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COMPREHENSIVE REVIEW

Prioritization of chemical food safety hazards in the European feed supply chain

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Abstract

Extensive monitoring programs of chemical hazards in the animal feed chain are in place, both organized by public and private organizations. The objective of this review was to prioritize chemical hazards for monitoring in the European animal feed supply chain. A step-wise approach was designed for the prioritization, based on: historical occurrence of the chemicals in animal feed ingredients and animal feeds (in relation to European guidance values or maximum limits in feed); information on transfer of the chemical to edible animal products, and; the extent of human dietary intake of the products and possible adverse human health effects of the chemical. Possible prioritization outcomes were: high (H), medium (M), or low (L) priority for monitoring, or classification not possible (NC) because of limited available data on the transfer of the chemical to edible animal tissues. The selection of chemicals included (with results in parentheses): dioxins and polychlorinated biphenyls (H); brominated flame retardants (H); per- and polyfluorinated alkyl substances (H); the heavy metals arsenic (H) and cadmium (H) as well as lead (M) and mercury (M); aflatoxins (H), ochratoxin A (NC), and other mycotoxins (L); pyrrolizidine alkaloids (H) and other plant toxins (NC); organochlorine pesticides (H) and other pesticides (L); pharmaceutically active substances (M); hormones (NC); polycyclic aromatic hydrocarbons (L), heat-induced processing contaminants (NC), and mineral oils (NC). Results of this study can be used to support risk-based monitoring by food safety authorities and feed-producing companies in Europe.

KEYWORDS
animal feed, chemical compounds, contaminants, prioritization, risk ranking

1 | INTRODUCTION

Feed production encompasses different stages, such as breeding, cultivation, processing, storage, and trading, resulting in feed ingredients, premixes, additives, compound feed, and other products intended for use as animal feed. Multiple actors are involved in the feed production chain including crop producers, traders, producers

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of intermediate products, and producers of end products (Fink-Gremmels, 2012a). In Europe, farm animals are fed with a total of 833 million tons of feedstuffs (FEFAC, 2019). Half of this amount concerns raw feed produced on farms, 15% grain produced on farms, 15% purchased feed materials, and 20% industrially produced compound feed. From 2010 till 2019, the use of compound feed production has increased in Europe, due to an increase in poultry and cattle feed production (FEFAC, 2019). However, in the recent years 2020–2022, the production has slightly dropped, also mainly due to compounds feed for poultry and cattle (https://www.fefac.eu). Main raw materials used for compound feed are cereals produced in Europe, followed by cereals and soy beans produced outside Europe (FEFAC, 2019).

Quality and safety of feed materials and animal feeds is controlled through public and private quality control programs, like quality certification systems, hazard analysis critical control point systems, and monitoring. In spite of the tremendous efforts to prevent and control food safety in the feed supply chain, it remains difficult to fully manage food safety, because of the multiple food safety hazards of different nature, the range of ingredients, and the possible entry points of the feed chain. Food safety hazards present in animal feed can be taken up by the animal and transferred to the edible parts of the animal, thereby presenting a potential risk for public health (van der Fels-Klerx et al., 2019). To protect human and animal health, the European Commission (EC) has set legal maximum limits (MLs) for the (maximal) presence of certain undesirable substances in animal feed in Directive 2002/32/EC (EC, 2002a). Also, guidance values (GVs) have been set for certain mycotoxins by the European Commission in Recommendation 2006/576/EC (EC, 2006b). On top of that, private organizations in the feed supply chain may have additional (and in some cases lower) thresholds for the presence of chemical hazards in animal feed and feed ingredients. For instance, GMP+ has developed a (voluntary) Feed Safety Assurance program, with threshold values for the presence of chemicals, such as heavy metals, mycotoxins, dioxins, and persistent organic pollutants, in animal feed (GMP+, 2016). Monitoring programs, both public and private, are established to detect possible chemical hazards in feed. Preferably, monitoring on food safety hazards is risk-based, see Regulation (EC) No 2017/625, focusing on the most relevant hazards for human and animal health. To this end, a complete overview of possible chemical hazards that may occur in animal feed and their ingredients, together with a prioritization for the aims of monitoring is needed.

The objective of this review is to obtain insights into (groups of) chemical hazards present in the European feed supply chain, with the aim to prioritize these hazards for monitoring based on their potential risk to human health. The potential risk to animal health and welfare, as well as the environment, was out of the scope. Results of this study can be used to guide risk-based monitoring of chemical hazards in the feed supply chain.

2 | MATERIALS AND METHODS

2.1 | Demarcation

Although feed supply chains are organized differently throughout Europe, with varying stages and actors involved, chemical food safety hazards that may occur in the feed chain are assumed to be comparable between chains. Hence, a hypothetical feed production chain was assumed. It was based on the typical feed supply chain in the Netherlands, which was described using expert opinion obtained from animal feed companies, Wageningen University and Research (WUR), and the Netherlands Food and Consumer Product Safety Authority (NVWA). A wide range of chemical hazards groups that may occur in the feed chain was considered at the start of this study. Here, the focus was on chemical hazards in feed for livestock production animals—that could be harmful to human health, hence, feed for nonproduction animals, for example, petfood, was not considered, neither was animal health and welfare. Chemical hazards groups included are: dioxins and polychlorinated biphenyls (PCBs), brominated flame retardants (BRFs), per- and polyfluorinated alkyl substances (PAS), heavy metals, mycotoxins, plant toxins, pesticides, veterinary drugs, hormones, polycyclic aromatic hydrocarbons (PAHs), processing contaminants, and mineral oils. A glossary of terms used in this study is added in Annex 1.

2.2 | Literature study

A literature review was performed to collect data on the included chemical hazards groups, focusing on their: occurrence in animal feed, transfer of the chemical to animal-derived foods, and toxicity/health effects. The Scopus database was used, considering peer-reviewed papers published in the English language in the period 2009–2023. Search terms used were: dioxin*, brominated flame retardant*, BFR, per- and polyfluorinated substance*, PFAS, heavy metal*, mycotoxin*, plant toxin*, pesticide*, veterinary drug*, hormone*, antibiotic*, polycyclic aromatic hydrocarbon*, PAH, processing contaminant*, chloropropanol*, furan*, acrylamide, and mineral oil*—and their synonyms and related terms—in combination with feed, egg*, milk, meat, toxicity, transfer, and human health effect*.

Relevant papers were selected based on title, abstract, and keywords. Full-text papers of the selected references were downloaded and read in full, based on which a final selection of relevant papers was made. Snowballing was used to find related relevant papers based on the reference list of the selected papers. Furthermore, European Food Safety Authority (EFSA) opinions related to the chemical hazard groups were consulted.

2.3 | Monitoring data

In addition to the literature, two databases with historical monitoring data on chemical hazards in animal feeds and ingredients were used to obtain insights into the occurrence of the chemical hazards in animal feed. Notifications of food safety hazards in feed produced in or imported into the European Union (EU) were subtracted from the EU Rapid Alert System for Food and Feed (EU RASFF) database (EU, 2024). The legal basis of the EU RASFF is laid down in article 50 of regulation (EC) No. 178/2002, also known as the General Food Law (EC, 2002b). All notifications (including noncompliance notifications) on chemical hazards in feed for food-producing animals, including feed materials, feed additives, compound feeds, and feed premixtures (see 2.4) in the period January 1, 2009, to January 1, 2024, were included. Data on the presence of chemical hazards in animal feed (analytical results) from the period 2010 to 2022 from the Dutch official control program animal feed in the Netherlands (National Plan Animal Feed, NPAF) were also used. The aim of the NP Animal Feed is to control feed safety of all animal feed ingredients and feed that are produced and/or marketed in the Netherlands. Since many ingredients are imported to the country, these data are informative on the presence of chemical hazards in a wide range of ingredients from many different origin countries. Also, a report on the presence of the chemicals hazards in animal feed production based on these NPAF data was consulted (van der Fels-Klerx et al., 2019).

2.4 | Prioritization of hazards

For prioritization of chemical hazards for monitoring, a step-wise approach was used, as illustrated in Figure 1. If occurrence data of the chemical hazard showed the absence of the chemical in animal feed or ingredients, the hazard was classified as low priority (L). When the chemical showed to be present in animal feeds or ingredients, occurrence data were evaluated for exceedance of the legal MLs or GVs, as defined in Directive 2002/32/EC (EC, 2002a) and Commission Recommendation 2006/576/EC (EC, 2006b), respectively. In case of no such exceedance, the hazard was also classified as low priority for monitoring. In case exceedances of MLs or GVs were found, possible transfer of the hazard to the edible parts of the animal was evaluated using information from the literature. For chemicals that have been found present in feeds but for which no MLs or GVs have been set based on Directive 2002/32/EC or Commission Recommendation 2006/576/EC, the step of evaluation of exceedance of ML or GV was not considered, and chemicals were further evaluated starting with the transfer to edible tissues in the animal.

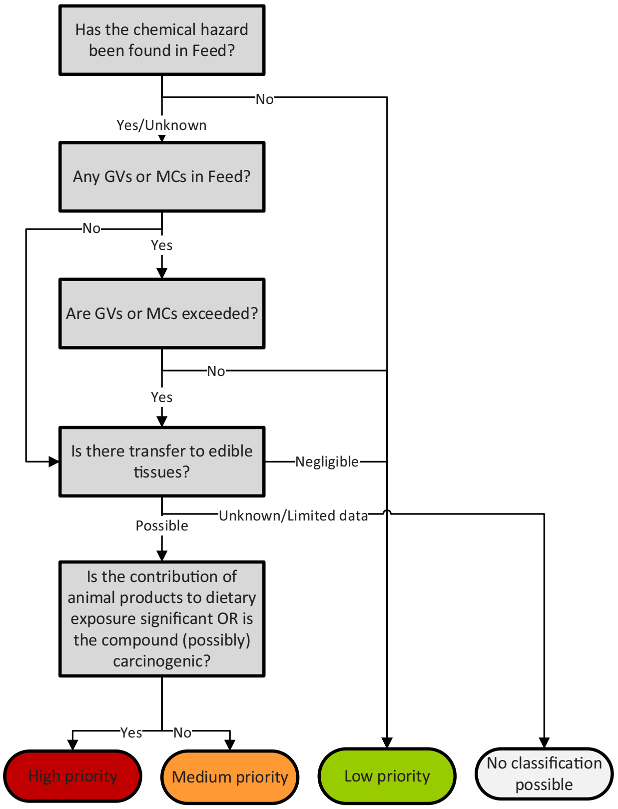


FIGURE 1 Ranking chemical hazards in the feed chain for monitoring.

