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Review

Review of food safety hazards in circular food systems in Europe

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ABSTRACT

European food production systems have become very efficient in terms of high yield, quality and safety. However, these production systems are not sustainable since, amongst other reasons, a significant proportion of the production is wasted or lost in the supply chain. One of the strategies of the European Union is to achieve climate neutrality by moving towards a circular economy with better waste management. This includes, reducing food waste and losses, and reusing or recycling by-products of the food and feed production systems. A circular economy would greatly improve the sustainability of the European food systems, but attention must be paid to the emergence of (new) food safety hazards. New or not well-known hazards can occur because by-products are reintroduced into the system or new processing steps are used for recycling, and/or known hazards can accumulate in the food production chain due to the reuse of (by-)products. This review addresses food safety hazards in the circular biobased economy, covering the domains of plant production, animal production, aquaculture, and packaging. Instead of an exhaustive list of all potential hazards, example cases of circular food production systems are given, highlighting the known and potential emerging food safety hazards. Current literature covering emerging food safety hazards in the circular economy shows to be limited. Therefore, more research is needed to identify food safety hazards, to measure the accumulation and the distribution of such hazards in the food and feed production systems, and to develop control and mitigation strategies. We advocate a food safety by design approach.

1. Introduction

Over the years, European food production systems have become very efficient in terms of high yields, quality and safety and low production costs. The downside of these production systems is that they are not optimal in terms of sustainability; soil is deteriorating, the use of artificial fertilizers, pesticides and antimicrobials is too high, as is the ammonia emission, and much food is wasted. The European Union (EU) has acknowledged these negative effects of our food production system, and to limit climate change, the EU advocates a more sustainable food production system. In its Green Deal, the EU describes her policy to achieve sustainable food production: Food waste - defined as “any substance or object which the holder discards or intends to or is required to discard” (EU, 2008b) - should be reduced, as well as the use of chemical pesticides and of artificial fertilizers, and nutrients should be brought back into the food system. The EU proposed the food waste hierarchy: The first tier is to prevent waste, the second is to reuse waste, the third is to recycle waste (e.g. use it as ingredient in animal feed), the fourth is to recover waste (e.g. recover energy and nutrients from waste through composting), and the fifth is to dispose waste (EU, 2008b; Salemdeeb, Zu Ermgassen, Kim, Balmford, & Al-Tabbaa, 2017). The General Food Law, Regulation (EC) 178/2002, defines safe food as food that has been produced, stored and processed such that it does not contain chemicals or microorganisms in concentrations that can be harmful to human health upon consumption. Thus, unsafe food implies that the food is contaminated with physical, chemical and/or microbiological hazards that can have negative consequences for human health (EU, 2002). Moreover, the EU has established a set of regulations and recommendations for food and feed, amongst which, i) general regulations, ii) regulations that define maximum allowed levels for concentrations of hazards that may be present in food, iii) regulations that list prohibited substances, iv) regulations for novel foods, and v) regulations specific for food contact materials such as packaging. Moving towards a circular biobased economy by reusing or recycling waste, should not

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endanger human and animal health or the environment, and food and feed products should comply with the EU's regulations in place to safeguard human health (EU, 2008b), even though specific regulations for the use of novel by-products or applications are not in place and amendments might be needed to reach the sustainability goals set.

In addition to waste, by-products, secondary products produced during the production of the main product(s), in plant and animal production are abundant (Ominski et al., 2021). Measures to reduce food waste and reuse by-products of food and feed production or aquaculture could lead to the accumulation of food safety hazards present in the biomass and distribution of those hazards in the production system, Also, new hazards can be introduced into the food system, for example, due to the reuse of by-products that have not used before, or formed during the processing of these by-products (Bodar et al., 2018; Garrett et al., 2020; Lange & Meyer, 2019). Examples of recycling or wrongly processing of by-products leading to food safety incidents, are for example the Belgian PCB incident of 1999, where recycled oil and fat containing transformer oil, a source of PCBs, was included in animal feed; or the Irish incident of 2008, where recycled mineral oil was used as fuel in direct flame to dry bakery waste used as ingredient in animal feed (Heres, Hoogenboom, Herbes, Traag, & Urlings, 2010; Hoogenboom et al., 2007). Another example is the well-known BSE crisis, where the epidemic was caused by incorporating cattle proteins in cattle feed (Smith & Bradley, 2003). The key issue is how to reuse by-products while avoiding the accumulation of chemical and microbiological hazards, or the spread of diseases when feeding farmed animals swill or other feed containing animal proteins, Available data on the wide range of possible food safety hazards when reducing food waste and reusing by-products in food production systems are limited and scattered across the multiple ways for circular food production. Thakali and MacRae (2021) proposed a first review covering the following classes of chemical and microbial contaminants: heavy metals, halogenated organic compounds, foodborne pathogens and antibiotic resistance genes (ARGs). Several pathways of contamination, and some risk factors that could prevent a safe circular system were identified. This review aims to provide insights into emerging hazards related to circular food production systems in the European context. It covers a wide range of chemical and microbiological food safety hazards. The possible ways to close loops and produce in a circular way are endless. Therefore, we did not attempt to provide an exhaustive overview of all possible food safety hazards that may occur. Instead, based on literature, exemplary cases of improved circularity in the food system are given with related, potentially emerging hazards. Even though this review discussed hazards within the European legal framework, knowledge on the presence and the accumulation of hazards by re-using by-products are applicable globally.

This review is divided into four production domains: the domains of plant production, animal production, aquaculture, and packaging. Per domain, a few relevant recycled inputs and outputs in a circular economy are discussed. For the domain of plant production, the inputs waste-based soil amendments – consisting of compost, biosolids, and manure – irrigation water, and soil are discussed. The outputs considered are plant by-products. For the domain of animal production, inputs discussed are plant-based feed materials, feed materials containing animal proteins, and insects. The outputs considered are animal by-products, such as slaughter waste. For the domain of aquaculture, since several inputs have been discussed in previous sections, only a few outputs, mainly used as fish or farmed animal feed, are discussed: Fish by-products – consisting of fish meal, mussel(meal) and other fish by-products – and seaweed. Furthermore, water as output is discussed. The last section discusses the domain of packaging. The section is not divided into inputs and outputs but instead is structured per type of packaging material.

2. Plant production

Plants are the main source of human food, as well as the main source of feed for production animals. Plants also provide raw materials for, amongst many industries, the textile industry (Kumar & Suganya, 2017). Main inputs of plant production relevant in the circular economy include soil amendments, irrigation water, and soil. Outputs, playing a key role in the circular economy, are plant by-products.

2.1. Inputs plant production

A main source of potential food safety hazards in the soil used for plant production are waste-derived soil amendments, such as animal manure, composts made from biodegradable wastes, or biosolids extracted from sewage systems. Furthermore, irrigation water and soil are inputs to plant production.

