Review

Congener patterns of polychlorinated dibenzo-p-dioxins, dibenzofurans and biphenyls as a useful aid to source identification during a contamination incident in the food chain

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HIGHLIGHTS

- Congener patterns are important tools for source identification.
- TEQ contribution may be preferred over contribution to total sum.
- Only PCDDs point to clay or chlorophenols, only PCDFs to PCB sources.
- Mixed patterns point to minerals or burning processes.
- Simple patterns indicate certain pesticides or herbicides.

GRAPHICAL ABSTRACT
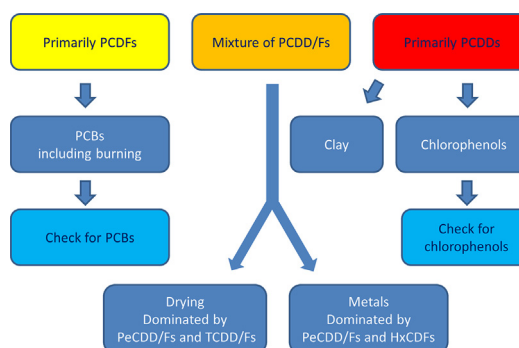
ABSTRACT

Polychlorinated dibenzo-p-dioxins (PCDDs), dibenzofurans (PCDFs) and biphenyls (PCBs) are still considered among the most important groups of contaminants in the food chain. Self-control by food producers and official control by authorities are important activities that allow contaminant sources to be traced and promote further reduction in food and feed levels. Strict but feasible maximum levels were set by the EU Commission for food and feed to support this strategy, as well as action levels and thresholds. When products exceed these levels, it is important to trace the source of contamination and take measures to remove it. Congener patterns of PCDD/Fs and PCBs differ between sources and are important tools for source identification. Therefore, patterns associated with different sources and incidents relating to various feed matrices and certain agricultural chemicals were collated from published scientific papers, with additional ones available from some laboratories. The collection was evaluated for completeness by presentations at workshops and conferences. Primary sources appear to derive from 5 categories, i) by-products from production of organochlorine chemicals (e.g. PCBs, chlorophenols, chlorinated pesticides, polyvinyl chloride (PVC)), ii) the result of combustion of certain materials and accidental fires, iii) the use of inorganic

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chlorine, iv) recycling/production of certain minerals, and v) certain naturally occurring clays (ball clay, kaolinite). A decision tree was developed to assist in the identification of the source.

Contents

1. Introduction

Polychlorinated dibenzo-p-dioxins and dibenzofurans (PCDD/Fs) and polychlorinated biphenyls (PCBs) are important contaminants in the food chain. The European Food Safety Authority recently reduced the tolerable weekly intake (TWI) from 14 to 2 pg TEQ (Toxic Equivalents)/kg bw per week, based on effects on sperm quality observed in humans (EFSA, 2018). It was also shown that at present the exposure of most consumers in the EU exceeds this TWI. To reduce the exposure of consumers, the EU, like several other countries, has set maximum levels for PCDD/Fs and PCBs in food and feed. During the last decades, various incidents have occurred, in many cases uncovered by the increased frequency of testing for these compounds by both governments (official control) and food and feed producers (self-control). Follow-up of these incidents has revealed a number of different sources and resulted in a strategy to remove these from the food chain. In many cases, feed was the source of these contaminants, in other cases it is environmental compartments like soil and sediments, as evidenced by the relatively high levels in foraging animals and wild fish, when compared to animals that are raised indoors. Some of these incidents will be briefly presented below but for a more detailed overview see Malisch and Kotz (2014), Hoogenboom et al. (2015a) or Malisch (2017). The rapid identification of a new source is an important step in the management of any new incident. Congener patterns are an important tool for this and some were presented in the aforementioned reviews. This paper extended the number of congener patterns. It describes different potential sources, grouped and individual patterns (supplementary files) and a decision tree based on both the presence and absence of certain congeners.

1.1. Toxic potency factors for PCDD/Fs and dioxin-like PCBs

In principle there are 75 PCDDs and 135 PCDFs but only the 17 congeners with at least 4 chlorine atoms and at least in the 2, 3, 7 and 8 positions are considered to be relevant for human health. These tetra-

(TCDD/TCDF), penta- (PeCDD/PeCDF), hexa- (HxCDD/HxCDF), hepta- (HpCDD/HpCDF) and octachlorinated (OCDD/OCDF) dioxin or furan congeners are relatively persistent against metabolic degradation and accumulate in the body. Eventually this leads to tissue levels (body burden) that may cause serious adverse effects, mediated by binding to the arylhydrocarbon receptor (AhR) and subsequent changed transcription of various genes (EFSA, 2018). These 17 congeners show different toxic potencies, which are expressed as toxic equivalency factors (TEFs) assigned to them based on in vivo and in vitro studies. The currently applied TEFs were established under the auspices of WHO and should be regularly reviewed, as evidenced by the last revision in 2005 (Van den Berg et al., 2006). The most toxic congener, 2,3,7,8-tetrachlorodibenzo-p-dioxin (TCDD) is used as the reference compound with an assigned TEF of 1. Current TEFs for other PCDD/Fs are 1 (PeCDD), 0.3 (2,3,4,7,8-PeCDF), 0.1 (hexaPCDD/Fs), 0.03 (1,2,3,7,8-PeCDF), 0.01 (hepta-PCDD/Fs) and 0.003 (octa-CDD/Fs).

