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To cite this version:

Rodney Feliciano, Paola Guzmán-Luna, Géraldine Boué, Miguel Mauricio-Iglesias, Almudena Hospido, et al.. Strategies to mitigate food safety risk while minimizing environmental impacts in the era of climate change. Trends in Food Science and Technology, 2022, 10.1016/j.tifs.2022.02.027 . hal-03689474

HAL Id: hal-03689474
https://hal.inrae.fr/hal-03689474v1

Submitted on 7 Jun 2022

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Trends in Food Science & Technology xxx (xxxx) xxx

Contents lists available at ScienceDirect

Trends in Food Science & Technology

journal homepage: www.elsevier.com/locate/tifs

Strategies to mitigate food safety risk while minimizing environmental impacts in the era of climate change

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ARTICLE INFO

Keywords:
Microbial risk
Chemical risk
Life cycle approach
Carbon footprint
Decision-making
Environmental sustainability

ABSTRACT

Background: Food value chains are linked to environmental issues such as greenhouse gas emissions, which are responsible for climate change. The presence of chemical and microbial hazards along food value chains is expected to be influenced by the future effects of climate change. This challenge creates a need to examine environmentally sustainable strategies to address food safety risks. The use of methodologies and/or tools that contribute both to reducing food safety risk under climate change conditions and to reducing the contribution to climate change of food value chains is necessary.

Scope and approach: To face this upcoming and complex challenge, this study presents the tools to mitigate food safety risk on one hand and to evaluate the environmental performance of food value chains on the other. Successful case studies in different fields in which both methodologies were integrated are analyzed in detail finally to suggest strategies to mitigate food safety risks while minimizing environmental impacts in the food value chain.

Key findings and conclusions: Food value chains can use both risk assessment and life cycle assessment to limit environmental impact and food safety risks. The use of these two tools can be through the integration of the methods or by a combination of results. However, this should be carried out with caution due to differences within their frameworks.

1. Introduction

Climate change is a multifaceted phenomenon that has an influence on food systems globally (IPCC, 2015). It is foreseen that climate change will increase the spread of vector-borne diseases (e.g., flies), including those that carry foodborne pathogens, which are expected to occur in the future due to favorable warmer temperatures. Likewise, the increased occurrences of flood and rain events will allow the spread of chemical hazards and pathogens in agricultural areas through runoffs, thus exposing farmlands (FAO, 2020; WHO, 2019). Also, these events have been linked to the disruption of the quality of water used for farming and drinking. On the other hand, the unfavorable warmer temperatures may induce stress to the health of livestock and fisheries, making them vulnerable to pathogens and increasing shedding by infected animals (FAO, 2020). In this respect, these events will represent emerging risks for food safety (IPCC, 2015).

Mitigation of food safety risks is currently addressed through a risk-based food safety approach implemented along the value chain through food safety programs. Through the adoption of risk analysis, and its three activities, risk assessment (RA), risk management and risk communication, a science-based strategy to mitigate food safety risks to consumers is in place (FAO & WHO, 2006b). However, some of these food safety strategies have also been linked to variable impacts on the environment (Lee & Okos, 2011). Food value chains cause negative impacts on the environment such as greenhouse gas (GHG) emissions through the use of energy, raw materials and land use change. In 2018, food systems were responsible for 33% (16 Gt CO_2e) of global anthropogenic GHG emissions, three-quarters of which were a result of agriculture (including land use and land-use-change-related emissions) (Tubiello et al., 2021). Globally, over 14% of food produced is lost before leaving the farm, while roughly 17% of the food available for consumers is wasted in retail outlets and households (FAO, 2019; UNEP,

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https://doi.org/10.1016/j.tifs.2022.02.027
Received 4 March 2021; Received in revised form 22 February 2022; Accepted 24 February 2022
Available online 8 March 2022
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Please cite this article as: Rodney J. Feliciano, *Trends in Food Science & Technology*, https://doi.org/10.1016/j.tifs.2022.02.027

2021). Other environmental impacts include eutrophication and acidification of water bodies (Li, Kroeze, Kahil, Ma, & Strokal, 2019) that alter aquatic ecosystems and their ecological resilience.

Life Cycle Thinking (LCT) is a key concept in achieving a transition toward a more environmentally sustainable food system (Notarnicola et al., 2017). It allows the evaluation of inputs, outputs and the potential environmental impacts along the life cycle of complex food systems. The UNEP/SETAC Life Cycle Initiative (2016) describes LCT as "going beyond the traditional focus on production sites and manufacturing processes to include environmental, social and economic impacts of a product over its entire life cycle". This concept has been at the core of many strategies, initiatives and policy action plans implemented at different scales, from single products (i.e., ecolabels, environmental declarations, product category rules) to complex food systems (i.e., Green Deal and Farm-to-Fork strategies; European Commission, 2021, 2020). When dealing with current global challenges, such as ensuring food safety and environmental sustainability of food systems under climate change conditions, LCT provides a conceptual basis to analyze them and look for potential trade-offs. This global challenge is already in the portfolio of policy agendas and is the motivation behind programs and initiatives worldwide.

It is clear that strategies across value chains must consider both food safety and environmental sustainability. However, the scope of risk analysis in assessing food safety intervention strategies is limited in terms of environmental impact. The integration of food safety and environmental sustainability is a relatively new undertaking that can build on methods already applied in research areas outside the domain of food science. Over the past two decades, efforts have been made to put together Life Cycle Assessment (LCA) and RA into one integrated framework in different areas of application such as chemicals (Sleeswijk, Heijungs, & Erler, 2003) and industrial processes (Sonnemann, Castells, & Schuhmacher, 2003). Altough limited to chemical hazards, Sleeswijk et al. (2003) concluded that the integration of RA and LCA was possible and Cowell, Fairman, and Lofstedt (2002) highlighted its benefit in decision-making processes.

Therefore, this paper aims to review the joint application of RA and LCA as a tool to aid risk managers in decreasing environmental impacts of food value chains without compromising food safety under climate change conditions. This paper highlights the effects of this global climate issue on the joint application of RA (considering both microbial and toxicological hazards) and LCA within the food sector. First, the main tools available to analyze food systems from both perspectives (i.e., food safety and environmental impacts) are presented (Section 2). Then, a literature review on the different ways of integrating RA and LCA is presented (Section 3) as well as initiatives in the public health domain (Section 4). The paper concludes with lessons learned and provides suggestions to support the continuity of the dual environment–safety agenda development across food value chains.

2. Tools for food systems-wide analysis

2.1. Mitigating food safety risk through risk assessment

2.1.1. Risk analysis and its role in food safety

Food safety has a long history that traces back to the industrial age. Throughout these years, food safety has covered toxicological (chemical), physical and microbiological hazards. This wide variety of hazards has not only become the impetus for food laws, regulatory agencies and food safety programs, but also for the development of risk analysis (Weinroth, Belk, & Belk, 2018; Wu & Rodricks, 2020). Schematicaly, food safety management has been presented as a pyramid on the top of which risk analysis makes the link between specific operational management at the industry level through pre-requisite programs and Hazard Analysis Critical Control Points (HACCP) plans and generic guidelines and regulatory decisions at the national or supranational level (Gorris, 2005).