If data on transfer were not available, the hazard could not be classified (NC) because of limited data. If transfer was considered low or negligible, the hazard was classified as low priority (L). In case transfer to edible parts of the animal was found possible, the hazard was classified as either medium (M) or high priority (H). For classification into medium or high priority, both the toxicological effects of the chemical hazard and the intake of the human population of the relevant animal-derived products, relative to the estimated total daily intake of the European population were considered. When the chemical hazards is classified

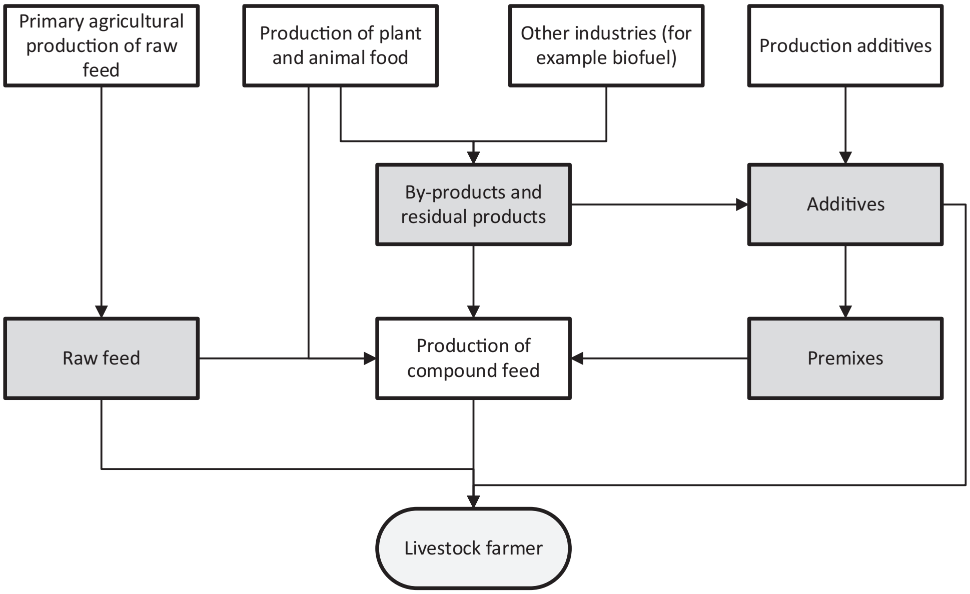


FIGURE 2 Overview of the various stages in the European feed supply chain.

as being carcinogenic by EFSA or the International Agency for Research on Cancer (IARC), this led to a high priority (H) classification for monitoring. Also, chemicals for which the intake via animal-derived foods relative to total intake of the particular chemical was high were also considered as high priority. In all other cases, the hazard was classified as medium priority.

3 | RESULTS AND DISCUSSION

3.1 | Feed supply chain

The European feed supply chain is a complex network of different actors involved in producing, trading, storing, and selling feed ingredients, premixes, additives, compound feed, and other products intended for use or used as animal feed. The typical feed supply chain starts with the cultivation or import of primary agricultural products and the purchase or import of byproducts and additives, which are then processed at the feed mill, after which the final animal feed is transported to the farm for feeding to the animals (Figure 2). The various stages of the feed supply chain are described in more detail below.

3.1.1 | Primary agricultural feed materials

Primary agricultural production includes the breeding, cultivation, and trade of nonprocessed or only minimally processed agricultural feed materials, which can be main products or byproducts and which are either directly used by the farmer or used as ingredient to produce compound feed. Examples of minimally processing of raw materials are drying of hay and ensiling of maize. Primary agricultural products are produced by (inter)national livestock farmers, arable or horticulture farmers.

Roughage such as grass or silage maize are often cultivated for own use by the livestock farmers. Other agricultural feed, such as wheat, barley, triticale, grain maize beets, and potatoes are in many cases produced by arable farmers.

3.1.2 | Byproducts

Compound feed nearly always contains byproducts of food production (van der Fels-Klerx et al., 2019). Byproducts from the food industry can be used, which can be divided into plant-based byproducts, animal-based byproducts, mixed byproducts of animal and plant-based material, or byproducts from the chemical or pharmaceutical industry. Meat with an expired shelf-life is not allowed to be used as feed for food-producing animals in Regulation (EC) No 1069/2009 (EC, 2009b) and, therefore, meat is not considered in this review. The various byproducts that may be used in the production of compound feed are indicated below.

Plant-based byproducts: The processing of crops (like grains, fruits, and vegetables, potatoes or oil seeds) for nonfeed uses results in byproducts, which can be used by the feed industry. Crops cultivated for human consumption can also be used in the feed chain when the quality is too low for human consumption. Byproducts may be formed, for instance, during the processing of grains, the processing of oil seed to raw oil, the processing of potatoes to crisps, potato starch, French fries or others, or the processing of fruits to juices. These products can be used by the livestock farmers, the compound feed industry, or for further processing. Examples of further processing are the processing of raw oil to pure vegetable oil, processing of starch, bread, or beer. The byproducts of these processes can also be used by the compound feed industry and livestock farmers.

Plant-based former foodstuffs: Plant-based former food products can be used in the feed chain. Examples are return bread, biscuits, or pasta due to recalls or expired shelf-lives. These return products are ground including the packaging. After grinding, the packaging is mechanically removed. For packaging materials, there is a zero tolerance in Regulation (EC) No 767/2009 (EC, 2009a). However, since residues of packaging materials cannot be omitted, the action limit (AL), for example, in the Netherlands, is 0.15% (w/w).

Animal-based byproducts: Production of animal products results into byproducts, which can be used by the feed industry. The use of animal byproducts in feed is regulated in Regulation (EC) No 1069/2009 (EC, 2009a) and Commission Regulation (EU) No 142/2011 (EC, 2011). Examples of animal byproducts are animal fat and fish meal. These can also be further processed into, for example, compost or biogas. Alternatively, these byproducts can be used by the feed industry or directly by livestock farmers.

Processing of other byproducts for feed: Due to the increased attention for the circular economy, the technology for the use and production of byproducts has increased over the last years. As a result, more byproducts can be made suitable for the use in feed, such as products earlier used for cofermentation and residual juice of grass biorefining.

3.1.3 | Feed additives

Feed additives are substances, microorganisms, or preparations other than feed material and premixtures, which are added on purpose to the feed or water to improve the quality of the feed or the animal products. Note that premixtures mean mixtures of feed additives or mixtures of one or more feed additives with feed materials or water used as carrier, not intended for direct feeding to the animal, see Regulation (EC) No 1831/2003 (EC, 2003). Premixtures typically are added to compound feed in a ration 0.2–0.5%. Examples of feed additives are enzymes, vitamins, and colorants. Additives can be produced in Europe or imported from other countries. The production can be the synthesis of substances, the processing of products from mining, or the extraction of colorants from vegetable products. Feed additives are used by the compound feed industry, premix producers, and livestock farmers as well.

3.1.4 | Compound feeds

Regulation (EC) No 767/2009 defines compound feed as "a mixture of at least two feed materials, whether or not containing feed additives, for oral animal-feeding in the form of complete or complementary feed." Diet feed, medicated feed, or milk replacers are also classified as compound feed. Maximum contents for the presence of undesirable substances in compound feed are defined in Directive 2002/32/EC. For optimal production of compound feed, premixes can be used. Different streams of raw materials and additives are mixed in an optimal composition for a specific animal species. The dosing can be automated or manual. If needed, the feed is pressed or extruded before packaging, storage, and transport.

Residues of earlier processed compound feed in the processing equipment may cause cross contamination of newly processed compound feed. Wet cleaning of the production line can often not be performed. Therefore, the order in which compound feeds are produced on the same line is established to prevent cross contamination.

3.2 | Prioritization chemical food safety hazards

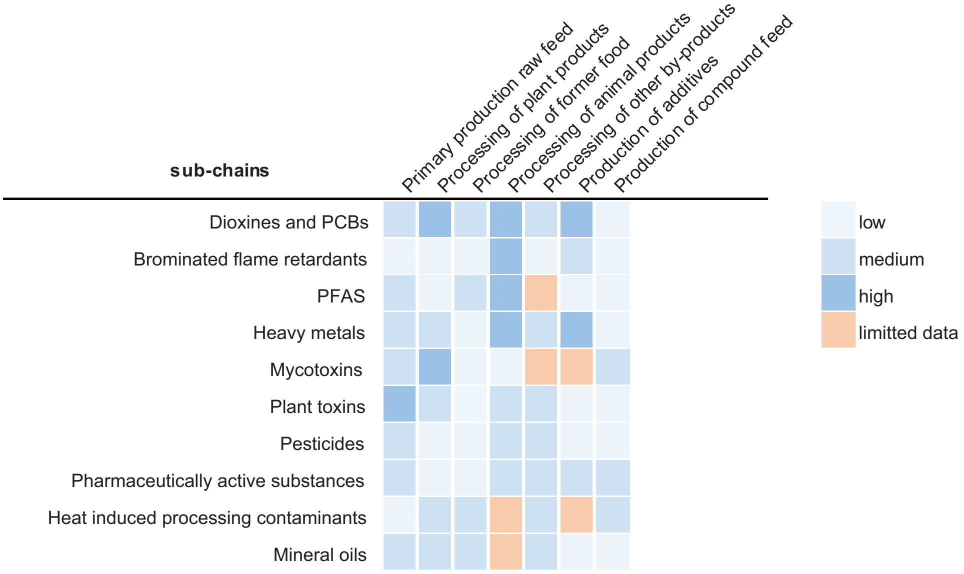
3.2.1 | Dioxins and polychlorinated biphenyls

Dioxins is a collective term for polychlorinated dibenzodioxins (PCDDs) and polychlorinated dibenzofurans (PCDFs). Apart from dioxins, there are also PCBs, which can be divided into dioxin-like (DL-PCBs) and non-dioxin-like (NDL-) PCBs (Piskorska-Pliszczynska et al., 2019).