2.1.1. Manure

The use of animal manure, a by-product of the animal production system, in plant production, can reduce the use of artificial fertilizers. However, animal manure can also be a source of multiple food safety hazards, both chemical and microbiological. First of all, manure is a source of heavy metal contamination: it was found that continuous and high manure application significantly increased the total concentrations of soil cadmium (Cd), chromium (Cr), copper (Cu), and zinc (Zn) (Lu et al., 2014; Nomeda, Valdas, Chen, & Lin, 2008; Zhen et al., 2020).

Pharmaceuticals are another major concern in animal manure. Pharmaceuticals, among which antimicrobials are widely used in animal production. A large fraction, often more than half, of the dose administered to animals is excreted unchanged via the urine and the feces, ending up in the manure. An extensive monitoring study in the Netherlands showed that antimicrobial residues were found in 55% of the swine feces and 75% of the calve feces (Berendsen, Wegh, Memelink, Zuidema, & Stolker, 2015). Tetracyclines, quinolones, macrolides, lincosamides and pleuromutilins are, in general, persistent in manure, with more than 10% of the native compound remaining after one year of storage of the manure (Berendsen et al., 2018). Some antimicrobials proved to be more persistent than generally assumed. In addition, uptake of certain antimicrobials from the soil by plants has been demonstrated. The level of uptake depends amongst other, on the properties of the antibiotic, such as polarity and ionic form and the composition of the soil. Although the uptake of antimicrobials by plants is most of the times low, bacterial resistance development and the spread of antibiotic resistance genes (ARG) remain important issues (Chitescu, Nicolau, & Stolker, 2013; Sun et al., 2021). ARGs are carried by the microbial population present in animal manure (Menz, Olsson, & Kümmerer, 2019). Manure fertilized soils show higher levels of ARGs than soils with artificial fertilizers. In addition, the use of manure, containing antibiotic residues and ARGs, changes the soil microbial community, shaping the soil ARG profile (Wang et al., 2020).

In addition to the potential presence of chemical hazards in animal manure, microbiological hazards can be present as well. Pathogenic bacteria of concern in manure are, amongst others, *Campylobacter coli* and *jejuni*, *Bacillus anthracis*, *Brucella abortus*, *Escherichia coli, Leptospira* spp.*, Listeria monocytogenes*, *Mycobacterium bovis*, *Mycobacterium avium paratuberculosis*, *Salmonella* spp.*,* and *Yersinia enterolitica*. Viruses of concern in animal manure are avian-swine influenza and Hepatitis E. Furthermore, parasites might be present in manure, including *Balatidium coli*, *Cryptosporidium parvum*, *Giardia* spp., *Toxoplasma* spp., or the helminths *Ascaris suum, Taenia* spp.*, Trichuris trichiara* (Millner, Reynolds, Nou, & Krizek, 2009). Manure may be heat-treated but this could be insufficient to remove all pathogens. Pathogens present in manure can affect the microbial community of the soils and crops to which it is applied (Hamilton et al., 2020), which could lead to the susceptibility of plants to new diseases. Evidence, however, suggests that although pathogenic bacteria might be present in animal-based composts, poultry litter does not promote *L. monocytogenes* and *S. enterica* growth and may even promote bacterial communities that suppress human pathogens (Devarajan et al., 2021).

2.1.2. Composts

Composts are the product of aerobic bioreaction of organic waste and can be used as soil amendments (Burketova, Trda, Ott, & Valentova, 2015). These composts can be a major source of chemical contaminants such as dioxins, per- and polyfluoroalkyl substances (PFAS), and heavy metals (Costello & Lee, 2020). Polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs) and polychlorinated dibenzo-p-dioxins (PCDDs) are frequently measured in green waste compost. During the composting process, PCDDs accumulate up to a factor of fourteen. Three-ring PAHs are reduced but five- and six-ring PAHs and PCBs increased up to a factor of two (Brändli et al., 2005). In a recent French study, several PFAS susceptible for uptake by plants, were found in a variety of composts for agricultural application (Munoz, Michaud, Liu, Vo Duy, Montenach, & Resseguier, 2021). Apart from being a source of contaminants, the application of green compost may on the other hand also mitigate the uptake of hydrophobic contaminants, as was demonstrated for rocket salad and the contaminants imidacloprid, boscalid, metribuzin, and the two endocrine disruptors 4-*tert*-octylphenol and bisphenol-A (Parlavecchia, Carnimeo, & Loffredo, 2020). In addition to chemical hazards, pathogens may survive in green waste-based compost. It was found that composts from green waste, mainly composed of waste from public and private gardens, did not support pathogen growth, but survival of pathogens was observed. *S. enteritidis* survived in green waste composts, even in mature composts. *E. coli* and *L. monocytogenes* survival was observed in four-week-old composts but not in mature composts (Lemunier et al., 2005).

2.1.3. Biosolids

Biosolids (sludge) can be extracted from civil waste water, industrial and mixed waste water systems, and the derived digestates and compost can then be used as top soil improvers in plant production. A wide range of organic contaminants are found in sewage sludge and waste water, relating to consumer and industrial products and applications. Gustavsson, Molander, Backhaus, and Kristiansson (2022) estimated the loads of more than 2000 chemicals in wastewater in Sweden. The diversity of chemicals in their study included detergents, surfactants, dyes and pigments, brominated flame retardants (BFRs) and many other chemical groups. Many of these may impact the safety of agricultural produce, although it remains to be determined to what extent. The organic carbon of biosolids from civil wastewater treatment plants binds persistent organic pollutants (POPs) and may in this way transfer POPs into the food chain (Brambilla et al., 2016). POPs are defined as environmental contaminants that persist in the environment, accumulating in the food chain and posing a risk for human health and the environment. POPs include well known pesticides such as Aldrin, Chlordane and DDT, but also industrial chemicals such as PCBs, dioxins, perfluorooctane sulfonic acid (PFOS), perfluorooctanoic acid (PFOA), short chain chlorinated paraffins (SCCPs), some BFRs and some pharmaceuticals. Aro et al. (2021) found a broad suite of PFAS in sewage sludge including perfluoroalkyl acids (PFCAs), - sulfonates (PFSAs), -sulfonamides (FOSAAs) and fluorotelomer phosphate mono- and diesters (mono and diPAPs). Bugsel, Bauer, Herrmann, Maier, and Zwiener (2021) studied a large number of PFAS in agricultural soils that were contaminated through application of sludge from paper production in Germany. Furthermore, heavy metals such as cadmium (Cd) and lead (Pb) have been described as a potential hazards in biosolids (Saha, Panwar, & Singh, 2010). Heavy metals are persistent, and tend to increase in concentration during the chemical and physical treatment of the biosolids due to the reduction in the organic content of the residual material (Thakali and MacRae, 2021).