Risk analysis is a structured approach that ensures that risk management decisions are taken and communicated based on the scientific assessment of health risk (FAO & WHO, 2006a). It has been incorporated into different food systems as a way of managing hazards across the segments of the food continuum while monitoring appropriate intervention strategies (Codex Alimentarius Commission, 2007). Its widespread application across the food value chain is what has been called "risk-based food safety management" (Koutsoumanis & Aspridou, 2016). RA, as a tool to inform decisions, is composed of four steps: hazard identification, hazard characterization, exposure assessment and risk characterization (Codex Alimentarius Commission, 1999; FAO & WHO, 2006a).

2.1.2. Chemical Risk Assessment and Microbial Risk Assessment

Although differences between Chemical Risk Assessment (CRA) and Microbial Risk Assessment (MRA) exist, the same four key steps are followed.

Chemical Risk Assessments are made to evaluate risks associated with the consumption of foods containing food additives, chemical residues or contaminants and exposure to these (FAO & WHO, 2009). Several guides and toolkits are available to be used in performing RAs of chemicals such as those published by the IPCS (FAO & WHO, 2009), Redbook by the USFDA, the WHO RA toolkit (WHO, 2010) and EFSA (Table 1), as well as databases on the maximum residue of veterinary residues, veterinary drugs and food additives in foods. On the other hand, information on the structure and activity of chemicals can also be used during hazard characterization, especially when there is relatively little information or a lack of existing studies (Camel, Rivière, & Le Bizec, 2018; WHO, 2010).

Microbial Risk Assessment (MRA) is "a tool used to compare risk management options in forming risk management actions and decisions aimed at improving food safety" (FAO & WHO, 2006b). It is composed of several component models that assess the consumer's exposure to microbial hazards in foods. A variety of ready-to-use software and tools are available (Table 2), including guidelines and online resources that can be accessed to aid in the performance of MRAs. The Codex Alimentarius Commission has crafted guidelines that can be used by risk managers for assessment activities such as the upcoming MRA guide (FAO & WHO, 2021).

When possible, the number of years of perfect health lost (Disability Adjusted Life Years, DALYs) are estimated to aggregate CRA and MRA results in terms of public health impact (Membré, Santillana Farakos, & Nauta, 2021). DALYs reflect the effects of both morbidities and mortalities brought about by disease (Pires et al., 2021) and has been used by the Global Burden of Disease (GBD) study, supported by the World Health Organization (WHO), when estimating the health effects of major diseases, injury and risk factors in the world since 1990 (WHO, 2009). Although DALY is a common health metric in food safety risk, there are cases where it is difficult to apply this metric. In particular, in the domain of toxicology it is not always possible to quantify accurately the disease/health effects per capita (number of cases, number of fatalities), resulting in the inability to obtain a DALY measure (Membré et al., 2021; Van der Fels-Klerx et al., 2018).

2.1.3. Food safety management in the context of climate change

Food safety has been highlighted as vulnerable to the effects of a changing climate (IPCC, 2015; Tirado, Clarke, Jaykus, McQuatters-Gollop, & Frank, 2010). This is due to favorable climatic conditions and the occurrence of extreme weather events (e.g., drought, storms) that would allow the proliferation of microbial hazards and the production or bioaccumulation of chemical hazards in agricultural products destined for human consumption (FAO, 2020). The increase in average temperatures has also been forewarned as favorable for the proliferation of vector-borne diseases impacting animal health, including pathogens in food (Miraglia et al., 2009; Tirado et al., 2010). A particular example of this is the microbial property of raw milk where

Table 1
Tools for performing Chemical Risk Assessments.

Resource	Resource Type	Risk Assessment Step				URL
		Hazard Identification	Exposure Assessment	Hazard Characterization	Risk Characterization	
JECFA database	Standards		X	X		
Echemportal	Database		X	X	X	https://www.echemportal.org/echemportal/
OpenFoodTox-EFSA	Database		X	X		https://data.europa.eu/euodp/en/data/dataset/openfoodtox-efsa-s-chemical-hazards-database
Food enzymes (FEIM)	Tool (online interface) for estimating consumer exposure		X			https://www.efsa.europa.eu/en/science/tools-and-resources
Feed additives (FACE)	Tool (online interface) for estimating consumer exposure		X		X	
Food additives (FAIM 2.0)	Tool (spreadsheet-based) for estimating consumer exposure		X		X	
Pesticide residues (PRIMo)	Tool (spreadsheet-based) for estimating consumer exposure		X		X	
Contaminants (RACE)	Tool (online interface) for estimating consumer exposure		X		X	
Risk thermometer	Tool	X	X	X		*Only the documentation is available online
Danish (Q)SAR Database	Tool (online interface/database)	X		X	X	http://qsar.food.dtu.dk/
OECD QSAR toolbox	Tool (online interface/database)	X		X	X	https://www.oecd.org/chemicalsafety/risk-assessment/oecd-qsar-toolbox.htm
Euromix Toolbox (Nl)	Tool (online interface/database)	X	X	X	X	https://mcra.rivm.nl/Select
EUSES 2.2.0	Computer program		X	X	X	https://echa.europa.eu/support/dossier-submission-tools/euses
Foodrisk.org	Online resource center	X	X	X	X	https://www.foodrisk.org/
QMRAwiki	Online resource center	X	X	X	X	http://qmrawiki.canr.msu.edu/index.php/Quantitative_Microbial_Risk_Assessment_(QMRA)_Wiki
EFSA knowledge junction	Online resource center	X	X	X	X	https://zenodo.org/communities/efsa-kj/?pag=1&size=20
ICPS manual	Reference material	X	X	X	X	https://www.who.int/publications/i/item/9789241572408
Red book	Reference material	X	X	X	X	https://www.fda.gov/regulatory-information/search-fda-guidance-documents/guidance-industry-and-other-stakeholders-redbook-2000

climate change might not only influence directly the proliferation of microorganisms but also contribute indirectly to it through negative impacts on animal health in terms of heat stress and increased susceptibility to pathogenic diseases (Feliciano, Boué, & Membré, 2020).

Among the microbial hazards previously mentioned is *Vibrio* spp. In seafood (Hsiao, Jan, & Chi, 2016; Marques, Nunes, Moore, & Strom, 2010; Misiou & Koutsoumanis, 2021), while other microorganisms influenced by climate change are *Campylobacter* spp. and *Salmonella* spp., which may also impact foodborne diseases (Misiou & Koutsoumanis, 2021). Climate change is also expected to influence the chemical hazards presented by different food products, such as seafood, due to biological toxins such as saxitoxins from harmful algal blooms, heavy metals in fisheries and organic pharmaceuticals, and mycotoxins in grain products, as reported in other papers (Chhaya, O'Brien, & Cummins, 2021; Misiou & Koutsoumanis, 2021). Given these climate-change-driven challenges posed by microbial and chemical hazards, researchers have suggested that food safety management systems might be adapted to the possible future effects of climate change (Vermeulen, Campbell, & Ingram, 2012). Among the changes mentioned are the possible revisiting of food safety programs and the establishment of early-warning systems (Feliciano et al., 2020; Janevska, Gospavic, Pacholewicz, & Popov, 2010; Marvin et al., 2013). The establishment of monitoring systems that can detect weather events that might have an impact on food safety has also been proposed. In the dairy supply chain this climate change impact is foreseen from the farming to the consumer phase, as transportation and storage of food products will be also affected (Feliciano et al., 2020). As such, the ensemble of current food safety tools and programs and the possible mitigation strategies presented must encompass the food value chain. Above all, climate-resilient food safety management must be sustainable and not induce further climate change through emissions.

