade-off between short and long-term impact decisions.

Consequently, it may be difficult to recommend one approach regardless the question, stakeholders involved, data and the timeframe. Current methodological toolset offers multiple solutions, and it is not suggested to concentrate further development on elaborating completely new tools, but to combine them in a feasible and flexible way. It seems appropriate to adopt a tiered approach starting with descriptive method (radar plots) to rough out the holistic assessment, and gradually enrich the decision-making by simultaneously conducting several methods and gain robustness. The decisions on the type of multi-criteria method to be used in a subsequent tier depend on the outcome of the assessment of the previous tier and on the exact question, data availability, timeframe, resource availability and the user needs of the final outcome. The tiered approach would not only mean a stepwise use of multiple methodologies, but also a transdisciplinary team of assessors, with the ability to conduct and follow the constant evolution of the models from a qualitative (or semi-quantitative) assessment towards a more data-driven quantitative methodology, as models (or just specific parts of the model) would be enriched with new data and metadata. Moreover, the uncertainty and assumptions underlying the construction of the assessment must be explicitly presented and discussed. Another recommendation is addressed to decision makers. Risk management issues should be formulated within a systems-thinking perspective, which would lead to better scientific advice when assessing interrelated risks in a food system. Fostering cross departmental and trans-disciplinary collaboration among risk assessors and regulatory authorities might be optimized if the initial question underlying the assessment is defined in a transdisciplinary manner. The various case-studies and methodological developments relating to holistic assessments of food systems that are expected to be conducted and published in the coming years, will certainly allow us to step back and refine these initial recommendations.

CRediT authorship contribution statement

Erika Országh: Writing – review & editing, Writing – original draft. **Constanza De Matteu Monteiro:** Writing – review & editing, Writing – original draft. **Sara M. Pires:** Writing – review & editing, Writing – original draft, Conceptualization. **Ákos Jóźwiak:** Writing – review & editing, Writing – original draft, Conceptualization. **Stéphan Marette:** Writing – review & editing, Writing – original draft, Conceptualization. **Jeanne-Marie Membré:** Writing – review & editing, Writing – original draft, Supervision, Conceptualization. **Rodney J. Feliciano:** Writing – review & editing, Writing – original draft, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

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

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