Microbial hazards are a key barrier to the reuse of this waste stream as well. Pathogenic bacteria commonly detected in biosolids are: *Campylobacter jejuni. E. coli, L. monocytogenes, Salmonella* spp, and parasites commonly detected in biosolids are *Cryptosporidium* spp. Furthermore, biosolids are a source of ARGs. Although ARG concentrations in biosolids are thought to be lower than in manure, application of either waste stream can increase concentrations of ARGs above background levels after application (Hamilton et al., 2020). Viral infectious pathogens seem to be persistent in biosolids and are thought to be of the highest risks in biosolids. Commonly detected viral pathogens in biosolids include adenovirus, enterovirus, and norovirus (Hamilton et al., 2020; Tozzoli et al., 2017).

2.1.4. Irrigation water

Irrigation water is another potential source of both chemical and microbiological hazards. Hazards specifically found in water are cyanobacteria, commonly known as blue-green algae, found in fresh and marine water. These bacteria may produce cyanotoxins, which can bioaccumulate in various food crops irrigated with cyanobacteria-contaminated water, for instance, lettuce, rice, broccoli, tomatoes, and carrots. To what extent cyanotoxins bioaccumulate in the crop depends on many variables, such as the plant growth stage when exposed to cyanotoxins (e.g., germination, growing, fruiting adult plant), composition of soil bacteria, concentration of cyanotoxin in the water, amount of water used for irrigation, length of exposure via irrigation, etc. (Miller & Russell, 2017).

Human pathogens are also a major hazard for the use of irrigation water. Irrigation water may be a source of contamination of soils and crops, and a vehicle for transmission of pathogens. *Salmonella* spp. have been reported frequently in surface water such as rivers, lakes or ponds. They originally come from the gastrointestinal tract of animals and humans and can end up in surface water used for irrigation via the feces (Islam et al., 2004; Liu, Whitehouse, & Li, 2018). *Campylobacter jejeni* and *coli*, a common cause of bacterial gastroenteritis in humans are also common pathogens found in surface water. These bacteria mainly come from animal feces, amongst other poultry and wild bird feces (Mughini-Gras et al., 2016; Mulder, Franz, de Rijk, Versluis, Coipan, & Buij, 2020). In addition, the pathogen *E. coli* O157 has been reported in surface water (Liu, Hofstra, & Franz, 2013). Furthermore, viruses such as noroviruses are frequently registered in water (Sterk, Schijven, de Nijs, & de Roda Husman, 2013). Expected climate changes might induce changes in pathogen fate and transport via (irrigation) water. Intense precipitation or flooding could increase surface runoff, leading to the transfer of pathogens present in manure at livestock farms to pastures or surface water used as irrigation water (Liu et al., 2013; Sterk et al., 2013). Periods of intense precipitation might also cause sewage overflow, leading to increased concentration of noroviruses in surface water. Drier summers decrease the moisture of the soil, increasing its hydrophobicity subsequently leading to increased runoff events, spreading pathogens (Sterk et al., 2013). Although pathogens might contaminate crops via irrigation water, the spread of pathogens via water distribution systems is lower with surface furrow and drip irrigation systems as compared to sprinkler systems because the latter irrigation water comes in direct contact with the edible portion of the plants (Alegbeleye & Singleton, 2018).

Civil waste water (sewage) can be treated and reused as irrigation water. Much research is performed on the treatment of waste water to remove chemical hazards such as POPs, among which PAHs (Zhen et al., 2020), and heavy metals. Current technologies are, however, not able to completely remove these chemicals yet. Particularly (persistent) water soluble contaminants are mobile and may not be removed in the water treatment. This came under the attention in recent years under the PMOC definition (persistent mobile organic contaminants) (Reemtsma, Berger, Arp, Gallard, Knepper, & Neumann, 2016) and research is needed to study their impact in agricultural production. Blum, Andersson, Ahrens, Wiberg, and Haglund (2018) identified several mobile industrial chemicals and fragrances (musks) from personal care products in effluents. Aro et al. (2021) investigated a broad suite of PFAS, and particularly the very short chain PFAS showed up in the effluent, and can be taken up by plants. Furthermore, the presence of pharmaceuticals (including residues of hormones), viruses and pathogens remains an issue in sewage.

2.1.5. Soil

All inputs discussed so far are applied to agricultural soil. Several food safety hazards previously discussed can accumulate in the soil, but in particular heavy metals and POPs, including several pharmaceuticals. These hazards can be toxic to both humans and animals, remain intact for many years, and can accumulate in living organisms. Both heavy metals and POPs originate either from the environment through ambient pollution deposition (especially in industrial areas), artificial fertilizers or pesticides, irrigation water, or waste-derived soil amendments such as manure, composts or biosolids (Costello & Lee, 2020; Ghisi, Vamerali, & Manzetti, 2019; Scher et al., 2018; Thakali & MacRae, 2021). These chemicals accumulate in the soil, leading to long-term contamination of the soil and can be taken up by plants. Examples of well-known POPs found in the soil are organochlorine pesticides (OCPs), dioxins, polybrominated diphenyl ethers (PBDEs), hexabromocyclododecane (HBCD), and some PFAS including PFOS and PFOA (Thakali & MacRae, 2021). The uptake of lipophilic contaminants like OCPs, PBDEs, HBCD and dioxins in the plant is limited, as they stay strongly associated with the soil organic carbon. On the other hand, as discussed in earlier sections, PFAS and other water-soluble contaminants are more prone to uptake by crops.

Examples of heavy metals accumulating in the soil are arsenic (As), mercury (Hg), nickel (Ni), Cd, Cr, Cu, Pb, and Zn (Thakali & MacRae, 2021). Heavy metals are adsorbed and accumulate in edible and non-edible plant tissues during growth (Zhou et al., 2016). Lead or arsenic-based pesticides were very common for fruit tree orchards in the first half of the 20th century. However, residues of these pesticides remain in the soil. The degree of contamination in the fruits are generally reported to be low. However, when these old orchards were used for the production of root of leafy crops, high levels of lead or arsenic were found in the edible portion of the crops, even causing phytotoxicity in sensitive crops (McBride, Shayler, Russell-Anelli, Spliethoff, & Marquez-Bravo, 2015).

Pharmaceuticals are introduced into the soil through wastewater, sewage biosolids, or manure. The fate and behavior of pharmaceuticals in soils (e.g. retained in the surface layers of the soil or leached into the groundwater) depend on the properties of the pharmaceuticals as well as on the soil properties. For example, tetracyclines tend to accumulate in the surface layers of the soil, whereas sulfonamides tend to leach into the groundwater. The uptake and accumulation of pharmaceuticals tend to be higher in plants grown on sandy soils than on soils with a higher organic matter content (Gworek, Kijeńska, Wrzosek, & Graniewska, 2021). In addition to the potential uptake of chemical contaminants by the plant, pathogens present accumulating in the soil due to the use of biological soil amendments or irrigation water might transfer to the plants, including the fruits and vegetables (Sharma & Reynnells, 2016).