In Europe, the maximum presence of dioxins and PCBs in animal feed is regulated in Directive 2002/32/EC. The regulation contains MLs and ALs. ALs were set to accelerate the process of lowering the levels of dioxins and PCBs in feed. In Directive 2002/32/EC, the MLs were defined by using WHO-TEF-1998. Later, in 2012, the MLs were adapted, incorporating the use of the WHO-TEF-2005 values, resulting in lower toxicity equivalency (TEQ) contents. TEQ contents are used to describe the cumulative toxicity of complex mixtures of these types of compounds.

Presence

The RASFF database contains 139 notifications for dioxins and DL-PCBs in the period 2009–2023 for a variety of feed products, but mainly additives, fat/fatty acids,



sub-chains	Primary production raw feed	Processing of plant products	Processing of former food	Processing of animal products	Processing of other by-products	Production of additives	Production of compound feed
Dioxines and PCBs	medium	high	medium	high	medium	high	low
Brominated flame retardants	low	low	low	high	low	medium	low
PFAS	medium	low	medium	high	limitted data	low	low
Heavy metals	medium	medium	low	high	medium	high	low
Mycotoxins	medium	high	low	low	limitted data	limitted data	medium
Plant toxins	high	medium	low	medium	medium	low	low
Pesticides	medium	low	low	medium	medium	low	low
Pharmaceutically active substances	medium	low	low	medium	medium	medium	medium
Heat induced processing contaminants	low	medium	medium	limitted data	medium	limitted data	medium
Mineral oils	medium	medium	medium	limitted data	medium	low	low

FIGURE 3 Possible occurrence of chemical hazards in parts of the feed production chain.

vegetable oils, and fish meal. NPAF data for the presence of dioxins and DL-PCBs in feed materials and animal feed showed that 0.6% of the samples exceeded the respective ML. Most ML exceedances were seen in fish oil, animal fat, insect protein, fish meal, clay minerals, and vegetable oils and byproducts. Occasional exceedances were seen in premixes.

Dioxins and PCBs occur throughout the entire feed chain (Figure 3). Besides environmental contamination, feed materials can become contaminated with dioxins and PCBs when they are dried with unsuitable fuel, like plastic waste, painted wood, or oil contaminated with dioxins and PCBs (Heres et al., 2010; Marnane, 2012; Tlustos et al., 2012). Hoogenboom et al. (2020) reviewed the use of dioxins and PCB contamination patterns for identifying the origins of these contaminations. Several cases with dioxins and PCB contamination were described, including illegal practices like mixing waste materials into feed, for example, as in the Belgian crisis in 1999 when PCB-containing mineral oil was mixed into chicken feed. PCBs have been historically applied in paints, and this may be another source of feed contamination at the farm level, where silos treated with these paints may contaminate the stored feed. Other sources are via contaminated minerals that are used in feed production (Hoogenboom et al., 2020). Furthermore, dioxins and PCBs can naturally occur in clays, for example, kaolinitic clays, arising during a natural process under high pressure and temperature. Clays are used in animal feed as an anticaking agent or a carrier for vitamins and minerals. In addition, kaolinitic clay can be used in food production processes, which leads to byproducts for animal feed that could subsequently be contaminated with dioxins (Hoogenboom et al., 2010; Jobst & Aldag, 2000).

Fish can contain dioxins and PCBs caused by pollution of the marine environment. Therefore, feed materials derived from fish or seaweed, such as fishmeal, fish oil, or minerals from seaweed, from a contaminated region may contain high concentrations of dioxins and PCBs (Ferrario et al., 2003; Maes & De Meulenaer, 2005). Global average DL-PCB levels in 102 samples fishmeal ranged from 0.12 to 1.02 ng/g dw (in Europe 0.27 ng/g dw) (Li, S. Dong, Wang et al., 2019). Fishmeal can also be used in aquaculture to grow carnivorous fish like eel, trout, salmon, and marine fish. PCBs in fishmeal can accumulate in these farm fish to predicted levels of 2.4–5.2 ng/g fish (dw).

For grazing animals, the diet is different as compared to indoor housed animals, and contamination from the environment may be important in contributing to total dioxin exposure (Abrahams & Steigmajer, 2003; Bertocchi et al., 2015). Several contamination routes exist where dioxins and PCBs can contaminate the feed at farms, for example, by using contaminated sludge as fertilizer at farmland, by using PCB-contaminated building debris to pave farm surroundings and tracks, historic open burning of waste at the farm or at floodplains where contaminated sediments deposit at places where cattle grazes (Weber et al., 2018).

Transfer to animal products

Dioxins and PCBs can end up in edible animal products via contaminated animal feed. Dioxins and PCBs are lipophilic and poorly degradable and, therefore, they accumulate in fat or fat-rich products, like milk and eggs (Hoogenboom, 2012). The efficiency of PCB assimilation from PCB-containing fishmeal to farmed fish was set to 55% (X. Li, S. Dong, P. Wang et al., 2019). Lower chlorinated dioxins appear to be more absorbent than highly chlorinated dioxins and some congeners can be degraded by certain animal species (Srogi, 2008). There is no direct relationship between the European ML for the presence of dioxins and PCBs in feed and those limits in food, because the relationship depends on the congener pattern in combination with the toxico-kinetics of a specific animal species (Hoogenboom et al., 2006; Hoogenboom et al., 2015; RIVM, 2020).

Prolonged exposure of animals leads to a relative increase in excretion of dioxins and PCBs in milk and eggs, until excretion reaches a steady state (De Vries et al., 2006; Piskorska-Pliszczynska et al., 2017). During this steady state, 40% of the dioxin intake can be excreted in milk and eggs. For cows, this means that when dioxin concentrations are present around the legal ML in feed, the milk will exceed the ML of 2.5 pg WHO-PCDD/F-TEQ/g fat in Regulation (EU) 1881/2006 (EC, 2006a). After termination of exposure, the dioxin concentrations in milk and eggs will decrease rapidly until 50% of the initial concentration. The decrease subsequently slows down as the body fat then becomes the source of the contaminants as a result of “internal dose” (Hoogenboom et al., 2007; Van Eijkeren et al., 2006). Rose et al. (2010) noticed that in 40% of the livers of lambs, levels above 6.0 pg WHO-PCDD/F-TEQ/g fat were seen, being the EU ML set at that time in Regulation (EC) No 2375/2001 (EC, 2001).

Toxicity/exposure

Dioxins, DL-PCBs, and NDL-PCBs are classified by IARC as human carcinogens (class I). The toxicity of individual dioxins and DL-PCBs is expressed by a toxic equivalency factor (EFSA, 2012e). Dioxins and PCBs can cause adverse effects in humans and animals such as altering the metabolism by inducing metabolic enzymes, affecting homeostasis, hormone modulation, affecting growth and fertility, and interaction with the aryl hydrocarbon receptor, a transcriptor that regulates gene expression on cellular level (Galimova et al., 2015; Piskorska-Pliszczynska et al., 2019; Schwarz et al., 2000) (EFSA, 2018). In 2018, EFSA stated that human intake and toxicity of dioxins and PCBs should be reviewed based on new scientific data: the earlier tolerable weekly intake (TWI) should be lowered seven times to 2 pg/kg bw. The exposure in the European population was estimated to be considerably exceeding the new TWI. However, EFSA also concluded that the toxicity of the most harmful DL-PCBs may be overestimated (EFSA, 2018).

Prioritization

Dioxins and PCBs can occur in animal feed, especially during the drying processes of feed materials. In addition, pollution of the environment is a source of dioxins and PCBs, but they can also occur naturally via clays. Monitoring data for the presence of dioxins and DL-PCBs in feed materials and animal feed showed that 0.6% of the samples exceeded the respective ML. Furthermore, several RASFF notifications were found. Dioxins and PCBs are lipophilic, transferable to edible tissue, and poorly degradable and, therefore, accumulate in fatty animal products like milk and eggs, and they are carcinogenic. Milk and eggs contribute to human exposure of dioxins and DL-PCBs via food consumption (EFSA, 2012e). Therefore, dioxins and PCBs were considered to be food safety hazards with a high priority for monitoring in the European feed supply chain (Table 1).

3.2.2 | Brominated flame retardants

BFRs are widely used in industrial and consumer products to prevent ignition or to slow down a fire. Some BFRs are persistent toxic compounds, which can accumulate in the environment, animals, and humans. BFRs consist of groups of related compounds; well-known BFR compounds are polybrominated diphenyl ethers (PBDEs) and hexabromocyclododecanes (HBCDDs) (EFSA, 2011a, 2011b). There are no MLs or GVs set for the maximum presence of BFRs in feed in Europe. Recently, EFSA published updates of the risk assessment of HBCDDs and PBDEs in food (EFSA, 2021, 2024b) with several more due to follow (tetrabromobisphenol A, brominated phenols, mixtures).

Presence

Given the absence of legal or guidance levels in Europe, BFRs are not widely monitored in the official control programs of Member States. In the Dutch NPAF, no data on monitoring BFRs in feed were available, and no notifications about BFRs were identified in the RASFF database.

Plants have been described as being capable of taking up PBDEs from contaminated soil. However, bioconcentration factors were low (0.01–0.1), implying plant uptake of PBDEs is relatively low as compared to the levels in the soil (Vrkoslavová et al., 2010). It is thus not expected that high levels will occur in plants, unless grown on highly contaminated sites.

Aquatic organisms are known to be able to accumulate lipophilic BFRs (EFSA, 2011b). The presence of both PBDEs and HBCDDs (1–27 ng/g) has been observed in fish oil to be used in feed (Ortiz et al., 2011). French monitoring data from 2014 to 2016 also showed the presence of PBDEs and HBDDDs in fish oil and in fish feed (Vénisseau et al., 2018). Several studies showed the presence of BFRs in fish feed, with a large difference between geographic origins of the samples (X. Li et al., 2018; Li, Dong, Wang et al., 2019; Ng et al., 2018; Nøstbakken et al., 2018). PBDEs often

TABLE 1 Prioritization of chemical food safety hazards for monitoring in the feed supply chain.