2.2. *Environmental evaluation and continuous improvement of food value chains*

Each of the stages in a food value chain is linked to different environmental impacts due to effects on natural resources, direct and indirect emissions, inefficient production systems, and consumption patterns that generate significant food losses and waste (FLW) (IPCC, 2014). Nevertheless, the environmental impacts of food value chains are variable and depend on the country, production system, sector and commodity produced (Frank et al., 2017). The environmental

Table 2
Tools that can be used in performing Microbial Risk Assessments.

Resource	Resource Type	Risk Assessment Phase				URL
		Hazard Identification	Exposure Assessment	Hazard Characterization	Risk Characterization	
Codex Alimentarius Commission guidelines	Standards	X	X	X	X	http://www.fao.org/fao-who-codexalimentarius/codex-texts/guidelines/en/
FAO/WHO Microbiological Risk Assessment series	Reference material		X			https://www.who.int/foodsafety/publications/risk-assessment-series/en/
FAO/WHO, 2020: Unpacking the burden of climate change	Reference material	X				http://www.fao.org/documents/card/en/c/ca8185en/
FAO/WHO, 2020: FAO Guide to Ranking Food Safety Risks at the National Level	Reference material	X				http://www.fao.org/publications/card/en/c/CB0887EN
FAO/WHO, 2011: performing RAs during emergency situations	Reference material					http://www.fao.org/3/ba0092e/ba0092e00.pdf
Risk ranger	Tool (MS Excel-based)		X			http://www.fao.org/food-safety/resources/tools/details/en/c/1191489/
Microhibro	Tool (online interface)		X			http://www.microhibro.com/#
sQMRA 2.0	Tool (MS Excel-based)		X			https://www.foodrisk.org/resources/display/56
iRisk-FDA 4.0	Tool (online interface)		X		X	https://irisk.foodrisk.org/
Foodrisk.org	Online resource center	X	X	X	X	https://www.foodrisk.org/
QMRAwiki	Online resource center	X	X	X	X	http://qmrawiki.canr.msu.edu/index.php/Quantitative_Microbial_Risk_Assessment_(QMRA)_Wiki
EFSA knowledge junction	Online resource center	X	X	X	X	https://zenodo.org/communities/efsa-kj/?page=1&size=20
ECDC burden of Communicable disease	Database	X			X	https://www.ecdc.europa.eu/en/burden-communicable-diseases
EU RASFF	Database	X			X	https://ec.europa.eu/food/safety/rasff_en
US FDA Import detention	Database	X			X	https://www.fda.gov/industry/actions-enforcement/import-alerts
Badbug book-USFDA	Reference material	X			X	https://www.fda.gov/food/foodborne-pathogens/bad-bug-book-second-edition
ANSES-Microbiological hazard files and data sheet on foodborne biological hazards	Reference material	X		X		https://www.anses.fr/en/content/microbiological-hazards-files

performance of the food sector has been extensively addressed in the literature (Weidema, Thrane, Christensen, Schmidt, & Løkke, 2008). Animal-based food value chains have shown higher GHG emissions compared to vegetable-based ones (Willett et al., 2019), pointing out livestock-based systems as significant contributors to climate change. Thus, changes in dietary patterns together with improved food production efficiencies have been identified as potential strategies to reduce food's global environmental impacts (Ridoutt, Hendrie, & Noakes, 2017).

2.2.1. *Tools and frameworks for environmental evaluation*

Methodologies have been developed to quantify the environmental performance of food value chains, and specific standards and guidelines have been created to support a harmonized calculation and provide more comparable results among studies. LCA is a standardized methodology recognized and implemented worldwide that quantifies the environmental impacts of the life cycle of products, processes or services and has been used extensively to evaluate the environmental performance of food supply chains (Djekic et al., 2018; Tsakiridis, O'Donoghue, Hynes, & Kilcline, 2020). LCA consists of four steps: i) goal and scope, ii) inventory analysis, iii) life cycle impact assessment (LCIA) and iv) interpretation (ISO 14040, 2006; ISO 14044, 2006). Broadly, the first step defines the functional unit (FU) and the system boundaries. The next step quantifies all the energy and material flows (i.e., inputs and outputs) across the life cycle stages. Later, the LCIA translates these inputs and outputs into potential environmental impacts (e.g., global warming, eutrophication, human toxicity, particulate matter, ionizing radiation, etc.) by multiplying them by the so-called characterization factors derived from available methods (e.g., ReCiPe, IMPACT 2002+ or USEtox). Those methods can be midpoint and endpoint depending where the impacts along the cause–effect chain are calculated. For midpoint indicators, an emission substance is modeled for its changes from natural environmental aspects (i.e., the increase in its concentration in a lake), while for endpoint indicators a emission substance is modeled for its damaging effects (i.e., the end of the cause–effect chain) on the areas of protection. These are the areas of the environment that are to be protected against harmful emissions and releases, such as human health (note than several LCIA endpoint methods estimate the damage to human health in DALYs in relation to the selected FU) or ecosystem quality. Lastly, the fourth step evaluates the results and draws conclusions and makes recommendations (Hauschild, Rosenbaum, & Olsen, 2018).

Many substances in the midpoint impact categories are directly and indirectly connected to the area of human health protection. For example, Fig. 1 presents the primary production of cereals for animal and human consumption, either directly or after further processing, where only the most relevant impact categories and the main substances involved are considered (Dekker, Zijp, van de Kamp, Temme, & van