2.2. Outputs plant production

2.2.1. Plant by-products

Plant by-products are reused, either as animal feed, as substrate for insects, as cover crops, green manure, or as compost in plant production. By these means, all hazards that have accumulated in the plant tissue remain in the food supply chain. Plant-based composts, green manure, and cover crops increase soil organic matter, important for soil fertility and crop productivity. Composts increase microbial diversity and activity in soils which could reduce pathogen (e.g. *L. monocytogenes* and *S. enterica*) survival in the soil (Devarajan et al., 2021). However, plant-based composts might also contain chemical food safety hazards such as POPs, and heavy metals. When plant waste is reused, these contaminants remain, and may circulate and accumulate in the food supply chain. One example is the reuse of clippings from road-verges as animal feed. The proximity of these verges to road traffic make these clippings prone to traffic related pollution. Road-verge biomass harvested at several locations in the UK showed, as expected, higher levels of, amongst others, metals and PAHs, compared to background levels in UK herbage and soils (Mason et al., 2020). It should thus be investigated if by-products can safely be treated so that they can be used as animal feed in the first place, or alternatively as compost, providing nutrients and keeping good microbial properties in the soil, without leading to further accumulation of hazards.

3. Animal production

The current ways of animal production are not sustainable as this is responsible for more than half of human-generated greenhouse gas (GHG) from the food system. In addition, 40% of global croplands are used to produce feed. Instead of feeding farmed animals crops also suitable for human food, alternative feed sources need to be investigated (Van Zanten et al., 2018). Plant-based or animal-based by-products from the food industry, waste-based feed materials, and insects reared on by-products, are ways to more sustainable animal production and are further discussed. The output – animal by-products – is discussed in the context of a circular economy.

3.1. Inputs animal production

3.1.1. Feed: plant-based by-products

In principle, plant-based products are allowed to be used as animal feed if regulated contaminants are below the legal limits (EU, 2013). By-products from food industry are frequently used as an ingredient for animal feed. Sugar-beet pulp, a by-product from the sugar industry is one of these products commonly used in animal feed (Boudra, Rouillé, Lyan, & Morgavi, 2015). Other frequently used by-products are brewers spent grains, germs and rootlets, by-products from the beer brewing industry due to their high nutritional value (Mastanjević, Lukinac, et al., 2019). Another example are the by-products from the olive oil industry (Gullón et al., 2020). All these plant-based by-products may contain food safety hazards (Boudra et al., 2015; Gullón et al., 2020; Mastanjević, Lukinac, et al., 2019). Potential hazards identified are mycotoxins, such as zearalenone, mycophenolic acid, roquefortine C and ochratoxin A found in sugar beet (Boudra et al., 2015). Deoxynivalenol (DON) or nivalenol tend to accumulate in the outer parts of the grains, and thus frequently end up in grain by-products, for example of the beer industry (Mastanjević, Šarkanj, Mastanjević, Šantek, & Krstanović, 2019). Other mycotoxins detected in the by-products of the beer industry are aflatoxins, ochratoxin A, zearalenone, patulin and gliotoxin (Wang, Li, Xiong, Guo, & Liu, 2019). Mycotoxins are unwanted substances in animal feed since they are detrimental to animal health and productivity, as well as human health. Most mycotoxins are metabolized by the animals and, therefore, will not accumulate further in the food supply chain in its initial form when present in animal feed. Metabolites can, however, be excreted by the animal. Most of the metabolites are not regulated. Furthermore, the metabolism of all mycotoxins and the toxicity of all metabolites have not been elucidated. For example, the metabolites deoxynivalenol-3-sulafte, a major DON metabolite excreted by chicken seems to be less toxic that DON itself (Schwartz-Zimmermann et al., 2015). A metabolite known to be toxic (and regulated) is aflatoxin M1. When dairy cows are fed aflatoxin B1 contaminated feed, aflatoxin B1 is metabolized in the cow's body into aflatoxin M1 and excreted in the dairy milk (van der Fels-Klerx & Bouzembrak, 2016). Pesticides may also be found in plant-based by-products, for example, copper residues, which are applied in different forms after harvesting to protect against fungal and bacterial infections (Hammann, Ybañez, Isla, Hilal, & Garrido, 2019; Molina-Alcaide & Yáñez-Ruiz, 2008). Pesticides not dissolving in water tend to concentrate in brewer's spent grains. Pesticide residues are highly persistent and degrade only to a limited extend (Navarro & Vela, 2009). Finally, heavy metals or other contaminants like antibiotic residues can be taken up from the soil, leading to for example, by-products such as sugar beet pulp potentially contaminated with these contaminants (van der Fels-Klerx et al., 2019).

3.1.2. Feed: by-products containing animal proteins

Animal by-products are defined as "entire bodies or parts of animals, products of animal origin or other products obtained from animals, which are not intended for human consumption, including oocytes, embryos and semen" (EU, 2009). The use of by-products containing animal proteins as ruminant feed (cattle, sheep and goats) is banned in the EU to stop the possible transmission of transmissible spongiform encephalopathy (TSE). TSE is a fatal neurodegenerative disease that arises as a result of misfolding of prion proteins. Prion diseases are irreversible and a cure is currently non-existent. TSE is known as scrapie in sheep and goat, Bovine spongiform encephalopathy (BSE) in cattle, and Creutzfelt-Jakob disease (CJD) in human. Since TSE does not affect pigs, poultry or fish, feeding consumer waste to these species could be conceivable for these animal species (Raamsdonk, 2017; Xu et al., 2013).

Processed animal proteins (PAP) include slaughter by-products obtained from healthy animals and include blood meal, meat meal, bone meal, horn meal, feather meal, and fish meal. Recently, Regulation (EU) No 1372/2021 amending Regulation (EC) No 999/2001 as regards the prohibition to feed non-ruminant farmed animals with proteins derived from animals, permits the use of PAPs from farmed insects to poultry and porcine animals. Furthermore, the use of processed poultry proteins are allowed in feed for porcine animals, and the use of processed proteins from porcine animals are allowed in feed for poultry. Intra-species recycling and the use of animal proteins for ruminants is still prohibited to avoid transmission of TSE (EU, 2021a). A remaining concern with between-species recycling of nutrients is that some viruses might be transmitted between species and some viruses become more virulent within other species, for example, pigs could become mixing vessels for avian flu or human flu viruses (Ma, Kahn, & Richt, 2009).

In addition to prions, other potential hazards in animal by-product are pharmaceutical residues, as has been demonstrated in chicken feathers. Antibiotic residues can be detected in the feathers long after treatment, and can remain in the feather meal (Jansen et al. 2017). In Japan and South Korea, up to 60% of household food waste is recycled and used as animal feed (Ominski et al., 2021). Regulations are in place in these countries prescribing heat treatment, storage and transport conditions of the waste. In the EU, the reuse of consumer waste in animal feed is not common practice. Only specific food wastes for specific animal species, for which it has been demonstrated that the consequences for human health are negligible, are allowed as animal feed (Salemdeeb et al., 2017). A main issue is that consumer waste contains meat, which could potentially transmit diseases such as foot-and-mouth disease, African swine fever or TSE (Gale, 2004). Meat containing waste is therefore prohibited in animal feed in the EU (EU, 2021a).