Chemical hazards		**Criteria for prioritization**				**Priority for monitoring**
Group	*Specific compounds*	*Found in feed in last 10 years*	*ML/GV in feed*[a]	*Transfer to animal products*	*Adverse human health effects*[b]	
Dioxins and polychlorinated biphenyls (PCBs)	PCDDs PCDFs DL-PCBs NDL-PCBs	RASFF: $n = 139$ notifications NPAF: 0.6% > ML	Yes	Milk and eggs	Carcinogenic	High
Brominated flame retardants (BFRs)	PBDEs HBCDDs	Yes	No	Meat, eggs, milk, fish	EFSA: dietary exposure to PBDEs raises health concern	High
Per- and polyfluorinated alkyl substances (PFAS)	PFOS PFOA PFNA PFHxS	NPAF: 17/45 PFOS-positive fishmeal samples of 2002	No	Meat, eggs, milk	Decreased response of the immune system. EFSA: Intake part of EU population > TWI	High
Heavy metals	Arsenic (As) Cadmium (Cd) Lead (Pb) Mercury (Hg)	RASFF: 161 notifications NPAF: 0–1.5% > ML	Yes	Possible, but low	Carcinogenic (As, Cd); other adverse effects EFSA: exposure not concern	As, Cd: high Others: medium
Mycotoxins	AFB1 AFM1	RASFF: 454 notifications NPAF: 0.1% > ML	Yes	AFM1 is a metabolite in milk	Carcinogenic	High
	OTA	2 samples > GV for OTA	Yes	Negligible eggs and milk. Possible meat (but uncertain)	Yes	More data on transfer to meat and human exposure needed (NC)
	Other mycotoxins (DON, ZEA, etc.)	NPAF: 0.3% > ML for DON; 0.3% > ML for ZEA	Yes	Negligible	→	Low
Plant toxins and harmful botanical impurities	Pyrrolizidine-alkaloids (PAs)	RASFF: 24 NPAF: 4–18% > 1 mg/kg	No	Possible, but low (milk, eggs)	Carcinogenic	High
	Other	Limited data in feed	No	Limited data	→	No classification due to limited data
Pesticides	Organochlorine pesticides (DDT, HCBD, lindane, etc.)	NPAF: 8% > MRL (all)	Yes	Possible	Severe effects Carcinogenic	High
	Other	NPAF: 8% > MRL (all)	Yes	Negligible	→	Low
Pharmaceutically active substances	Antibiotics NSAIDs Anthelminthics Sedatives, and so on	RASFF: 11 notifications NPAF: 5% positive antibiotic	Yes	Possible	Several adverse human health effects	Medium
	Hormones (steroid)	1 RASFF, 1 incident. Limited data	No	Limited data	→	No classification due to limited data

(Continues)

TABLE 1 (Continued)

Chemical hazards		Criteria for prioritization				Priority for monitoring
Polycyclic aromatic hydrocarbons (PAHs)	Benzo(a)pyrene Benzo(a)anthracene Benzo(b)fluoranthene Chrysene	Limited data	No	Negligible	→ (Mutagenic, carcinogenic)	Low
Heat-induced processing contaminants (HIPCs)	Acrylamide	Limited data	No	Possible, low	Carcinogenic	No classification due to limited (occurrence) data
	Chloropropanols GE, HMF, furan	Limited data	No	Limited data	→	No classification due to limited data
Mineral oils (MOs)	MOH MOSH MOAH	Limited data	No	Limited data	→ (Mutagenic, carcinogenic)	No classification due to limited data

[a] Maximal limit (ML) of guidance value (GV) for the presence of the chemical hazards feed, as set in European legislation.

[b] → indicates that specific information was not needed for the prioritization.

coincide with PCBs in fishmeal analyzed in global collected fishmeal during 2012–2014 (X. Li, Dong, Wang et al., 2019). In the UK, PBDE concentrations were found between 0.11 and 9.6 ng/g in feed and between 0.02 and 8.9 ng/g in food samples (Fernandes et al., 2016).

Apart from animal-based feed, the feed additive choline chloride has been observed to be contaminated with BFRs, PBDEs, octabromo-1,3,3-trimethyl-1-phenylindane, and tri-bromophenols (Traag et al., 2009).

Transfer to animal products

Transfer of BFRs from feed to animal-derived food products has been observed in several animal species. PBDEs originated from feed were found in milk and liver of cows. The transfer into milk was 15–35% for BDE-47 and BDE-99. The lowest transfer rates were observed for BDE-28, BDE-49, and BDE-66 (Kierkegaard et al., 2007; Kierkegaard et al., 2009). In a study performed in France, concentrations of a large range of BFR were determined in > 600 food and feed samples between 2014 and 2016. In general, the concentrations measured in fish and fish products were higher than in other food categories investigated, being milk, egg, sheep liver, and meat samples (Vénisseau et al., 2018). In the UK, based on > 200 food and feed samples, highest concentrations were found in fish, fish feed, and processed foods (Fernandez et al., 2016). Alpha-HBCDD in the chicken diet has been shown to be transferred to eggs (23%) and to accumulate in adipose tissue in laying hens (Dominguez-Romero et al., 2016). Ingested α-HBCDD and PBDEs have also been observed to accumulate in chicken (Jondreville et al., 2017; Wang et al., 2017; Zheng et al., 2017). Using chicken as representative animal for human consumption, it was concluded that there is a low potential health risk to humans based on the presence of PBDEs in feed (Wang et al., 2019).

BFRs can also accumulate from feed into cultivated fish (van Leeuwen et al., 2009). The accumulation of PBDEs in the filet of fish was 30–59% of the PBDEs as present in the feed (Blanco et al., 2011; Isosaari et al., 2005). The uptake of α-HBCDD from feed was observed to be 31% in salmon filet (Berntssen et al., 2011).

BFRs were detected in foods from 12 terrestrial and 21 aquatic species from the Netherlands by Gebbink et al. (2019) who presented data of the presence of PBDEs and HBCDDs in foods over the years 2009–2014. These data show that meat, eggs, milk, and fish are important food groups with respect to dietary exposure of humans to BFRs; however, they contained generally lower concentrations compared to other terrestrial samples. A decline of PBDEs in time was observed in several foods from terrestrial animal origin. This decline may reflect reduced application of PBDEs due to regulatory actions, and reduced levels in animal feeds (Gebbink et al., 2019). The transfer of PBDEs from feed to food mainly accumulated in liver and fat tissues in laying hens, broilers, ducks, cows, pigs, and fish. In laying hens, transfer to eggs was also seen. The transfer of PBDEs from feed to milk has been described in cows and goats (EFSA, 2024b).

Toxicity/exposure

The EFSA Panel on Contaminants in the Food Chain (CONTAM) recently concluded that the most important contributors to the human chronic dietary exposure to HBCDDs and PBDEs were meat and meat products, eggs, fish, and seafood. The Panel concluded that it is likely that current dietary exposure to PBDEs in the European population raises a health concern (EFSA, 2024b).

Prioritization

BFRs can occur in the processing of animal products (like fish products) and feed additives. Based on limited available data, the occurrence of BFRs in most of the other subchains of the feed supply chain (Figure 3) seems to be low. However, BFRs have been shown to be transferred substantially from feed to animal products. Combined with the high contribution of animal-derived products to human exposure, BFRs are prioritized high.

3.2.3 | Per- and polyfluorinated alkyl substances

Per- and PFAS is a general term for a group of substances that contain a perfluoralkyl moiety (OECD, 2021). The group consists of over 4700 perfluorinated and polyfluorinated compounds with a variety of chemical structures (OECD, 2021) and biological properties. Due to the extremely strong carbon-fluorine bond, most PFAS are chemically and thermally stable. PFAS are man-made and used for consumer products, medical and industrial applications, among others, due to their inert and repellent characteristics (Glüge et al. (2020). Via manufacturing, usage, and disposal of products, PFAS ends up in the environment (Kotthoff et al., 2015) and because of their persistence and extensive usage, to date, PFAS have been found in the environment around the globe.

Initially, the most studied PFAS were PFOS (perfluorooctane sulfonic acid) and PFOA (perfluorooctanoic acid) because these compounds are frequently present in the environment and human exposure pathways. PFOS is a persistent and bioaccumulative compound, whereas PFOA is less bioaccumulative, but similarly persistent as PFOS (Buck et al., 2011). Other PFAS with shorter carbon chain lengths are more water soluble as compared to PFOS and PFOA. There are no regulatory MLs or GVs for the presence of PFAS in feed ingredients or feed in Europe.

Presence

Monitoring data are available for PFOS in fish meal from the NPAF only for the year 2022. PFOS concentrations in 17 out of 45 samples were 0.9–11.0 ng PFOS/g fish meal. Xiaomin Li et al. (2019) collected 92 commercial fishmeal samples from fishmeal-producing countries and found that the sum of 16 perfluoroalkyl acids (PFAAs) ranged from 0.65 to 85.5 ng/g with an average of 18.2 ng PFAAs/g fishmeal.

Due to the presence of PFAS in the environment, in groundwater, and water intended for irrigation, these compounds can accumulate in raw feed materials. Depending on the chain length, PFAS are more or less taken up by the roots of plants (EFSA, 2020b). The presence of PFAS is likely in feed supply subchains that are closely connected to the environment, like in primary crop production (Figure 3).