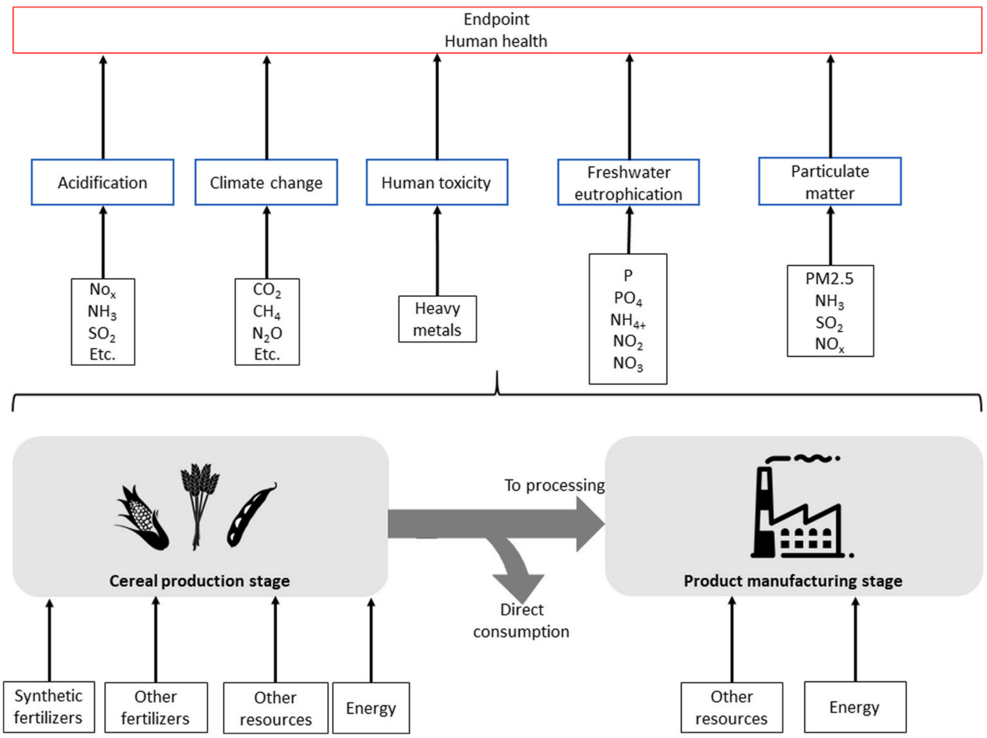

Fig. 1. Main environmental impacts of a simplified value chain of a cereal on damage to human health. The ReCiPe methodology (Huijbregts et al., 2017) was used to translate the most common midpoint impact categories (i.e., blue boxes) to the endpoint human health (i.e., red box), i.e., the area of protection on which this paper focuses. Synthetic fertilizers include N–P–K fertilizers, whereas other fertilizers include manure and sewage sludge. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Zelm, 2020). These emissions contribute to a variety of midpoint impact categories, which in turn, have direct and indirect implications for human health. For instance, the application of sewage sludge on croplands at the primary production stage is computed under the human toxicity midpoint category but also affects the human health endpoint category due to the heavy metal content (Lamastra, Suciu, & Trevisan, 2018; Laura et al., 2020; Przydatek & Wota, 2020). Also, along the value chain of cereals, GHGs are released from both energy production and fertilizer application, contributing to climate change and ammonia released from cereal farming, combined with volatile organic compounds, nitrogen oxides and sulfur dioxide from cereal processing, form particulate matter (Gu, Sutton, Chang, Ge, & Chang, 2014), which also contributes to the endpoint damage to human health (Huijbregts et al., 2017). The same applies to the discharges to water from cropland fertilization that is behind freshwater eutrophication, which in turn is associated with consequences to human health.

LCA-related standards belong to the ISO 14000 family (ISO 14000, 2021), which is composed of a series of international standards linked to the management of environmental systems. This family covers ecolabels and voluntary systems as well as environmental product declarations (EPDs; EPD, 2021) together with the respective product category rules,[2] which are available for a large number of food product categories. Standards within this family are available and are used for companies and organizations of any type to manage and communicate their environmental responsibilities. With the same motivation but at the European scale, the Product Environmental Footprint (PEF) program (European Commission, 2012) is an LCA-based method built on international standards, which aims to evaluate the environmental impacts of products. Within this program, the respective PEF category rules, available for many different product categories including food items, provide guidance in the calculation of relevant environmental impacts of the life cycle of products as well as allowing the comparison of results within the same product category.

2.2.2. *Single indicators: carbon and water footprints*

Over time, different concepts have emerged to track the environmental impacts of food value chains. At present, two individual indicators have gained attention worldwide: carbon footprint (CF) and water footprint (WF). Regarding the former, CF quantifies the amount of GHG emissions along the life cycle of a product quoted as carbon dioxide equivalent (CO_2e; ISO 14067, 2018). Being easy to communicate (Weidema et al., 2008) and useful in addressing SDG13, CF has become one of the most popular indicators; however, it has some limitations. For instance, environmental sustainability goes beyond climate change alone and covers other environmental burdens. Thus, the use of CF as a single indicator can underestimate other life cycle environmental impacts (Laurent, Olsen, & Hauschild, 2012). Concerning the latter, WF evaluates the environmental impacts related to water by considering direct and indirect water use and its consumption along the life cycle of a product (ISO 14046, 2014). Its relationship with LCA will depend on the method used to perform the WF study. For instance, the AWARE midpoint method evaluates the potential impacts of water use, as well as water scarcity (Boulay et al., 2018). Also, nitrogen and phosphorus are two elements of interest, since they are crucial in food production; nevertheless, they result in a cascade of multiple negative impacts to the environment. Within the LCA methodology, the environmental impact of these two elements is included in the eutrophication impact category. Recently, other indicators to track in detail and estimate the nitrogen and phosphorus pollution in the environment have been proposed, such as the nitrogen and phosphorus footprint (Lewis & Cohen, 2022).

2.2.3. *Success stories in strategies to limit environmental impact of food value chains*

The global population is growing, food demand is expected to increase and, at the same time, the effects of climate change have become more severe. Thus, the need to shift to more responsible consumption patterns and sustainable food systems resilient to climate change is clear (Soussana, 2014). To do so, different actions in line with climate change commitments and based on voluntary schemes and policy requirements have been taken worldwide.

The FAO has played an important role in improving the

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[2] Description and library available at www.environdec.com/product-category-rules-pcr.

environmental sustainability of food value chains through its global initiative “SAVE FOOD” (FAO, 2021). In line with SDG12 and SDG2, it looks at reducing the global FLW by raising awareness of the different actors involved in the food value chains and reducing inefficiencies at different lifecycle stages. Across Europe, the support of the CAP (European Commission, 2019) toward farmers in applying more sustainable practices, such as fostering organic farming and promoting responsible use of pesticides and fertilizers, should also be highlighted.

On the other hand, private initiatives with a commitment to GHG emission reductions have been developed in different sectors. Thus, large food industries have defined short- and medium-term strategies to contribute to this global commitment. For instance, Arla Foods, the largest organic dairy producer in the world and one of the largest dairy cooperatives in Western Europe and Scandinavia, launched in 2019 an ambitious objective to reduce GHG emissions by dairy farms by 30% per kilo of milk over the next decade, with a goal of net zero carbon by 2050[3] Another example is Tetrapak[4] one of the leaders in processing equipment and packaging solutions for the food industry. This company has calculated and mapped the environmental impact of their products, based on LCA, to show straightforwardly the CF of carton packaging and encourage consumers to make more informed choices at the time of selecting their products.

2.3. *The need for and the potential of joint implementation of risk and environmental assessments*

In the food value chain, risk-based food safety management enables the control of risks to human health related to both microbial and chemical hazards. However, these management strategies may present an impact on the environment, probably contributing to climate change, and, in turn, influencing the existing food safety hazards in food value chains (Guzmán-Luna, Mauricio-Iglesias, Flysjö, & Hospido, 2021). Thus, ensuring food safety and the environmental sustainability of food systems under climate change is a current challenge included in the agenda of policy plans and initiatives worldwide.