3.1.3. Feed: insects

Due to their nutritional properties and the fact that they can be reared with minimal resources on a wide variety of organic by-products, such food waste, swill, or manure, insects are a promising sustainable alternative for conventional protein sources such as soybean, fish meal, as well as animal protein (van der Heide, 2021; Veldkamp, van Rozen, Elissen, van Wikselaar, & van der Weide, 2021). As stated earlier, Regulation (EU) No 1372/2021 permits the use of processed animal proteins from specific species of farmed insects to poultry and porcine animals, in addition to the already allowed use in petfood and fish feed (EU, 2021a). However, contaminants present in the substrate that is used for rearing insects can be carried over to the insects and, subsequently, to the animals fed with these insects. Hazards found in insects include heavy metals (As, Cd, Hg, Pb), pesticide residues, pharmaceuticals, hormones, dioxins and PCBs, and pathogens. Mycotoxins and PAHs seem not to accumulate in insects (Meyer, Meijer, Hil, & Van der Fels-Klerx, 2021; van der Fels-Klerx, Camenzuli, Belluco, Meijer, & Ricci, 2018). Insects can be a vector of prions, therefore, plant-based by-products from the food and feed industries are considered safe substrate for insects but consumer waste, potentially containing ruminant meat, needs extra precautions (van Raamsdonk, van der Fels-Klerx, & de Jong, 2017).

3.2. Outputs animal production

3.2.1. Animal by-products

Regulation (EC) No 1069/2009 categorizes animal by-products in three risk categories, and sets the required ways of disposal or reuse for each category. Category 1, the highest risk-category, containing for example by-products suspected of being infected with diseases or subjected to illegal treatments, and category 2 by-products containing products such as manure, or animal products containing residues of authorized substances or contaminant exceeding legal limits, are not allowed as animal feed, and must be destroyed. Some category 2 by-products can be used for the production of organic fertilizers, or used in an approved composting or anaerobic digestion plant (EU, 2009). Manure can directly be applied to land, provided there is no risk of transmitting diseases such as Foot and Mouth Disease. Category 3 by-products contain low-risk products which can be used for the production of petfood, or as organic fertilizer. Depending on the origin, the treatment (e.g. into processed animal proteins), and the intended use, some category 3 by-products may be used as farmed animal feed (EU, 2009, 2011).

Animal carcasses potentially contain a large variety of food safety hazards such as viruses, bacteria, protozoa, parasites, prions, pharmaceuticals and other chemicals, such as heavy metals and dioxins (Gooding & Meeker, 2016; Lee et al., 2021). In particular, cattle tissues such as the brain, eyes, spinal cord, ganglia, spleen, and some parts of the gut might contain TSE prions (EU, 2009). These animal by-products could be a hazard in animal feed as well as when applied to the land since plants such as alfalfa, corn, and tomatoes can take up prions (Pritzkow et al. 2015). Composting of cattle carcasses under thermophilic temperatures (>55 °C) kills most pathogens. Due to a variety of biological, chemical, and physical changes during composting, the behavior of prions is still uncertain, even though Xu et al. (2013) did not detect prions in samples after two or four weeks of composting. The composting matrix presents a challenge to detect prions and, therefore, the study could not prove that prions were completely degraded during composting. Other studies conclude that pathogens survived composting, even when recommended time–temperature conditions were met (Gooding & Meeker, 2016).

4. Aquaculture

Aquaculture represents almost half of the global seafood production and is currently the fastest growing animal food production sector (Campanati, Willer, Schubert, & Aldridge, 2021). In aquaculture, much effort is put into finding alternative, more sustainable, feed-sources than the currently used fish feed. The main inputs of aquaculture are feed and water. Fish by-products, both inputs and outputs of the system, are discussed in the section "Outputs aquaculture". The examples of fish meal, mussel(meal) are included. Furthermore, seaweed as an output is discussed. Insects as an alternative feed-source has been previously discussed in the section animal production. Water is discussed in the section "Outputs aquaculture".

4.1. Outputs aquaculture

4.1.1. Fish by-products

Most by-products from aquaculture production can be diverted back into food production systems. By-products consist of damaged fish, body parts, carapaces, shells, or trimmings from processing. About half of these by-products is used in the production of fish meal and fish oil in Europe. By-products are commonly reused as feed ingredients for aquaculture, and for pet feed (Campanati et al., 2021). Common food safety hazards in seafood (by-products) are parasites, pathogenic bacteria, dioxins, biotoxins, pharmaceuticals, heavy metals, pesticides, and disinfectants (Bodin et al., 2007). In aquaculture feed, fish oil is the main contributor of lipophilic contaminants (POPs), as reviewed by Amlund, Berntssen, Lunestad, and Lundebye (2012). Refining of fish oil can be performed for reduction of these contaminants by distilling (Oterhals & Berntssen, 2010). An undesired side-effect of this heat treatment may be the formulation of esters of 2- and 3-monochloropropanediol (2-/3-MCPDEs) and glycidylesters (GE). Merkle et al. (2017) showed that MCPDEs may be formed during deodorization of fish oils at high temperatures, and they found substantially higher levels in refined fish oils, compared to crude fish oils. Fish meal as PAP, derived from aquatic animals (not sea mammals), is widely used as animal feed. Fish meal can, however, contain POPs such as dioxins, PBDEs, some PFAS, some pharmaceuticals and also organotin compounds (Suominen et al., 2011). Poultry, swine, and especially ruminants that are fed fish meal can transfer heavy metals or dioxins originating from this feed ingredient into eggs, meat, and dairy products (Doréa, 2006).

Mussels not used for human consumption, such as undersized mussels or mussels grown to reduce the overload of nitrogen and phosphorus nearby urban areas, can potentially be used as feed ingredient for fish or even for pigs or poultry (Suplicy, 2020; van der Heide, 2021). Mussels pump and filter the water in order to feed, leading to accumulation of many food safety hazards from the water such as parasites, viruses, bacteria, antimicrobials or other pharmaceuticals, antimicrobial resistance genes, chemical contaminants such as PFAS, biotoxins such as tetrodotoxin, nanoparticles (López Cabo, Romalde, Simal-Gandara, Gago Martínez, Giráldez Fernández, & Bernárdez Costas, 2020) and heavy metals like Cd, Pb, and Hg (Zhelyazkov et al., 2018). Chemicals accumulating in mussels are, when mussels are used as fish feed, potentially carried-over from the mussels to the fish.