Transfer to animal products

PFAS are transferred to animal products via animal exposure to the environment and via consumption of raw feed materials and related animal feeds that are contaminated by PFAS from the environment during cultivation, as well as from water (Death et al., 2021). Intake of PFAS leads to the accumulation of PFAS in the liver, kidneys, and other animal-derived products (RIVM, 2020). In farmed fish, the highest concentrations of PFAS were found in blood (6.16–31.4 ng/g) and liver (2.54–16.9 ng/g) with variation between species of farmed fish (Shi et al., 2012; Van Leeuwen et al., 2009). In a study published in 2019, most of the farmed fish (e.g., trout, catfish, turbot, salmon, tilapia, pangasius) contained PFAS with averages ranging from 0.06 to 1.5 ng/g ww (Zafeiraki et al., 2019). In a Danish study, PFOS containing fishmeal as ingredient in chicken feed was shown to bioaccumulate in eggs with a transfer factor of 2.3 from feed to egg, meaning that 1 ng PFOS/g feed is transferred to a concentration of 2.3 ng PFOS/g egg (Granby et al., 2024). PFAS concentrations ranging < 0.05–4.5 ng/g were found in commercial liver samples of horse, sheep, bovine, pig, and chicken (Zafeiraki et al. 2016b). Furthermore, PFAS accumulation was found in the liver, kidneys, and muscles of cattle. Concerning cattle, short-chained PFAS were shown to be excreted via urine, while longer-chained molecules accumulated and were excreted via the milk (Kowalczyk et al., 2013). In sheep, PFAS were also taken up via contaminated grass from floodplains resulting in higher PFAS levels in these animals as compared to sheep fed on lower contaminated feed. PFAS were also found in commercial and noncommercial eggs. Especially in the latter case, the levels of PFAS were elevated due to outside foraging (Zafeiraki et al., 2016a).

Toxicity/exposure

Uptake from PFAS by humans via the environment and water and food consumption can cause health effects. In 2023, MLs have been set in the EU for the presence of PFAS in food, especially in eggs, milk, and meat (EC, 2023b). In their scientific opinion on PFAS, EFSA (EFSA, 2020b) concluded that decreased response of the immune system to vaccination is the most critical human health effect. In addition, PFAS may also result in effects on the liver (EFSA, 2020b). EFSA has defined a TWI of 4.4 ng/kg bw per week for the sum of four compounds, being PFOS, PFOA, perfluorononanoic acid (PFNA), and perfluorohexane sulfonic acid (PFHxS) via food consumption. A substantial part of the European population exceeds this TWI (EFSA, 2020b).

Prioritization

Manmade PFAS are ubiquitous in the environment, causing accumulation in feed materials. In addition, several PFAS accumulate in animal tissue and thereby in animal-derived products. A substantial part of the European population exceeds the TWI (EFSA, 2020b). This leads to a high priority for monitoring PFAS in animal feed.

3.2.4 | Heavy metals

The term heavy metals is commonly used to refer to metals and metalloids associated with environmental pollution, toxicity, and adverse effects on biota (Ali & Khan, 2018). Heavy metals are generally considered as food safety hazards, because of their serious effects on human health. Sources of heavy metal contamination can be both natural or anthropogenic. Natural sources are magnetic, sedimentary, and metamorphic rocks, weathering, and soil formation. Anthropogenic sources are a result of industrial production and agriculture. In areas with high industrial activities or agriculture, soil, water, and air can be highly polluted with heavy metals (Chételat et al., 2015; Rajaganapathy et al., 2011; Yingliang et al., 2014; Zhang & Wong, 2007).

The maximum allowable presence of total arsenic compounds (As), cadmium (Cd), lead (Pb), and mercury (Hg) in feed and ingredients thereof is regulated in Directive 2002/32/EC (EC, 2002a). Inorganic arsenic is also regulated in this directive as far as its presence in palm expeller, fish(products), and seaweed.

Presence

Given the ML set for As, Cd, Pb, and HG, monitoring in animal feed focuses on these four heavy metals. During 2009–2023, 161 RASFF notifications were related to the four heavy metals in animal feed, feed materials, feed additives, feed premixes, and compound feed, mainly in palm kernel expeller, fish(products), and mineral feed/additives (Cd 38, Pb 51, Hg 30, and As 42). NPAF data over 2010–2022 show the following average exceedances of the ML (between brackets the ranges found) for all different types of animal feed: total arsenic 1.5% (0–>10%), cadmium 0.5% (0–16%), lead 0.5% (0–10%), and mercury 0.2% (0–3%). The variation in percentages between parentheses is due to specific products (like high arsenic levels in seaweed or low heavy metal levels in plant-based oils and fats).

Heavy metals occur in different subchains of the feed production chain (Figure 3). In general, their occurrence in plant-based feed depends on the plant species and area of origin. Plants can get contaminated with heavy metals via soil (irrigation or drinking), water, and atmospheric deposition. The level of pollution of soil and plants depends on soil characteristics, type of fertilizers used, and plant species (van der Fels-Klerx et al., 2011). Heavy metal levels can be high for leafy crops, tubers, and root vegetables in high industrialized areas resulting in a higher probability of elevated levels for raw materials originating from those areas (Elliott et al., 2017). Raw and processed feed materials from marine origin may contain high levels of arsenic (seaweed) or mercury (fish) as compared to other feed materials. High levels of arsenic and mercury can be found in fish meal and fish oil (Benford et al., 2008; Rosas-Castor et al., 2014). Livestock animals with outdoor access can forage on grass or plants contaminated with heavy metals (López-Alonso, 2012) and in this way be exposed to heavy metals.

Finally, additives used in compound feed production from mineral origin can contain high levels of lead and arsenic (Adamse et al., 2017), which can end up in animal products, manure, soil, or water (Li et al., 2019).

Transfer to animal products

In general, heavy metals can be transferred to humans via animal food products but transfer is low. After feed consumption, heavy metals mainly accumulate in the liver and kidneys of animals (MacLachlan, 2011). In mammals, inorganic arsenic is metabolized into the less toxic organic form (Hughes et al., 2011); hence, arsenic in food derived from production animals is primarily present in its organic form. In general, the carry-over of cadmium to fish is low (Amlund et al., 2012). For lead, the carry-over to fish and milk has been shown to be low (Amlund et al., 2012; Khan et al., 2013; J. D. MacLachlan, 2011). Total mercury levels in products from land animals are usually low or below quantification limits of the analytical procedures used (Khan et al., 2013; J. D. MacLachlan, 2011). But, bioaccumulation of methyl mercury in fish can be high (Amlund et al., 2012; EFSA, 2008; FAO, 2011).

Toxicity/exposure

Arsenic, inorganic arsenic, and cadmium are classified as human carcinogens (EFSA, 2009, 2014). Inorganic arsenic has a higher toxicity than organic arsenic and is a genotoxic carcinogen (EFSA, 2024a). The critical organ for cadmium, lead, and mercury is the kidney. Furthermore, lead can negatively affect brain development in children (EFSA, 2012a, 2012b, 2012d).

EFSA concluded that animal-derived products are not significant contributors to human dietary exposure to inorganic arsenic (EFSA, 2014) or to cadmium (EFSA, 2012a) via food consumption. For methylmercury, EFSA concluded for the general adult population the calculated intake of this hazards does not exceed the human provisional tolerable weekly intake (EFSA 2012d). The current level of total mercury in fish feed does not pose a threat to consumer's health (EFSA, 2008).

Prioritization

Overall, data over 2010–2022 from the NPAP show exceedances of the ML in the various feed materials and feed products. Heavy metals occur in specific animal-derived products; transfer of heavy metals to animal-derived foods is possible but low. Serious adverse effects on human health are known, in particular for As and Cd, although consumption of animal-derived food does not contribute much to the total human intake. Taken all these together, As and Cd are classified as high priority, and other heavy metals as medium priority.

3.2.5 | Mycotoxins

Mycotoxins are a large diverse group of toxic secondary metabolites produced by filamentous fungi upon and after infection of the crop with the fungus. Fungal infection and mycotoxin production in arable crops occur under specific circumstances. Weather conditions, such as moisture and temperature, agronomic factors, such as variety of the crop, sowing and harvesting dates, and storage conditions all have an important influence on fungal infection and mycotoxin production (Battilani et al., 2012; Parikka et al., 2012). The main mycotoxins that occur in feed and their raw materials are toxins produced by *Aspergillus*, *Claviceps*, *Fusarium*, and *Penicillium* fungal species (Drejer-Storm et al., 2014). These are aflatoxins, ergot alkaloids, trichothecenes, zearalenone (ZEA), and fumonisins (Binder et al., 2007).

Aflatoxins B1, B2, G1, G2 are carcinogenic (IARC classification group 1: sufficient evidence), as well as aflatoxin M1 (group 2A: probably carcinogenic to humans) (Tolosa et al., 2021; Ünüsan, 2019) and are cytotoxic for humans and animals. Aflatoxins are mainly present in products produced in (sub)tropical countries, such as maize, rice, sunflowers, and peanuts. Geographical distribution may change due to climate change. Aflatoxins are also regularly found in cereals cultivated in Southern Europe (Camardo de Rijk et al., 2015; Leggieri et al., 2015; Mauro et al., 2015). In Europe, rye is the most frequently known product infected with ergot sclerotia and ergot alkaloids (EFSA, 2017). *Fusarium* mycotoxins are found particularly in cereal grains, particularly in maize, wheat, barley, and oats, and mainly include trichothecenes, like deoxynivalenol (DON), nivalenol, T-2 toxin, and HT-2 toxin, as well as ZEA and fumonisins. Ochratoxin A (OTA, IARC group 2A) can be produced by certain *Penicillium* and *Aspergillus* species. This toxin mainly occurs in coffee, wine, and beer, but is also found in feed ingredients such as grain, rice, and beans (Malir et al., 2016).

In Europe, maximum concentrations for the presence of aflatoxin B1 (AFB1) and ergot alkaloids in feed are regulated via Directive 2002/32/EG. GVs are defined for the presence of DON, ZEA, T-2 toxin/HT-2 toxin, OTA, and fumonisin B1 and B2 in Recommendation 2006/576/EC. In animal feed production, the GVs are generally used (in practice) as if they were legal limits, because these toxins can be of risk for animal health and (re)production (Ünüsan, 2019). In the near future, these are expected to become official legal limits.

Presence

In the period 2009–2023, 454 RASFF notifications were recorded for high concentrations of aflatoxins in feed, mainly in groundnuts (often used for bird feed) and maize. Only 13 notifications involved rye ergot *(Claviceps purpurea)*, and five notifications involved T-2 toxin.

As far as aflatoxin B1 is concerned, NPAF from 2010 to 2022 show an overall 0.1% of the samples with concentrations above the ML, mainly related to maize/corn. Similar data for DON showed 0.3% (mainly maize) and ZEA 0.3% ML exceedances (mainly maize and barley). For OTA, there were only two sample results (in 2011 and 2019) with a concentration above the GV. In 2010–2022, *Claviceps purpurea* was analyzed as part of NPAF, but concentrations of rye ergot never exceeded the ML.