As mentioned above, LCA is the most preferable and commonly used tool to evaluate and address the environmental sustainability of food systems, as it allows the detection of trade-offs and hidden costs, not only among different stages along the product value chain but also among different environmental impact categories. LCA also allows the identification of the main environmental burdens, so that improvement actions can be more effectively defined and put into practice. However, when evaluating risk to human health and/or the environmental impacts of food systems in a specific geographic area, the LCA methodology needs to increase the granularity of its analysis to regionalize these risks and impacts. To do so, LCA has to move from its global perspective to the concrete site-specific focus of RA. Nowadays, this can be achieved by using site-dependent characterization factors (Saouter et al., 2017), national databases (Environmental Protection Agency, 2021; NREL, 2012), and grid cell-based inventories (Hill et al., 2019; Thakrar, Goodkind, Tessum, Marshall, & Hill, 2018). In this context, when LCA moves in the direction of RA, the integration of both methodologies becomes more harmonious. Nevertheless, the present study does not cover this discussion within its objectives.

In addition, RA has the strength to provide results that can reflect threshold values, whereas LCA cannot identify a possible exceeding of the limits allowed for a certain substance (Barberio, Scalbi, Buttol, Masoni, & Righi, 2014). A joint application of both tools allows a more comprehensive evaluation of the intertwined challenges in food value chains under climate change. Let us illustrate this latter point with the example of a meat-based product value chain (Fig. 2) in which the effects of climate change create suitable conditions for the introduction and proliferation of microorganisms at different steps of the chain, leading to an increased risk in terms of safety but also of spoilage. The meat-based product value chain encompasses the production of raw meat until its consumption by the consumer. To ensure the health of consumers and reduce spoilage risks, RA is applied to evaluate risk but also to identify which steps within the value chain have a significant impact on such risk. For instance, in a slaughterhouse, cooling to and maintaining low temperatures could be a key step. The associated mitigation strategies would then involve changing the cooling system. However, these strategies could result in environmental consequences. Hence, LCA comes into play by providing risk managers with a way to evaluate their effects on the environmental performance of a system and to help them select the more environmentally friendly alternative. If the intervention does not look at only ensuring mandatory food safety but also at finding a way to implement it at a lower environmental cost, a win-win strategy will potentially be achieved. In contrast, risk managers looking only at ensuring mandatory food safety, leaving aside the resulting environmental costs will probably lead to a trade-off, as the CF of the product will increase (i.e., assuming that the environmental burden per unit of energy remains the same) and, consequently, will contribute to climate change as well as having other environmental impacts. Extrapolating from this example, an integration of both LCA and RA in the food domain will help to detect and avoid trade-offs between the implementation of strategies to reduce food risk and the potential increase of contributions to global warming and other environmental impacts along the value chains. In other words, the integration of the two methodologies will take a step forward as it will allow for win-win management actions that ensure food safety and environmental sustainability.

3. Framework to integrate life cycle assessment and risk assessment

A literature search on integration of LCA and RA was performed using the Web of Science search engine with the combination of search terms “Risk Assessment” (title) and “Life Cycle Assessment” (all fields) and a time span of 2010–01-01 to 2022-02-01. No spatial filter was applied to capture papers across the globe, resulting in 107 papers. Subsequently, three selection filters were used to select papers to be included in Table 3. The first filter was the sector of application (i.e., water treatment, nanomaterials, and human health risk). These sectors were selected because papers on such areas as these have dealt with risks to human health that are similar to the exposure pathways of microbial and chemical hazards in food. The second filter was the type of paper, where research papers were selected, leaving aside review and perspective papers. The third filter referred to the two selected schools of thought (i.e., Knowledge Integration and Comparison or Combination of Results). Ultimately, eight research papers involved in the risk of nanomaterials and water treatment systems to human health are presented in Table 3 and discussed in this section. In fact, the initiative of combining and integrating RA and LCA is not a new topic in the scientific community; the debate surrounding this has been running for almost 30 years. Guinée, Heijungs, Vijver, and Peijnenburg (2017) described four schools in the context of nanomaterials and their manufacturing processes that are highly relevant and potentially transferable to the food safety domain. These schools are presented below:

I. ***Knowledge Integration*** *is when RA models are used in the LCIA stage of an LCA. This approach is the most used and allows the integration of those impacts with others under the umbrella of the endpoint category of human health quantified by LCA. Two different characterization factors were developed to assess risks to human health from potassium hydroxide-based fertilizers. One focused on the*

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[3] www.arla.com/company/news-and-press/2019/pressrelease/arla-foods-aims-for-carbon-net-zero-dairy-2845602/.

[4] www.tetrapak.com/sustainability/planet/environmental-impact/a-value-chain-approach/carton-co2e-footprint.

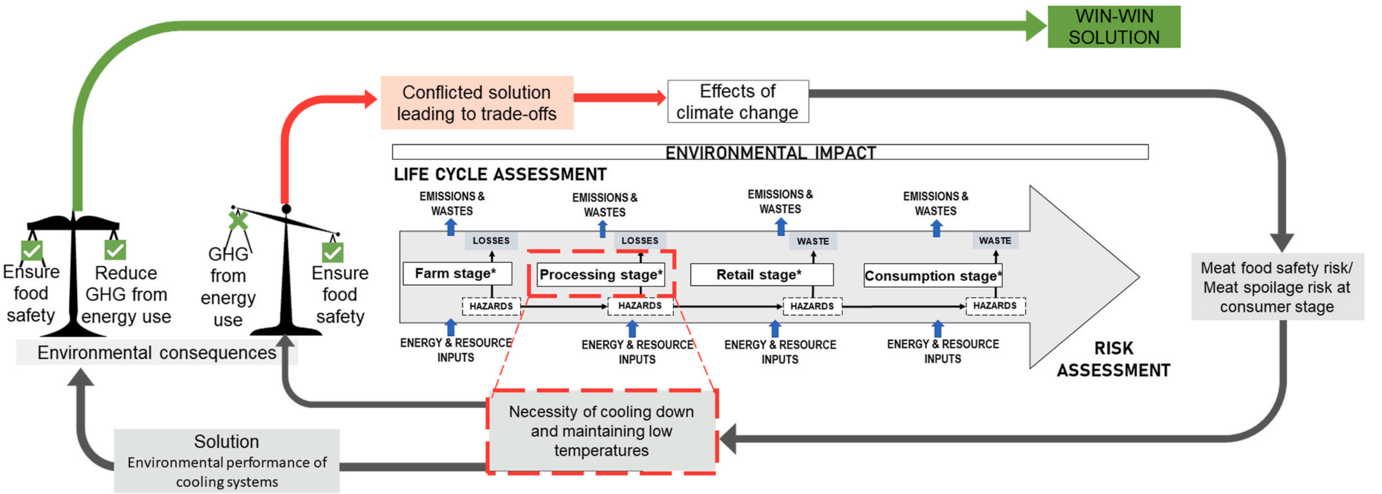

Fig. 2. Broad overview of the scope of a joint application of LCA and RA using as case study a general life cycle of meat production under climate change conditions. *Respective transportations are included in each of the life cycle stages mentioned. RA identifies the vulnerable part of the supply chain and is highlighted in the red-dashed box. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

area of fertilizer manufacture, while another focused on the area of fertilizer use. Some of these CFs were created with RA models as a component and subsequently included in the LCIA.