4.1.2. Seaweed

Seaweed is considered a novel source of proteins, and can be used as food and/or animal feed, for both terrestrial and aquatic animals (Morais et al., 2020). Seaweed is considered a sustainable source of nutrients in animal feed for mainly farmed fish, oysters, and poultry (Morais et al., 2020). Seaweed is also considered a "novel food", so a food for which human consumption was negligible in the EU before May 15, 1997 when Regulation (EC) 258/97 came into force. When introducing a novel feed product, not containing any animal proteins and complying to legal limits and other regulations, on the market, only a notification is needed (EU, 2013). When introducing a novel food product, the precautionary principle applies, referring to situations when, for example, there is no sufficient data to complete a comprehensive risk assessment (Article 7 of Regulation (EC) 178/2002). Regulation (EC) 258/97, the first novel food regulation, applies this principle: the producer of a novel food notifies the member state, a competent authority makes an initial assessment regarding its safety and forwards this to the EC. If no objections are made, the food is authorized on the market. Regulation (EU) 2015/2283 introduces a more efficient and fully centralized authorization procedure at EU level, allowing innovative food products to be placed on the market faster without compromising a high level of public health (EU, 2015). Several seaweed species, from the groups Phaeophyta (brown), Rhodophyta (red), and Chlorophyta (green) are nowadays listed as edible seaweed species in the EU (Banach, Hoek-van den Hil, & van der Fels-Klerx, 2020).

The downside is that seaweeds are known to accumulate contaminants present in their environment. Major known hazards in seaweeds are heavy metals (As, Cd, iodine (I)) and *Salmonella* spp. (Banach et al., 2020). Especially sludge-grown algae can contain high amounts of heavy metals (van der Spiegel, Noordam, & van der Fels-Klerx, 2013). Algae, when cultivated in open basins, are especially prone to contamination by pathogenic bacteria (van der Spiegel et al., 2013). Furthermore, other potential hazards include POPs, pharmaceuticals, marine biotoxins, microplastics, norovirus, and hepatitis E virus (Banach et al., 2020).

4.1.3. Aquaculture waste water

In a circular system, aquaculture waste water can be used for biomass production, such as microorganisms (single cell proteins) or algae that can be used as animal feed (Asiri & Chu, 2020). This waste water however potentially contains unconsumed feed, fish waste or residues of manure or pharmaceuticals. The use of manure as pond fertilizer may lead to a wide range of enteric pathogens including *Salmonella* and *Campylobacter* in the aquaculture waste water (Klase et al., 2019). Furthermore, high levels of ammonia were found in this wastewater and the release of aquaculture wastewater in the environment could cause algal blooms, eutrophication, water acidification, increase of the presence of pathogenic bacteria and viruses in water systems, or the spread of antibiotic resistance genes (Campanati et al., 2021).

Generally, aquaculture sludge contains lower levels of contaminants as compared to sludges retrieved from industry or municipal waste (Van Rijn, 2013). However, high concentrations of pathogenic bacteria, viruses, and/or antibiotic residues are found in aquaculture sludge, making its direct use as fertilizer on agricultural lands difficult. One proposed solution is the retainment of solid waste through mechanical filtration or sedimentation, and the recovery of dissolved nutrients using bacteria. In this way, biosolids can be reused for land application as fertilizer or can be used to produce omega-3 rich aquafeeds. Another proposed solution to treat aquaculture sludge is through vermicomposting. Vermicomposting is the use of worms to decompose waste and make nutrient rich compost. The earthworm biomass can in turn be used as feed for fish, pets or even livestock. Kouba et al. (2018) concluded that, after vermicomposting, the sludge (vermicompost) was safe for use in agriculture and that the earthworms were safe feed for fish, even though higher levels of heavy metals were observed in the final vermicompost as compared to the initial sludge as a result of the decomposition process. Heavy metals were also detected in the earthworm biomass, being cited as potentially problematic. Levels remained, however, below the EU legal limits. Heavy metals accumulate either in the vermicompost, or in the earthworms: Pb, Ni and Zn seemed to accumulate in the vermicompost whereas As seemed to accumulate in earthworms (Kouba et al., 2018; van der Fels-Klerx, Camenzuli, van der Lee, & Oonincx, 2016).

A first example of the reuse of waste water is recirculating aquaculture systems (RAS), in which wastewater is treated and reused within the system. Solid waste is removed from the waste water, nutrients are removed or detoxified, and the water is sterilized to remove pathogens. This water is then used again in the system. Chemical contaminants such as heavy metals, enter the system mainly via the feed and may stay and accumulate in the system (Klinger & Naylor, 2012). Martins, Eding, and Verreth (2011) showed that the concentration of heavy metals decreases in general with increasing water exchange rates, in particular for arsenic. The study suggests that fish cultivated in RAS systems did not accumulate heavy metals at levels hazardous to human health.

A second example of the reuse of wastewater is integrated multi-trophic aquaculture (IMTA). In such a system, the organic and inorganic waste from reared aquaculture species (e.g. finfish, shrimp) are assimilated by organic (e.g. mussels, sea cucumbers, sea urchins) and inorganic (e.g. seaweed) extractive species that are cultivated alongside the reared aquaculture species. The drawback of such systems is that hazards present in the wastes from fed aquaculture species can be carried over to the extractive species, potentially being a problem in case these species are used for human consumption or for animal feed (Buck, Nevejan, Wille, Chambers, & Chopin, 2017; Irisarri, Fernández-Reiriz, Labarta, Cranford, & Robinson, 2015).

A third example of a circular system that reuses wastewater and connects aquaculture and plant production is aquaponics, which can be used in urban areas. This system integrates bacteria, aquatic organisms (fish and crustaceans), and plants. In such close systems, water is circulated between these three organisms (Wirza & Nazir, 2021). Aquaponics combine a recirculating aquaculture system with the soilless (hydroponic) cultivation of vegetables. The waste generated by the aquatic organisms is treated by the bacteria and plants. Furthermore, a limited amount of water is lost via evapotranspiration and transpiration by plants, potentially leading to accumulation of heavy metals in the systems and potentially taken up by the plants of the fish. On the other hand, limited water polluted by animal production, and plant production is used as input (Joly, Junge, & Bardocz, 2015).

5. Packaging

In order to comply with the food waste hierarchy, waste from packaging needs to be reduced, reused and recycled as much as possible. Hazards may be present or accumulate in the packaging materials when reused or recycled, and in turn migrate to the food. Microbiological hazards are largely removed by the recycling process. Chemical contaminants present in raw materials, on the other hand, will mostly remain in the produced packaging materials. A proportion of packaging material is recycled, leading to accumulation or redistribution of the contaminants present in the previously manufactured packaging materials (Geueke, Groh, & Muncke, 2018). Recycling packaging materials is essential for a sustainable future, but food packaging made from recycled materials needs to be safe. Regulation (EC) 282/2008 on recycled plastic materials requires for example that the recycled packing has the same food safety as the virgin materials (EU, 2008a). A recent example of a food safety issue originating from the packaging are the "bamboo cups". Bamboo fibers were added to melamine plastic altering the migration rate of melamine and formaldehyde to the food, leading to a high number of RASFF notifications (Bouma, Kalsbeek-van Wijk, & Sijm, 2022).Conventional plastic relies on nonrenewable resources, therefore, this type of packaging in not sustainable. Biobased, biodegradable food packaging could be an alternative. However, the role of packaging of protecting and preserving the quality of the food, contributing in this way to limited food waste, remains crucial, also for biobased packaging materials. These required properties often leads to complex biomaterials including the incorporation of many substances, making the manufacturing costly. Therefore, their application as food packaging is still limited (Nilsen-Nygaard et al., 2021). The focus of the remainder of this section is therefore the reuse and recycling of conventional food packaging, including aluminum or steel cans, glass, paper and conventional plastic.