Mycotoxins mainly accumulate in the outside fractions of grain kernels. These outside fractions can be byproducts of the processing of grains for food or other production, and used in feed (Brera et al., 2013; Tittlemier et al., 2014). Given the accumulation of the toxins in these outer grain fractions, it may result in peak exposure of food-producing animals, in particular when not mixed to a large extent with other feed ingredients.

Application of Good Agricultural Practices can limit mycotoxin contamination during the cultivation of the agricultural commodities used for feed production. However, mycotoxin presence not only depends on agronomics but also on the climatic conditions (van der Fels-Klerx & Booij, 2010). After harvest, good practices such as appropriate drying and storage should be performed in order to prevent fungal growth and subsequent mycotoxin formation during storage. An overview of the possible occurrence of mycotoxins in subchains of the feed chain is depicted in Figure 3.

Transfer to animal products

In general, the transfer of mycotoxin from animal feed—via feed consumption—to animal-derived product is low, except for aflatoxins. Aflatoxin B1 can be converted by ruminants into aflatoxin M1 (AFM1), which is actively secreted via the milk with a transfer rate between 2% and 6% (Tolosa et al., 2021; van der Fels-Klerx & Camenzuli, 2016). Moreover, as reported by EFSA, when the transfer rate from feed to milk exceeds 2%, the AFM1 concentrations in milk may exceed the established ML for milk (Tolosa et al., 2021). Saha Turna and Wu (2021) published data of AFM1 in raw milk (in France, Greece, and Italy), pasteurized milk, and UHT milk (in Portugal) in their review. The EU ML (0.05 µg/L milk) was never exceeded in the years 2002–2017. The transfer of aflatoxin B1 to animal products such as eggs is lower than 2% (Hussein & Brasel, 2001).

Tolosa et al. (2021) reported bioaccumulation of aflatoxin residues in the liver and muscle of Nile tilapia (*O. niloticus*) and lambari fish (*Astyanax altiparanae*). Some authors reported aflatoxin transfer in the muscle of sea bass (*Dicentrarchus labrax*) higher than described for meat from livestock animals.

Fusarium mycotoxins are transferred from feed into meat, milk, or eggs to a lower degree than aflatoxins. ZEA is rapidly metabolized by the animal and excreted via urine and feces (Liu & Applegate, 2020; Tolosa et al., 2021).

OTA is lipophilic and can be stored in fat and liver (Battacone et al., 2010) and is reported to occur in animal-derived products like meat and meat byproducts (Tolosa et al., 2021). In feed ingredients from animal origin, OTA was found in kidneys, pork, and chicken liver, in concentrations between 0.1 and 1 mg/g. Transfer of OTA via the animal's body into milk is possible, but reasonably low (Malir et al., 2016). Transfer of OTA from feed to milk in ruminants and donkeys as well as to eggs from poultry is also confirmed but low (EFSA, 2023). The EFSA opinion of the Scientific Panel on Contaminants in the Food Chain recommended to study the OTA occurrence in animal blood and tissues in order to assess the significance of residue contents in animal tissues with respect to human exposure (Tolosa et al., 2021).

Toxicity/exposure

Human dietary exposure to mycotoxins mainly occurs through consumption of plant-based products, not via animal-derived foods, except for aflatoxins. The milk and dairy products food category is an important source of total aflatoxin and AFM1 exposure for infants (40%), toddlers (26%), and other children (19%), while for other age groups, it is below 15% (EFSA, 2020a). For ZEA, EFSA concluded that human exposure to this toxin via consumption of animal products derived from animals exposed to ZEA-contaminated feed is minimal in comparison to the consumption of other food products. (EFSA, 2016).

Prioritization

Many RASFF notifications of aflatoxins in feed were recorded, transfer of aflatoxins into animal-derived food—mainly in milk as (carcinogenic) metabolite AFM1—is possible, and aflatoxin M1 is carcinogenic for humans. Therefore, aflatoxin B1 is classified as a high-priority hazard in feed. For OTA, some positive samples were seen and transfer to meat is possible, though data are lacking; OTA, therefore, is classified as NC. Other mycotoxins are considered as low priority because of their negligible transfer rate to animal products.

3.2.6 | Plant toxins and harmful botanical impurities

Plant toxins are secondary metabolites formed in plants, which have a negative impact on human and/or animal health. The group of plant toxins is very large and the molecular structure of plant toxins is diverse (Frohne & Pfänder, 2005). Concentrations of plant toxins in plants mainly depend on agricultural management and environmental factors, like type of plant, seasons, and years (Cook et al., 2015; Pfister et al., 2011; Schimming et al., 2005). In general, plant toxins present in feed will negatively affect animal production due to reduced fertility, birth defects, reduced weight, and effects on the immune system (Chenchen et al., 2014; Devanaboyina et al., 2007; Diaz et al., 2014; Dierengezondheidszorg_Vlaanderen_(DGZ), 2013; Fink-Gremmels, 2012b; Gatta et al., 2013; Welch et al., 2014; Wocławek-Potocka et al., 2013).

The ML for the presence of plant toxins in animal feed, feed materials, and complete feed is regulated via Directive 2002/32/EC and includes gossypol, hydrogen cyanide, theobromine, vinylthiooxazolidon (5-vinyloxazolidine-2-thion), and volatile mustard oil. These are inherent plant toxins that can occur in plants used for feed production. Furthermore, some (seeds of) plants are included in this Directive as well, like *Crotalaria* spp., *Ambrosia* spp., *Datura* spp., and *Ricinus* spp. For pyrrolizidine-alkaloids (PAs), limits for the maximum presence in feed have not been set in the EU.

Presence

The RASFF database showed 24 notifications related to the presence of the following plant toxins in the period 2009–2023: 14 notifications for cyanide in line seed, 5 for thorn-apple in sunflower seeds, 4 for meadow saffron, and 1 for crotalaria in hay. Furthermore, in this time period, there were 96 notifications for ragweed (*Ambrosia* spp.) in feed materials. These seeds are also used for bird feed.

In a Dutch survey, traces of PAs were found in 21% of 147 feed samples. Some individual samples showed concentrations of up to 5.4 mg PA/kg (Mulder et al., 2009). In the period 2010–2022, PAs were detected in 422 out of 634 samples (67%) (LOD 10 microgram/kg) in the NPAF. NPAF data for the period 2011–2016 (subset) showed that 4–18% of the feed samples contained levels of 1 mg PA/kg or higher. Animal exposure to plant toxins is mainly via intake of raw feed, either fresh or silage. Plant toxins can also be present in byproducts or in compound feed when herbs are added as sensory additives or because of their (assumed) positive health effects. Figure 3 shows in which subchains plant toxins can occur.

Transfer to animal products

PAs can be found in feed and can be transferred to animal-derived food products, such as milk and eggs (Diaz et al., 2014; Dickinson et al., 1976; Hoogenboom et al., 2011; Mulder et al., 2015). In the period of January 2014 till April 2015, low levels of PAs (> LOD) were found in 6% of 182 milk samples, and very low levels of PAs were found in 1% of 205 egg samples from European retail markets (Mulder et al., 2015) confirming PAs are transferred to animal-derived products, but to a low extent.

Toxicity/exposure

From the PA group of plant toxins, several individual compounds are considered possibly carcinogenic to humans by IARC. Recently, MLs for the presence of plant toxins in food have been set in the EU to protect human health (EC, 2023a). Other plant toxins can also possibly be transferred to animal-derived food products. However, available data on their presence in both feed and in animal-derived food are limited.

Prioritization

PAs have been found in animal feed, can be transferred into animal-derived food products, and are possibly carcinogenic to humans. Hence, PAs are considered as high priority for monitoring in the European feed chain. For other plant toxins, data on transfer were lacking, and hence they could not be classified.

3.2.7 | Pesticides

Pesticides are chemical compounds used as plant protection products and biocides. In Europe, 466 active compounds are allowed as plant protection products in Regulation (EC) No 1107/2009 (EC, 2009c). Besides residues of these pesticides, residues of other pesticides in feed may be seen as well in Europe due to the import of feed materials or feeds from non-European countries. For instance, in soy imported from South-America, paraquat, a pesticide which is not allowed in the EU, was found in the NPAF (2014–2019). Persistent prohibited pesticides such as organochlorine pesticides (OCPs) can remain in the environment and, therefore, end up in the feed chain (van der Fels-Klerx et al., 2019). As a result, OCPs are not allowed to be used in the EU. These are the only pesticides that are regulated for feed in the EU (Directive 2002/32/EG). For other pesticides, maximum residue limits (MRLs) are determined for primary agricultural products, independent of their final application as food or feed in Regulation (EC) No. 396/2005 (EC, 2005). To derive maximum allowable levels for the presence of pesticide residues in processed feed, processing factors can be used. These are dilution/concentration factors for pesticide residues during feed production from raw materials for which MRLs have been established. Li and Fantke (2023) proposed a framework for defining pesticide MRLs in processed feed based on processing factors.

Presence

In the RASFF database from 2009 to 2023, the presence of 42 pesticide residues was notified, mainly in feed materials. Pesticide residues were mostly reported in maize, barley, and sunflower seeds (chlorpyrifos, chlorpyrifos-methyl, and chlormequat). Data from NPAF in the period 2016–2022 showed a considerable probability of the presence of pesticide residues in feed materials, with exceedance of the MRL for one or more pesticides in 8% of the samples. Noncompliant samples for pesticide residues were found among several grains, oilseeds, legumes, and products derived thereof and herbs (including spices and edible flowers). Paraquat (10%), haloxyfop (20%), glyphosate (4%), pirimiphos-methyl (1.5%), and chlorpyrifos (12%) were the most commonly found noncompliant pesticides. In most feed materials, several samples showed to contain multiple pesticides in levels above their respective MRL.