II. *The **Chain Perspective** school goes beyond analyzing just the risk to human health posed by a product. Instead, it focuses on the value chain of substances used in a product but covering some or all of the different applications that substance might have in a specific geographical area. Potassium hydroxide is used for fertilizer production but is also used for making soap, as an electrolyte in alkaline batteries and in electroplating, lithography, and in the manufacture of paint and varnish removers. Within this school, the site-specific risk to human health of potassium hydroxide and all its applications in certain sites are analyzed.*

III. *In the **Risk Assessment for Life Cycle Hotspot** school, an RA is applied at the life cycle stage(s) previously identified as the most significant by the application of an LCA. In the example used, a screening LCA is first performed on the life cycle of a potassium hydroxide-based fertilizer identifying the manufacturing stage as the hot spot, and then, a detailed RA of this stage is carried out to quantify the risks to human health.*

IV. *In the **Comparison or Combination of Results** school, RAs and LCAs are conducted separately and their results either compared or combined by a multicriteria decision analysis (MCDA). On the one hand, a gate-to-gate LCA is performed to evaluate the impact on human health of the production of potassium hydroxide-based fertilizers (i.e., covering only the manufacturing plan). On the other hand, an RA is also conducted on the same system to evaluate the risk to human health. Later, the outcomes, both expressed in DALYs, are compared.*

After reviewing the four schools, the second and the third (i.e., *Chain Perspective* and *Risk Assessment for Life Cycle Hotspot* approaches) were left aside, since they seemed to be difficult to adapt to the microbiological risks encountered in food safety. The *Chain Perspective* is useful when considering the risks associated with a substance, such as a synthetic chemical, in all its potential applications. The *Risk Assessment for Life Cycle Hotspots* is based on the following heuristic: the stages with the most relevant use of chemicals in a process or in a value chain are likely to be identified as a hotspot in the LCA. Therefore, the LCA narrows down the potential substances to be tackled in an RA. In food value chains, the stages where the risk to individuals is high are often uncoupled from life cycle hotspots.

In contrast, the first and the fourth schools (i.e., *Knowledge Integration* and *Comparison or Combination of Results*) seemed to be the easiest to be adapted to the MRAs and CRAs encountered in food safety. Thus, the following sections describe the studies obtained from the literature search by pointing out the authors' motivation to integrate both methods and revisits the key elements that allowed their successful integration (Table 3).

3.1. *Review of the Knowledge Integration school*

Following the *Knowledge Integration* school (Guinée et al., 2017), the results of health risks from the RA are merged into the results of health risks from LCA on the basis of the DALY unit. Nevertheless, special attention needs to be paid when adding them together (as further discussed in Section 5), since they do not share systematically the same FU. This school has already been applied in different fields but, to the best of our knowledge, no case study on the food area is available.

In the urban water system, this approach was applied to evaluate the environmental impact of different water treatment processes including the impact on human health due to pathogen exposure (Harder, Peters, Molander, Ashbolt, & Svanström, 2016; Heimersson, Harder, Peters, & Svanström, 2014). Heimersson et al. (2014) in their evaluation analyzed two different sludge management configurations by choosing 10 000 m^3 of wastewater treated in a day as the FU and covering the primary and secondary treatment as well as the chemical phosphorus removal and anaerobic digestion of the sludge. They firstly evaluated the pathogen risk associated with the two different configurations through a Quantitative Microbiological Risk Assessment (QMRA) model expressed in DALY per year. Secondly, they performed an LCA for the same sludge configurations covering six impact categories resulting in damage to human health (i.e., global warming, human toxicity, stratospheric ozone depletion, particulate matter, photochemical ozone formation and ionizing radiation). To do so, they used two alternative LCIA methods: USEtox and ReCiPe, since the choice of method to analyze human toxicity can influence the endpoint results. They expressed their results in DALY per FU and concluded that the contribution of pathogen risk remains lower with the USEtox method. They also pointed out that the use of the same FU and system boundaries facilitate the integration of LCA and RA. The QMRA results of pathogen risk and the LCA results for the six impact categories (which excluded pathogen risk due to the limitations of LCIA methods at that time) were simply summed to give a more complete picture of the consequences for human health of the different sludge management alternatives. Similarly, Harder et al. (2016) also included the results for pathogen risk resulting from a QMRA

Table 3
Classification of RA and LCA Integration methods (Adapted from Guinée et al., 2017 and Kobayashi, Peters, & Khan, 2015).]

Classification systems	Characteristics	Examples of papers	Motivation of papers
Knowledge Integration	#The elements of RA are commonly adopted into the LCIA as an input of this phase.	Heimersson et al. (2014)	To include pathogen risk as another impact category in LCA and compare its contribution to the total life cycle impacts on human health.
	# A potential complement of LCA that can provide further improvement of it. # Provision of absolute and relative values.	Harder et al. (2016)	To explore the opportunities of using QMRA to evaluate pathogen risk and include it as an impact category in LCA.
Comparison or combination of results	# Separate performance RA and LCA.	Liu et al. (2012)	To enhance decision-making process through the use of an integrated LCA-RA-MCDA framework.
	# Individual results can be compared or integrated using MCDA. # Results comparison has been facilitated using DALY.	Barberio et al. (2014)	To present ways on how LCA and RA can be combined and used in nanomaterial production systems. The application of these two is used to select the processing steps to limit these impacts.
		Ribera et al. (2014)	To evaluate the environmental impact and benefits to human health resulting from the implementation of nanomaterial filtration in a drinking water treatment plant.
		Tsang et al. (2014)	To present consistent and transparent ranking of alternatives through the integration of LCA and MCDA.
		Kobayashi et al. (2015)	To assess a more holistic impact assessment of water treatment systems. The advantages and disadvantages of using DALY metric in assessing the impacts of the systems were also determined.
		Anastasopoulou et al. (2018)	To compare the performance of a nanomembrane toilet system against conventional sanitation system.

as an impact category on LCA in the same context. In contrast to Heimersson et al. (2014), they focused only on the human toxicity impact category, which was addressed by the USEtox methodology. They concluded that the inclusion of pathogen risk from a QMRA needed to be done with caution due to the differences between the RA and LCA frameworks. The selection of some factors, such as individuals exposed and their frequency of exposure, as well as methods to estimate pathogen risk, had a significant influence on the outcome.

3.2. *Review of the comparison or combination of results school*

The difficulties due to the inherent differences in some LCA and RA steps, such as the modeling approaches and assumptions made, are sometimes irreconcilable (Csiszar & Meyer, 2017). Therefore, recent reviews of studies outside the food domain have recommended the use of the *Comparison or Combination of Results* school (Csiszar & Meyer, 2017; Muazu, Rothman, & Maltby, 2021). The papers within this school have performed RAs and LCAs separately and compared and/or combined their results to assess products and processes in a more holistic manner, overcoming the gaps of RAs and LCAs and aiding the decision-making process (Liu, Ko, Fan, & Chen, 2012; Ribera et al., 2014; Tsang, Bates, Madison, & Linkov, 2014).