5.1. Aluminum, steel, glass

Recycling of aluminum or steel cans might result in the accumulation of heavy metals or metalloids, frequently originating from alloying elements used to increase the strength of the cans (e.g. manganese (Mn), Cr), or the coating residues left from previous use (e.g. tin (Sn), Zn). Coatings are often based on titanium dioxide and zinc oxide, or impurities (e.g. Cd, Pb). Special attention should be paid to the presence of heavy metals during the recycling of food containing metal (Geueke et al., 2018).

Glass packaging is inert and easy to sanitize and is, therefore, suitable to be reused or recycled. Since for both metal and glass packaging the material properties do not change and microorganisms and organic compounds are destroyed during the remelting process, recycling of these types of packaging is in principle safe. Glass packaging might contain the heavy metal Pb, a trace element found in the sand used to produce glass (Marsh & Bugusu, 2007).

5.2. Paper packaging

Food safety hazards in paper and board come from fillers, retention aids, sizing agents, coatings, biocides, printing inks, adhesives, plasticizers, solvents, and pigments. Typical contaminants found in paper and board are mineral oil hydrocarbons (MOHs), bisphenol-A (BPA) and analogues, phthalates, diisopropylnaphthalenes (DIPN), PAHs, PFAS, and heavy metals (Geueke et al., 2018). Next to these, often intentionally added substances (IAS) during production, also non-intentionally added substance (NIAS) can be present in paper and board, as a result of reaction by-products, oligomers, degradation processes, chemical reactions between packaging materials and foodstuff, or as impurities from the raw materials used for the FCM production (Peters et al., 2019). Upon recycling of paper, such NIAS may accumulate in the recycled paper and board. This may lead to potential hazards, and research is needed to address the safety assessment of NIAS in recycled paper and board. The chemical safety of paper packaging could be improved by phasing out hazardous substances in materials that are recycled. Simulation modeling showed this approach to be effective in reducing BPA, di-ethylhexylphthalate (DEHP), and MOHs in recycled paper and board. However, the lag time before the concentrations of these chemicals could be considered insignificant were estimated to be between one and three decades (Pivnenko, Laner, & Astrup, 2016). Phenylphenol (OPP), used as fungicide, disinfectant for surfaces or as raw material for pigments is frequently detected in paper packages. Even though considering the level measured and the migration potential of OPP, safety risks for the consumer are unlikely, the levels of OPP increased with increasing amount of recycled paper used during the manufacturing of the paper packages (Votavová, Hanušová, Vápenka, Dobiáš, & Kvasnička, 2014).

5.3. Plastics

The recycling of plastic as food contact material is more difficult. Even though one of the EU's strategies towards a circular economy is that by 2030, all plastic packaging in the EU should be either reusable or should be recycled in a cost-effective manner (EU, 2021b), up to now, the EU strictly regulates and limits the use of recycled plastic as food contact material due to safety reasons (EU, 2008a). Food safety hazards in plastics include degradation products of polymers (oligomers and monomers), additives such as phthalates (DEHP, DBP, BBP), flame retardants (PBDE, HBCD), fuel oils, or heavy metals (Cd, Ni, Pb). The levels of oligomers, formed during the synthesis of plastics or generated during use and recycling, are much higher in recycled plastics than in virgin plastics. Plastics absorb these chemicals during waste management, as food contact plastic and non-food grade plastic are not separated. Since these oligomers can migrate into the foods, they present a major food safety hazard. Mitigation strategies to reduce the levels of these contaminants are currently being investigated (Matthews, Moran, & Jaiswal, 2021). In the EU, particularly polyethylene terephthalate (PET) based packaging can be recycled and is allowed to be used again into food contact material. Recycling of other polymers (e.g. polyethylene, polypropylene) is more challenging from product properties and safety point-of-view. However, research on accumulation of potential hazards in these recycled polymers is still in it's infancy. This absence of knowledge of potential risks is a true hurdle for a rapid acceptance of recycled plastics to support the aims for sustainable FCMs.

6. Discussion and conclusion

A key hurdle in moving towards circular food systems is the potential presence and accumulation of (emerging) food safety hazards. Therefore, knowledge is required into the degree of accumulation of food safety hazards at all stages of the supply chain. By knowing which hazards might be present in which circular by-products, safe-use options for these by-products can be chosen. Fig. 1 highlights the main potential (food) safety hazards in the circular biobased economy; showing the possible accumulation in the main production domains (plant, animal, aquaculture, packaging) and the secondary production systems through the reuse of (by-) products. Table 1 lists the main known food safety hazards related to selected inputs and outputs relevant to the circular economy in the domains of animal production, plant production, and aquaculture. Such hazards can be introduced into the system by reuse of by-products that were previously discarded or can be introduced or