Pesticides can enter the feed chain via various routes. Plant protection products are often used in primary crop production and residues thereof can be present in feed materials when the crops are directly used as feed or as ingredients for feed production (van der Fels-Klerx et al., 2019). The levels and type of pesticides depend, among others, on the crop, country, and the time of the year. Furthermore, crops may contain OCPs since, although they are not allowed to be used anymore, these pesticides are persistent and can still be present in the environment (Hoogenboom et al., 2020) and are taken up by the plants. In herbicide-resistant genetically modified organism (GMO) crops (cultivation not allowed in Europe, but can be imported), residues are more often found as compared to non-GMO crops, due to the regular use of glyphosate and gluphosinate on GMO crops. Besides this, because of the presence of glyphosate and gluphosinate in the environment, these pesticides can also be present in non-GMO crops (van der Fels-Klerx et al., 2019). Although paraquat is not allowed to be used in Europe, residues can be found in byproducts of soy bean oil, which are used for feed. Although processing of former foods is not expected to contain high levels of pesticide residues, such former food products consisting of fish can contain organochloride pesticides (van der Fels-Klerx et al., 2019). Besides, high concentrations of DDXs (sum of o,p′—and p,p′-DDT, -DDD, and -DDE and p,p′—22 DDMU) were found in trash fish (marine fish with no or little market value for human food, and used for fish meal production) and farmed fish (Guo et al., 2009). Figure 3 summarizes the occurrence of pesticide residues in the feed supply chain.

Transfer to animal products

Knowledge on the transfer of pesticides to animal products like milk, eggs, and meat is mainly available for persistent lipophilic pesticides, like OCPs for which it has been shown that transfer to animal products is possible (van Asselt et al., 2017). Indeed, OCPs can accumulate in milk, eggs, and fat (Kan & Meijer, 2007; Pulina et al., 2014). For other pesticides, no MRL exceedances were found in animal-based food products, while ML exceedances were found in feed. Therefore, transfer to the edible parts of the animal is considered to be negligible.

Prioritization

OCP residues are (still) present in the environment because of their persistent nature and can—via this route—enter the feed chain. Transfer to edible products is possible, and OCPs can be carcinogenic. Therefore, OCPs have a high priority. Transfer to edible products of other pesticides is negligible. Therefore, pesticides other than OCPs are considered as low priority in the feed supply chain.

3.2.8 | Pharmaceutically active substances

Pharmaceutically active substances are used to prevent or cure diseases in animals and can be provided to the animal via feed either as premix or as top dressing. They include antibiotics, anthelminthics, sedatives, antiparasites, nonsteroidal anti-inflammatory drugs (NSAIDs), hormones, and coccidiostats. Coccidiostats can be used without a veterinary prescription but should, however, be registered in the register for feed additives in Regulation (EC) No 1831/2003 (EU, 2003).

Pharmaceutical compounds can be toxic for nontarget animals and the environment (Isidori et al., 2005). Frequent use of antibiotics can lead to antimicrobial resistance (AMR) not only due to direct antibiotic use but also due to the presence of antibiotic residues in the environment (Allen, 2014); even very low concentrations of antibiotic residues seem to contribute to AMR (Wallinga & Burch, 2013).

In addition to medical purposes, antibiotics are also used as growth promoters in Africa, North and South America (WHO, 2018). Europe banned the use of antibiotics as growth promoter in the year 2006 by Regulation (EC) No 1831/2003 (EC, 2003). Authorized veterinary drugs are included in Regulation (EU) No 37/2010 (EC, 2010). Directive 90/167/EEC contains requirements for preparation, selling, and the use of medicated animal feed (EC, 1990).

Hormones can be added to the feed during feed production, or at the farm. Hormones added to the feed have an anthropogenic source and can access the feed in three ways: authorized, unauthorized, and unintentional. Steroid hormones are banned in the EU according to Directive 96/22/EC; an exception is made for therapeutic or zootechnical treatment. To comply with this ban, national programs for monitoring residue levels have been implemented. In the United States, six artificially produced hormones are allowed: estradiol 17ß, progesterone, testosterone, zeranol, trenbolone, and melengestrol acetate (U.S. FDA, 2023). In imported animal feed and with illegal use with home-produced feed, the presence of residues of these hormones cannot be excluded.

The production of a batch medicated feed can result in carry-over of the used medicines to compound feed in the feed production plant, when the same production facilities are used. Residues of veterinary drugs stay in the feed installation and end up in the batches that are produced afterward. Although these feed batches are intended to be fed to animals that are not slaughtered within a short period of time, such as piglets, residues of veterinary drugs may then end up in feed intended for other animals (Stolker et al., 2013; Zuidema et al., 2010).

Antibiotics can also be found in animal byproducts used as feed ingredients, such as hydrolyzed proteins, offal from antibiotic-treated fish (Gill, 2000), or blood meal. Furthermore, waste milk from animals treated with antibiotics can be used as calf feed (Aust et al., 2013; Love et al., 2012). Another entry route of veterinary drug residues to animal feed is via soil fertilized with manure from animals treated with antibiotics. Feed crops grown on these soils may subsequently take up these antibiotic residues (Azanu et al., 2016; Berendsen et al., 2013; Hamscher et al., 2005). Finally, byproducts from bioethanol production may contain antibiotic residues due to added antibiotics during the biofuel fermentation process (Van Asselt et al., 2011).

Presence

In 2009–2023, 11 RASFF notifications related to the presence of veterinary drug residues in feed materials and compound feed have been reported. Most of the notifications considered residues of antibiotics in feed additives. No RASFF notifications about steroid hormones in feed were found (2009–2019), and in 2020, one alert was registered (zilpaterol) in feed material (sugar cane molasses) in Ireland. In the NPAF data of 2015, 7 out of 147 compound feed samples for pigs (5%) tested positive for antibiotics (NVWA, 2015). In the same year, 7 out of 10 samples of feather meal contained antibiotic residues (Zhu et al., 2016). Anthelmintics were hardly found in the NPAF data: in 2014, none of the samples, and in 2015, one sample out of 59 samples tested positive for flubendazole (NVWA, 2014, 2015). Dutch monitoring data showed that carry-over of coccidiostats between batches during feed production often occurs: 50% of the poultry feed samples in 2014 and 49% of the poultry feed samples from 2015 contained coccidiostats. However, nonconformities to the allowed percent carry-over were limited: 2% and 3%, respectively.

In 2022, an incident with hormones occurred. Cows that did not get pregnant had unintentionally been exposed to medroxyprogesterone acetate (MPA). Further research revealed that a molasses byproduct from pharmaceutical origin had been used as animal feed ingredient. The molasses byproduct was used to coat contraceptive pills and, therefore, contained MPA. Further information on hormone residues in the feed chain is limited. Figure 3 gives an overview of the possible occurrence of pharmaceuticals in the different subchains of the feed chain.

Transfer to animal products

Application of pharmaceutically active substances to animals can lead to the transfer of residues to edible animal products, including milk, eggs, and meat (Bacanli & Başaran, 2019). For example, flubendazole was observed to be transferred to eggs in laying hens after hen treatment with experimental diets containing 2.5%, 5%, and 10% of the flubendazole therapeutic dose. In the same study with 2.5%, 5%, and 10% of the tylosin therapeutic dose, no transfer of tylosin to eggs was found (Vandenberge et al., 2012). Antibiotics can also be transferred in fish. In a study from Elia et al. (2014), oxytetracycline was fed to carps in 75, 150, and 300 mg/kg and found to be transferred to muscle at all doses.

Toxicity/exposure

Antibiotic residues in food can—after human consumption—lead to allergies, immunopathological effects, carcinogenicity, liver disease, and other health effects in humans (Nisha, 2008). Also, hormone residues in edible tissues of animals can have a negative effect on human health.

Prioritization

Residues of pharmaceutically active substances have been reported in feed, among others in RASFF, can be transferred to food, and these substances showed to have negative effects on human health. Therefore, medium priority was considered for pharmaceutically active substances. Please note that antibiotic resistance is another concern which can cause harm to both human and animal health.

For hormones, one RASFF notification has been recorded, and one incident occurred. Although residue data are limited, hormone residues can be present in animal feed, and added hormones can result into human health effects. Because of limited information, this hazard could not be classified (Table 1).

3.2.9 | Polycyclic aromatic hydrocarbons

PAHs are aromatic hydrocarbons with two or more fused benzene rings, which can be formed during incomplete combustion and pyrolysis of organic material. Sources of PAH can be both natural and anthropogenic. Natural sources are fires, oil seeps, volcanic eruptions, and exudates from trees. Anthropogenic sources are burning of fossil fuel, coal tar, wood, garbage, refuse, used lubricating oil and oil filters, municipal solid waste incineration, and petroleum spills and discharge. Because the burning of fossil fuels is a source of PAH, these compounds are also counted among mineral oil hydrocarbons (MOHs). Considering all sources together, PAHs are ubiquitously present in the environment where they are resistant toward biodegradation and can potentially accumulate.

Presence

PAH can enter the feed chain via the use of fats, oils, and fatty acids add/or can be formed during the production of feed, for example, during drying of feed ingredients. As regards vegetable oil refining for food purposes, PAH present in crude oil can be reduced substantially during bleaching and refining, as shown by Ma et al. (2017). The PAHs are transferred to the distillate byproducts, which may serve as feed ingredient. In a Chinese study, PAHs were detected in distillates up to 1.5 mg/kg (Sun & Wu, 2020). The RASFF database showed one notification of PAH as an industrial contaminant in dried alfalfa in feed materials in 2021 in Belgium.

Benzo[a]pyrene and the sum of benzo[a]pyrene, chrysene, benzo[a]anthracene, and benzo[b]fluoranthene (PAH4) are used as a marker for PAH as a group. In general, PAHs are not included in monitoring programs for feed in Europe since maximum legal limits for PAH in feed have not been established. As a result, information on the presence of PAHs in feed is limited (van der Fels-Klerx et al., 2019).

Transfer to animal products

PAHs were shown to occur in feed of cows and goats, but limited information is available about the transfer rate to animal-derived products (Bulder et al., 2006). Kan et al. (2003) demonstrated that PAH levels (expressed as benzo[a]pyrene equivalents) in milk were 10,000 times lower than in the feed (grass) (Kan et al., 2003). Another study demonstrated that PAH with less than five benzene rings and its metabolites can transfer via feed into milk, but the observed transfer was very low; the highest levels were found in milk samples from industrialized areas. PAH levels in milk fat ranged between 0.2 and 16.2 ng/kg (Grova et al., 2002) and up to 70 µg/kg was found in meat (SCF, 2002). Lutz et al. (2006) detected only PAH metabolites in cow milk after oral exposure to PAH but the toxicological properties of these metabolites are unknown.