For instance Barberio et al. (2014) aimed to highlight and compare the results identified by th LCAs and RAs in supporting the choice between two alumina nanofluid processes. They evaluated the environmental performance of the two processes to produce 1000 kg of alumina nanofluid, focusing on global warming, human toxicity and many other midpoint impact categories with the use of the IMPACT 2002+ method. In parallel, they also performed a qualitative RA to evaluate and compare the risks to the workers' health from each of the two production processes. The qualitative RA outcomes were risk-prioritized based on the severity of the disease resulting from nanomaterial exposure. The results from both methods, LCA and RA, were simply qualitatively compared. In other words, only the conclusions drawn from the results were compared with no attempt to combine them in an MCDA framework. It was found out that the LCA and RA recommended different optimal production processes in terms of reducing environmental and human health impact, so the authors concluded that trade-offs between these two objectives were necessary.

Some studies have pursued the comparison of results by following a different approach. In the field of water supply systems, other authors have first expressed their results on the basis of the same metric (i.e., DALYs) in order to enable the comparison. For example, Kobayashi, Peters, Ashbolt, et al. (2015) normalized the LCA and RA results to the same metric. They analyzed two water systems and focused on six midpoint impact categories (i.e., climate change, human toxicity, ionizing radiation, ozone depletion, particulate matter formation and photochemical oxidation) that contribute to damage to human health. Through the ReCiPe endpoint methodology, the LCA results were expressed in DALY lost per FU (i.e., provision of 18 GL of environmental flows to a river system per year). Also, a QMRA was performed to assess the risk to river water users from waterborne pathogen exposure, obtaining the results in DALYs lost per illness per year. When they compared the results of both methods, they pointed out that the DALYs obtained from the QMRA were lower than those obtained from the LCA in the evaluated systems. Similarly, Anastasopoulou et al. (2018) presented the LCA results in DALYs per FU after evaluating the environmental performance of three toilet systems by the endpoint ReCiPe methodology. As endpoint indicators, they evaluated damage to human health and also to resources and ecosystems per FU, defined as "the provision of a sanitation service for the daily defecation of a 10-adult occupant household in South Africa". The RA results were also expressed in DALYs per year, as they assessed the exposure of people involved with maintaining the system and users of the stream into which the treated water was released. The authors found that the benefits of reduced DALY loss resulting from toilet systems were greatly outweighed by the negative health impacts shown by higher DALY associated with these toilet system. Both studies concluded that the use of the same metric facilitated the comparison of the results of impact on human health. However, besides normalizing the results on the basis of the same metric, consideration of other elements should be included when comparing the results within this school (as further discussed in Section 5).

Other studies have used the MCDA technique to combine results obtained. In the study by Liu et al. (2012) a combined MCDA-LCA-RA framework was developed to allow the combination and evaluation of the impact of environmental management systems and help the decision-making process. The combined framework identified and quantified the aspect-pathway-receptor-impact causal link in the evaluated systems. This was followed by quantifying the severity of an environmental aspect (i.e., emission released), the probability of the exposure of receptors (i.e., people using the river) and the probability of impact on them. Within the MCDA part of this framework, the decision-makers were able objectively to choose and prioritize the environmental impact of concern. This was based on how likely these impacts were to occur and how great the impacts would be. In another study, Tsang et al. (2014) evaluated different lumber treatment technologies. The MCDA was used to evaluate the benefits and risks associated with the chemical treatment of 1000 m^3 lumber, from the extraction of the raw materials to the end use. The benefits were scored according to the sum of cost, durability, and corrosiveness, while the risk scores were summed from the human health and environmental impacts. These impacts were obtained from the selected midpoint impact categories (i.e., ozone depletion, eutrophication, human health criteria and human health toxicity) through the Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI) method developed by the US Environmental Protection Agency. Later, the criteria that made up the benefits and risks were assigned different weights. The MCDA algorithm was then used to compute the scores from these and generate the ranks of the different lumber treatment technologies. This improved the decision-making process by providing an unbiased method of determining the highest-ranking alternative based on the different criteria.

A similar approach was presented by Ribera et al. (2014), who evaluated conventional and nanofiltration drinking water treatment processes. They first performed an LCA on both processes and the FU was defined as 1 m^3 of final drinking water produced by a treatment plant with a lifetime of 60 years. Some of the impact categories chosen were climate change, ozone depletion and eutrophication, following the ReCiPe method. Subsequently, a human health RA was performed to estimate the cancer risk arising from the water treatment and the ability of the nanofiltration method to reduce such risk. The health risks were estimated for several pathways, namely ingestion, inhalation and dermal contact. Ultimately, a multicriteria tool was used to determine the cost and benefits for human health and the environmental impact of the two water treatment methods.

4. Existing attempts to consider the environment and health in food systems

There are other initiatives that analyze together the environmental and health impacts of a food system, although they may be less comprehensive than those described above. Other tools have been used to evaluate environmental impact and risk to human health. However, insights on other possible ways to assess food systems from a multi-aspect perspective have been presented.

In Duret et al. (2019), different types of MCDA are compared, namely the Analytic Hierarchy Process (AHP) and ELimination Et Choice Translating REality (ELECTRE), in evaluating the best intervention studies in the production and supply-chain of ham to control the risk to consumers posed by *Listeria monocytogenes*. The intervention strategies were assessed in terms of three criteria: environmental impact, food safety and food waste. Environmental impact was determined by computing energy consumption, food safety through DALYs due to listeriosis and food waste through ham products spoiled by lactic acid bacteria. The MCDA techniques allowed the generation of scores to indicate the most crucial intervention strategy applied in the process. This was possible through scoring based on the performance of the different alternatives with respect to the criteria and the weightings assigned to each. The two MCDA techniques indicated the same crucial part of the chain: home refrigeration. These two methods showed that by providing a score based on the impact of alternative criteria and ranking them based on this score, selection will be easier and can be based on the ranking generated by the MCDA methods.

Linear programming is also a useful MCDA technique to understand the trade-offs between variables such as food safety, nutritional health impact, sustainability and costs (Gazan et al., 2018). In this review, papers demonstrating the use of this technique and the points to consider in estimating the model parameters in optimizing diets are presented. This technique was recently applied to integrate environmental, health, economic, and cultural dimensions of school meals (Eustachio Colombo et al., 2019). In their study, they were able to conclude that these goals are achievable, but trade-offs between goals such as lowering the target reductions in carbon emissions to maintain a source of protein and an acceptable diet are necessary.

Another approach that does not involve MCDA is the Solution-focused Sustainability Assessment (SfSA), which is an assessment framework that evaluates sustainability, nutritional impact and food safety (Hollander, De Jonge, Biesbroek, Hoekstra, & Zijp, 2019), and the Food Triad Index, which combines nutritional, safety and environmental impact dimensions (de Almeida Sampaio Guido et al., 2020). The former was applied to current fish production, consumption practices and alternative dietary scenarios to evaluate the impact on food safety using changes in terms of DALY through the risk–benefit assessment model QALIBRA, while the environmental impact was evaluated through LCA using the ReCiPe method. In the study by de Almeida Sampaio Guido et al. (2020) they have developed a Food Triad Index that aimed to quantify the impacts of products in terms of nutrition, human health and environmental impact into a single radar graph. The outputs obtained in the latter were plotted as a triad to deduce a performance region of a food product reflecting its multi-aspect effects.