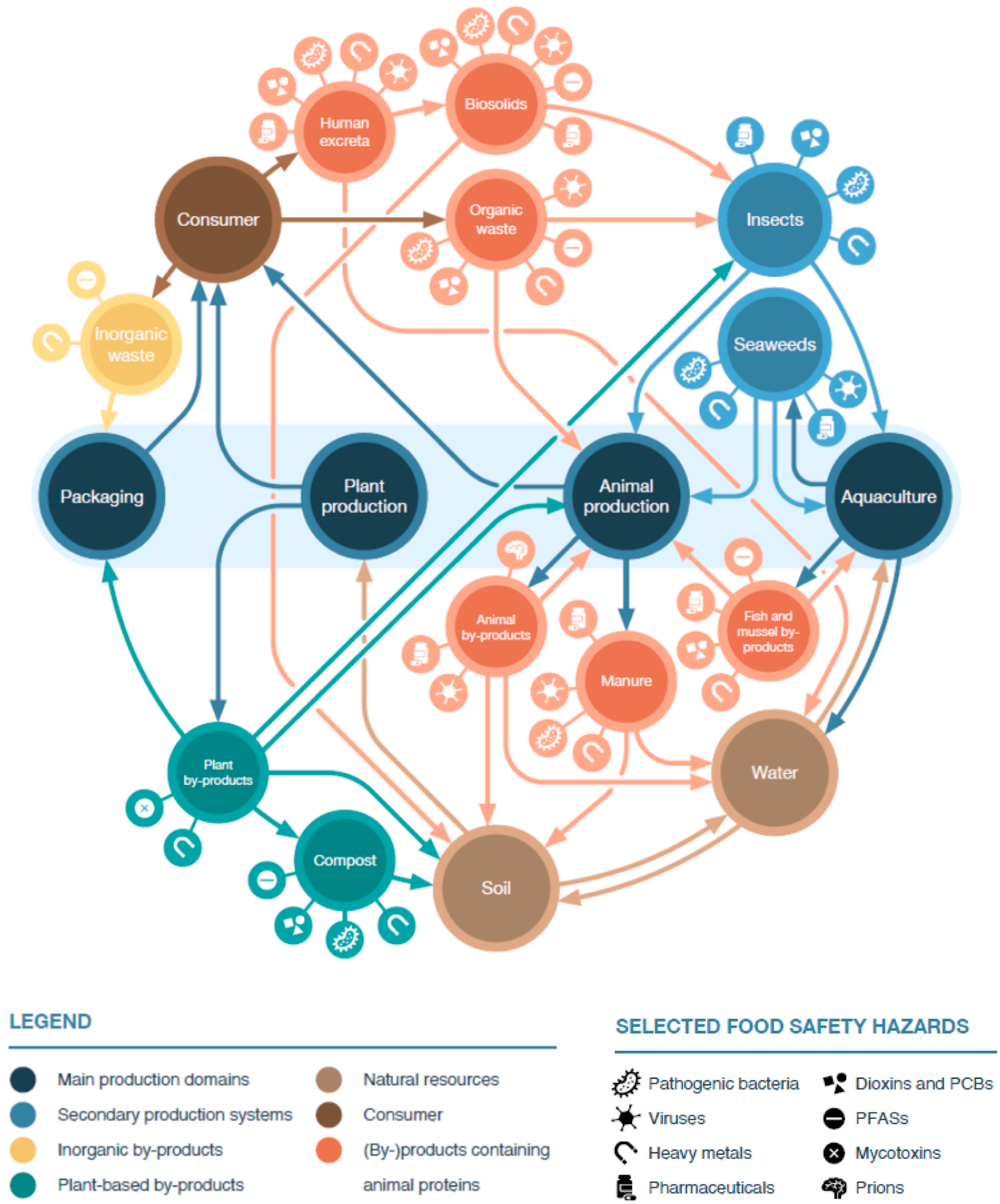

Fig. 1. Potential (food) safety hazards in the circular biobased economy; showing the possible accumulation in the main production domains (plant, animal, aquaculture, packaging) and the secondary production systems through the reuse of (by-)products.

formed during processing steps required for recycling.

Our results show that – in the four domains covered of plant production, animal production, aquaculture and packaging industry – most research has been done on pharmaceuticals, dioxins and PCBs, heavy metals and pathogens. However, many other microbiological and chemical hazards may be present in circular food production processes, and new, yet little- or unknown hazards may arise. Therefore, more research is needed to identify emerging hazards in practices to close loops in feed and food production. In a circular system, temporal effects become relevant to consider as long term accumulation of hazards is possible. For example, hazardous pesticides used in the past might still be present in the soil today, or hazardous substances used in the past in packaging materials might take decades to phase out when the materials are recycled. When closing the loop, spatial effects also play a role as hazards might spread more throughout the food production system compared to regular food production. For example, hazards present in consumer waste fed to farmed animals, insects or fish, might enter and accumulate in these production systems. When combined with regional production, on the other hand, regional spread of hazards may be less, and hazards may accumulate on the local scale.

Even though Europe cannot be considered an isolate community since in the modern world, food and feed is traded globally, and the European diet does not only consist of locally grown and produced food, this review discussed potential food safety hazards within the

Table 1
Selected inputs and outputs relevant to the circular economy with a list (not exhaustive) of main identified and known hazards.

Plant production		**Animal production**		**Aquaculture**	
Inputs	*Main known hazards*	*Inputs*	*Main known hazards*	*Inputs*	*Main known hazards*
Biosolids	Heavy metals Dioxins and PCBs PFAS Pharmaceuticals Pathogenic bacteria Viruses	Plant by-products	Heavy metals Mycotoxins	Seaweed	Heavy metals Pharmaceuticals Pathogenic bacteria Viruses
Manure	Heavy metals Pharmaceuticals Pathogenic bacteria Viruses	Animal by-products	Pharmaceuticals Viruses Prions	Fish by-products	Heavy metals Dioxins and PCBs PFAS Pharmaceuticals
Compost	Heavy metals Dioxins and PCBs PFAS Pathogenic bacteria	Fish by-products	Dioxins Heavy metals PFAS Pharmaceuticals	Organic waste	Heavy metals Dioxins and PCBs PFAS Pathogenic bacteria Viruses
(Waste)water	Heavy metals Pharmaceuticals Pathogenic bacteria Viruses	Insects	Heavy metals Pesticide residues Pharmaceuticals Dioxins and PCBs Pathogenic bacteria	Insects	Heavy metals Pesticide residues Pharmaceuticals Dioxins and PCBs Pathogenic bacteria
		Seaweed	Heavy metals Pharmaceuticals Pathogenic bacteria Viruses	(Waste)water	Heavy metals Pharmaceuticals Pathogenic bacteria Viruses
Outputs	***Main known hazards***	***Outputs***	***Main known hazards***	***Outputs***	***Main known hazards***
Plant by-products	Heavy metals Mycotoxins	Manure	Heavy metals Pharmaceuticals Pathogenic bacteria Viruses	Seaweed	Heavy metals Pharmaceuticals Pathogenic bacteria Viruses
Compost	Heavy metals Dioxins and PCBs PFAS Pathogenic bacteria	Animal by-products	Pharmaceuticals Prions Viruses	Fish by-products	Heavy metals Dioxins and PCBs PFAS Pharmaceuticals

boundaries of European Law. Knowledge on the presence and the accumulation of hazards by re-using by-products are however applicable globally.

In the second half of the twentieth century, food production shifted globally, increasing the production and stabilizing prices. Today, production is stagnating, leading again to volatile prices. Furthermore, today's agriculture and food production is highly dependent on the availability and the costs of energy and might not be sustainable in the near future anymore (Kirikkaleli & Darbaz, 2021). Innovations are needed and circular agriculture might be one of these innovations contributing to a more sustainable agricultural system. However, governance might not be able to keep up with these rapid innovations and EU regulations that safeguard human and animal health are not frequently updated for innovative changes in food production (van der Berg, Kleter, Battaglia, Bouwman, & Kok, 2020). Therefore, new ways of thinking are needed. The concept of "safe-by-design" may create opportunities to avoid food safety hazards in the end products. This concept should consider possible food safety issues at all stages of innovation, from the first stages of research and development to the post-market stages. In this way, early awareness of potential food safety hazards is raised, creating the opportunity to pro-actively implement preventive measures at each stage of the process (van der Berg et al., 2020). To date, most research regarding circular food systems focused on the performance, in terms of productivity, of these systems. Future research on circularity should perform environmental, economic and safety assessments and consider synergies and trade-offs between these aspects (Barros, Salvador, de Francisco, & Piekarski, 2020). As the transition towards a total circular biobased economy requires a systemic change, a circular redesign of our primary production systems is needed and the principles of safety by design should be included in the redesign of our future food productions systems.

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.

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