Prioritization

Data about the presence of PAHs in feed are limited and no legal limits in feed have been defined. Transfer or PAH from animal feed into edible animal products is negligible; most animals metabolize PAHs. Therefore, although PAHs are toxic, mutagenic, and carcinogenic, this hazard has a low priority for monitoring (Table 1).

3.2.10 | Heat-induced processing contaminants

Processing contaminants can be formed when raw materials are processed in order to improve the characteristics of raw materials such as taste and shelf-life. Various processing procedures are possible, but in this review, only heat-induced processing contaminants (HIPCs) are addressed given their relevance for feed production (Wenzl et al., 2007). Examples of HIPCs are acrylamide, (esters of) 2- and 3-monochloropropane-1,2-diol (MCPD) (also called chloropropanols), glycidyl fatty acid esters (GE), 5-hydroxymethylfurfural (HMF), furan, fructose-lysin, and carboxymethyl-lysin. PAHs (Section 3.2.9) can also be processing contaminants.

Acrylamide is formed when asparagine or 3-aminopropionamide reacts with reducing sugars under low moisture conditions during Maillard reactions. Acrylamide is present in heat-induced products like potato chips and bakery products (Li et al., 2011; Wenzl et al., 2007). Chloropropanols are formed from glycerol, acylglycerol, and chloride ions in heat-processed, fat-containing raw materials with low water activity. 3-MCPD, a chloropropanol, is seen in, for example, bakery products, malt products, and fatty acid distillates. Esters of 2- and 3-MCPD and of glycidol have been found in fish oil (Sadowska-Rociek, 2020) and fish oil may be a source of these contaminants into feed. The formation of furan is based on several different pathways in thermally treated and various kinds of raw materials (Wenzl et al., 2007).

No MLs are established for processing contaminants in feed in the EU.

Presence

Livestock animals may come into contact with HIPCs by eating feed or raw materials that have been heated, or by eating feed ingredients that otherwise have received thermal treatment. An overview of the occurrence of processing contaminants in the feed chain is presented in Figure 3. The RASFF database contains six notifications on processing contaminants in feed in the period 2009–2023, mainly on HMF in additional feed for honey bees (so not in livestock production animals). In the NPAF, HIPCs are not included.

Transfer to animal products

In general, limited information is available about the transfer of HIPCs to animal-derived products. Pabst et al. fed 1.5 g/day acrylamide to a cow for 10 days, which resulted in a concentration of 175 µg/kg acrylamide in milk. The commercially mixed feeds with various protein content tested in this study contained less acrylamide than the experimental feed: 140–180 µg/kg acrylamide, presumably resulting in lower levels in the milk compared to the feeding trial results (Pabst et al., 2005). In a study of Halle et al. (2006), laying hens were fed a diet with potato meal containing 671 ± 32 µg/kg acrylamide and a control group with 125 ± 40 µg/kg acrylamide. The acrylamide levels in both experiments increased from 2.0 to 5.9 µg/kg in the control group and from 7.9 to 17.2 µg/kg in the experimental group during a 4-week period. On a mass balance basis, 1% of the acrylamide intake was transferred to the eggs. Thus, increased intake of acrylamide by cow and laying hen can lead to an elevation of acrylamide in milk and egg, respectively. No information about carry-over of chloropropanols and furan to animal products was found.

Prioritization

NPAF data are not available and RASFF contains several notifications but mainly in feed for nonlivestock animals. Animal studies have shown that acrylamide can be transferred from feed to milk, eggs, and animal products, but data are limited. Thus, data about the actual presence of HIPCs in feed and their transfer to animal products are limited. HPICs are potentially carcinogenic to humans (Wenzl et al., 2007). No MLs are established for processing contaminants in feed in the EU. Due to limited data, no classification was possible.

3.2.11 | Mineral oils

Mineral oils is a common name for MOHs, which usually contain between 10 and 50 carbon atoms. MOH can be divided into two main types: mineral oil saturated hydrocarbons (MOSHs) and mineral oil aromatic hydrocarbons (MOAHs), which contain cyclic hydrocarbons like naphthenics and aromatics. Sources of mineral oils are crude mineral oils, coal, natural gas, and biomass (Brühl, 2016; EFSA, 2012c). MOHs can be present in feed due to several routes: used as additive, as pollutant, via packaging, during processing (machine oils and antidust products), and as residue from ingredients in pesticides (Van Heyst et al., 2018) and likely also as residue in distillate byproducts from vegetable oil refining. Packaged raw materials are at risk to be contaminated with MOHs because ink on the packaging can contain MOHs and can be transferred to the product (Van Heyst et al., 2018). Because of their liquid state and low economic value, mineral oils are at risk for fraud: technical fats with a lower economic value can be mixed with oils and fats intended for animal feed (de Jong et al., 2016; Grundböck et al., 2010). No MLs have been established for the presence of mineral oils in animal feed or feed ingredients in Europe.

Presence

Limited information is available about the presence of MOHs in animal feed. The RASFF database from 2009 to 2023 contains one notification about the presence of diesel oil in sugar beet pellets from France in 2015 and one notification of mineral oil as an environmental pollutant in compound feeds for cattle and horses in Belgium in 2020. No information on MOH was available from the NPAF. In Figure 3, an overview of the possible occurrence of mineral oils in the feed supply chain is depicted.

Transfer to animal products

Only one study was found indicating that MOHs in contaminated feed eaten by food-producing animals can be transferred to animal-derived products: results show that in laying hens, fed with feed containing 400–800 mg MOHs/kg, 1.5–3% of the consumed MOHs was transferred to eggs (Grob et al., 2001).

Prioritization

Occurrence data on mineral oils in animal feed is very limited. Also, limited information on the transfer of mineral oils to animal-derived products is available. Mineral oils have been shown to be mutagenic and/or carcinogenic (Zhao et al., 2005). No MLs have been established for mineral oils in animal feed or feed ingredients in Europe. Therefore, classification of this hazard was not possible due to limited data (Table 1).

4 | CONCLUSIONS

This study classified chemical food safety hazards in the feed chain with regard to their prioritization for monitoring based on their occurrence in animal feed, transfer to animal-derived products, and potential human health effects. Chemical hazards with a high priority for monitoring in the European feed supply chain: dioxins and PCBs, BFRs, PFAS, As, Cd, aflatoxin (B1), PAs, and OCPs. The heavy metals lead and mercury, and pharmaceutically active substances (excluding hormones) were considered as medium priority. Limited data were available for: OTA, plant toxins other than PA, hormones, heat-induced processing contaminants, and mineral oils, so the priority for monitoring of these substances in feed could not be classified. However, risks for human health due to the possible occurrence of these substances can not be excluded. The priority for monitoring was low for other mycotoxins (than aflatoxins and OTA), and other pesticides than organochlorine, PAHs, and acrylamide as transfer to animal-derived food products was estimated to be negligible or the hazards had not been reported in concentrations above the ML or GV.

Ultimately, the results of this study on the prioritization of chemical hazards in the European feed supply chain can be used to support risk-based monitoring.

AUTHOR CONTRIBUTIONS

H. J. van der Fels-Klerx: Conceptualization; investigation; funding acquisition; writing—original draft; formal analysis; project administration; supervision; methodology. **E. D. van Asselt**: Investigation; writing—original draft; formal analysis; methodology. **S. P. J. van Leeuwen**:

Writing—review and editing; validation. **F. O. Dorgelo**: Formal analysis; writing—review and editing. **E. F. Hoek – van den Hil**: Formal analysis; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors state to have no competing conflict of interest.

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ANNEX 1: GLOSSARY

A

AFB1 aflatoxin B1
AFM1 aflatoxin M1
AL action limit (in feed, according to Directive 2002/32/EC)
AMR antimicrobial resistance
As arsenic

B

BDE brominated diphenyl ether
BFR brominated flame retardant

C

Cd cadmium
CONTAM EFSA Panel on Contaminants in the Food Chain

D

DL-PCB dioxin-like PCB
DON deoxynivalenol

E

EC European Commission
EFSA European Food Safety Authority
EU European Union
EU RASFF EU Rapid Alert System for Food and Feed

F

FDA US Food and Drug Administration

G

GE glycidyl fatty acid ester
GMO genetically modified organism
GV guidance value

H

H high priority
HBCDD hexabromocyclododecane
Hg mercury
HIPC heat-induced processing contaminant
HMF 5-hydroxymethylfurfural

I

IARC International Agency for Research on Cancer

L

L low priority

M

M medium priority
MCPD 2- and 3-monochloropropane-1,2-diol
ML maximum limit
MO mineral oil
MOAH mineral oil aromatic hydrocarbon
MOH mineral oil hydrocarbon
MOSH mineral oil saturated hydrocarbon
MPA medroxyprogesterone acetate
MRL maximum residue limit

N

NC not classified
NDL-PCB non-dioxin-like PCB
NPAF National Plan Animal Feed (Dutch official control program animal feed)
NSAID nonsteroidal anti-inflammatory drug
NVWA Netherlands Food and Consumer Product Safety Authority

O

OCP organochlorine pesticide
OTA ochratoxin A

P

PA pyrrolizidine-alkaloid
PAH polycyclic aromatic hydrocarbon
Pb lead
PBDE polybrominated diphenyl ether
PCB polychlorinated biphenyl
PCDD polychlorinated dibenzodioxin
PCDF polychlorinated dibenzofuran
PFAA perfluoroalkyl acid
PFAS per- and polyfluorinated alkyl substances
PFHxS perfluorohexane sulfonic acid
PFNA perfluorononanoic acid
PFOA perfluorooctanoic acid
PFOS perfluorooctane sulfonic acid

T

TEQ toxicity equivalency
TWI tolerable weekly intake

W

WHO World Health Organization
WUR Wageningen University and Research

Z

ZEA zearalenone