5. Lessons learned from these existing studies

Our initial objective was to perform a literature review on how RA and LCA have been integrated and applied to the food sector. We did not find many papers covering this topic. This might be due to the compartmentalization that exists in the food value chain, where LCA and RA are two activities run separately. One of the possible reasons is that food safety is a relatively old, well-established and regulated domain. For instance, sterilization guidelines were set in the middle of the 20th century. Public authorities and private sectors (from farmers and industries to retailers) have learned to work hand-to-hand in the food sector to guarantee food safety for decades, while environmental impact is still too often a relegated priority. The incentives are not yet set to facilitate the incorporation of LCA into food safety decision-making. Introducing a new way of thinking (by introducing environmental impact into the equation) might be a challenge. Nevertheless, studies of the non-food sector allowed us to understand the mechanism and philosophy behind the integration of RA and LCA and to transfer lessons learned to the food domain.

Due to the fundamental differences between LCA and RA, several aspects need to be considered when integrating them. Firstly, the definition of the same FU, together with the same system boundaries in terms of groups of individuals evaluated and geographical region in both methods, is a key aspect to be taken into account. For instance, in the context of sanitation systems, Anastasopoulou et al. (2018) defined the same FU and scope for the QMRA and LCA to enable a further comparison of both results. The FU was defined as the provision of certain treatment of human waste produced daily, whereas the scope was set as the exposure of a single household members in South Africa. The authors pointed out that the selection of common assumptions were also relevant in comparing the results, and thus they assumed that a single exposure event took place within the scope and context of the defined FU.

Secondly, even when both methods use DALYs to express their results, these are presented in particular units, which may differ. Whereas

LCA expresses its DALY per FU, such as daily water treatment in a country, RA often quotes it per inhabitant of a country per year. A solution to deal with these differences is to normalize both DALY results in order to define the same unit of reference; however, time and space are two elements to be considered. From an LCA perspective, the normalization of DALY can be related to the use of different reference flows for the same FU. For instance, in the context of urban water systems, instead of evaluating the daily water treatment, as by Heimersson et al. (2014), scaling it to an annual figure could be chosen instead, as by Kobayashi, Peters, and Khan (2015); thus, both results will be expressed as DALY lost per inhabitant of a country per year (Harder, Peters, Ashbolt, & Svanström, 2017). Nevertheless, it is not enough merely to adjust both FUs in terms of time, since the groups of individuals and the population served within the defined geographical region differ. For instance, RA is characterized by its site-specific severity factors, which are different from the factors used in an LCA to evaluate human toxicity impacts characterized by their broader scope. This can lead to differences between the groups of individuals exposed as well as in their frequency of exposure. In this context, a careful selection needs to be made when setting the system boundaries of a RA and an LCA (Harder et al., 2016). Heimersson et al. (2014) defined the same geographical boundaries for both methods, selecting Europe. Thus, they proposed to choose the severity factors in the RA models with a wider geographical scope, i.e., Europe, than for just one country.

However, even if the same FU and geographical scope are selected, there is another point that needs to be considered in the integration: the representation of the different groups of people evaluated. From an LCA perspective, different groups, such as workers participating in a particular stage of the product value chain (i.e., production or processing), people living in the neighborhood or final users of a product, are included, while from an RA perspective only consumers exposed to the products are the targets. For policymakers the sum of these different groups within an LCA in a single DALY measure is valuable, since it indicates the overall impact on public health. However, this composite metric, which aggregates very different endpoint sources, can be difficult to determine for the individual of a specific group (e.g., worker, neighbor or consumer). This aggregation of information from groups of people makes it difficult to ascertain the granularity of the data and leads to a loss of transparency in the single metric. Nevertheless, when evaluating the impact on public health, policymakers have to be aware that the events take place at different points in time and are assessed by different methods; for instance, LCA calculates potential impacts while RA tends to estimate real ones.

Finally, when looking to evaluate the severity of damage to human health, endpoint indicators from an LCIA cannot provide the same detailed information as that provided by an RA (Barberio et al., 2014). In other words, even though results from both tools are compared relative to the system under study, the LCA results on damage to human health are not interpreted in threshold values, making it difficult to contextualize the damage. In contrast, an RA can provide information to contextualize damage, since its results have regard to acceptable limits and exceeding them represents a potential impact on human health.

On the other hand, when an LCA and an RA are integrated through MCDA, the fundamental differences mentioned above (i.e., unit, geographical limits, groups of people evaluated) are relatively easier to handle during the integration process. Also, MCDA indicates other criteria that need to be assessed vis-à-vis the decision-making process. This route might be promising, although it requires somewhat arbitrary choices (such as weighting among criteria) to go beyond qualitative integration (e.g., through radar graphs).

Despite all these limitations, a key lesson learned is that the integration of LCA and RA can provide a complete assessment of the total health impacts from exposure to chemicals and pathogens in the food domain. As pointed out by Heimersson et al. (2014), the inclusion of pathogen risk in a human health impact assessment can constitute up to 20% of the total health impacts evaluated. Thus, applying only LCA and ignoring the pathogen risk by using RA will significantly underestimate the other life cycle human health impacts.

In the context of climate change, there is an urgent need for the application of an integrated LCA and RA framework to support management actions that guarantee the food safety of food value chains while reducing global warming and other environmental impacts. The reason is that international (e.g., SDGs) and European (e.g., Green Deal and Farm-to-Fork) initiatives have aimed at the mitigation of climate change, shifting to environmentally sustainable food systems as well as providing safe healthy food as their primary objectives. These have become the impetus for the food sector to take environmentally friendly management actions for food safety. Research studies encompassing other methodologies and/or applications, are needed to put this goal into action.

6. Conclusions: toward sustainable food systems in the era of climate change

Impacts of climate change represent significant challenges to food safety, placing human health at risk. At the same time, strategies to mitigate food safety risks contribute to this global issue and have other environmental impacts, creating a loop between the cause of the problem and the effect of the solution. The integration of food safety and environmental sustainability of food value chains takes on special relevance given the challenges posed by the effects of climate change on food production and supply. For decades, RA and LCA have been established as valuable tools to support food safety and ensure the transition to environmentally sustainable food systems. However, in the food field, these tools have mainly been used separately, and their integrated application has not yet been fully addressed. The reason for this limited integration is likely to lie in the respective scopes of RA and LCA. While RA is focused on consumer health, LCA aims to describe the full picture of a system. In other words, RA and LCA do not have the same focus: specificity in the former, comprehensiveness in the latter. Therefore, even when they express the result by the same DALY metric, they still differ in their time and space scales. To overcome this difficulty, the *Knowledge Integration* and *Comparison or Combination of Results* are added-value schools to be considered in order to support food value chains facing the challenge of climate change. The lessons learned from the collected studies in the non-food domain, as well as current initiatives involving environmental and health aspects in food systems, pave the way toward promising applications within the food domain.

Acknowledgments

This project has received funding from the European Union's Horizon 2020 research and innovative programme under the MSC-ITN grant agreement No. 813329 (PROTECT) (http://www.protect-itn.eu/). Paola Guzmán-Luna, Miguel Mauricio-Iglesias and Almudena Hospido belong to a Galician Competitive Research Group (GRC), co-funded by FEDER.

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