In the case of PCBs, there are 209 theoretically possible congeners (not considering enantiomers). However, only the 12 with at least four chlorines and the ability to obtain a planar molecular structure show similar AhR-receptor activity and persistence properties as the PCDD/Fs, and as such were assigned a TEF. A planar structure configuration is achieved by lateral chlorine substitution, i.e. when there is none (non-ortho), or only one (mono-ortho) chlorine atom at the four ortho positions. The non-ortho PCBs have assigned TEFs of 0.1 (PCB 126), 0.03 (PCB 169), 0.001 (PCB 77) and 0.003 (PCB 81), whereas all eight mono-ortho PCBs (# 105, 114, 118, 123, 156, 157, 167, 189) have been assigned a TEF of 0.00003 (Van den Berg et al., 2006).

To determine the overall TEQ level for a sample, the individual congener concentrations are first multiplied with the TEF value and then summed. Animal derived foods including oily fish contribute most to human exposure (EFSA, 2018). In this regard it is important to note that not all congeners are equally absorbed. Furthermore, some are excreted to milk or transferred to eggs, and/or accumulate in fatty tissues or organs such as the liver. Various studies have been performed to study this transfer and to derive so-called carry-over rates (CORs, now preferentially termed transfer rates (TRs)), bioconcentration factors

(BCFs), or biotransformation factors (BTFs) for individual congeners from feed to food (reviewed by EFSA, 2018, Fernandes et al., 2019).

In practice, both the TEF value and the abundance of a specific congener determine the relative importance for the exposure of consumers. EFSA (2018) reported that 63% of the TEQ exposure of consumers is caused by DL-PCBs compared to 23% for PCDFs and 14% for PCDDs. When focussing on congeners, the average contribution was 54.7% for PCB-126, 10.7% for 2,3,4,7,8-PeCDF, 7.4% for 1,2,3,7,8-PeCDD, 4.9% for 2,3,7,8-TCDF, 3.4% for 2,3,7,8-TCDD, 3.7% for PCB-169 and 2.7% for the most relevant mono-ortho PCB 118 (EFSA, 2018). Other congeners were less relevant. This was based on WHO-TEFs$_{2005}$. Of course, this may be different for certain incidents with specific sources, as will be shown below.

1.2. Sources of PCDD/Fs and PCBs

Sources of PCDD/Fs related to human activities can be attributed to one of 5 main categories. These are (i) by-products in the manufacture of organochlorine chemicals (e.g. PCBs, chlorophenols, chlorobenzenes, chlorinated pesticides, polyvinylchloride (PVC)); (ii) as a result of incomplete combustion when there is a source of chlorine present (e.g. the burning of certain plastics); (iii) as a result of the use of inorganic chlorine (e.g. as was previously common in the paper bleaching industry); (iv) recycling/production of certain minerals; (v), as a result of natural formation and presence in certain clays (e.g. Mississippi ball clay, kaolinite) that form part of feed and food supplements or can be used in feed and food production.

PCBs arise in the environment mainly as a direct consequence of their production and use, the number of secondary sources being much smaller than for the PCDD/Fs. PCBs have been used for different purposes and were produced by several companies in different parts of the world, as mixtures with varying degrees of chlorination and hence compositions. Typical products are Aroclors 1242, 1254, 1260, Kanechlors 300, 400, 500 and 600, Phenoclor DP-3, −4, −5 and − 6, and Clophens A30, A40, A50 and in particular A60. Dioxin-like PCBs, both mono-ortho and in particular the more toxic non-ortho PCBs, are minor components of these mixtures. A set of six (formerly seven) PCBs was selected as the significant congeners that can be used to identify a contamination source for the PCBs, these being PCBs 28, 52, 101, 138, 153, 180 (and formerly 118). They covered the different lower and higher chlorinated PCB mixtures produced, and hence were called indicator PCBs. Six of these PCBs (termed non-dioxin-like (ndl) PCBs) were also subject to EU maximum level (ML) regulations since 2012, although many countries had already established MLs at a much earlier stage. PCB 118 was not included in the EU regulations because, being a dl-PCB, it was already included in the regulations for the sum of PCDD/Fs and dl-PCBs. In food, normally PCBs 138, 153 and 180 contribute the most to the sum of ndl-PCBs, due to their higher persistence in the fat of food-producing animals as compared to lower chlorinated ones.

1.3. Congener patterns for source identification

When an elevated contamination level in feed or food is detected, it is very important to identify the source, allowing appropriate measures to track and trace affected products, and the farms or producers involved in the incident. Additional measures can be taken to eliminate the source and avoid future contaminations. The patterns of congener occurrence are an important tool for identifying the potential origin of the PCDD/Fs and/or PCBs and as such the potential source of the contamination. For example, in the Belgian dioxin/PCB incident of 1999, the congener pattern for the PCDD/Fs (only PCDD/Fs were analysed initially), rapidly pointed to PCBs as the origin, which was then confirmed by specific analysis (Bernard et al., 1999). The analysis of ndl-PCBs was actually allowed as a substitute for the much more expensive analysis of dioxins. In 2004, the discovery of elevated levels of PCDD/Fs in milk from a farm in the Netherlands was traced back to kaolinic clay that was used in the production of potato-based products, based on the

similarity with patterns previously observed in these type of clays when used in feed production (Hoogenboom et al., 2010). The pattern can also be helpful to link additional samples to the same incidents, even if the pattern had not been seen before, as in the case of the gelatine incident in 2006 (Hoogenboom et al., 2007).

To support laboratories, risk assessors and risk managers, various known congener patterns for PCDD/Fs (and where relevant, PCBs) that have been implicated in food contamination incidents globally will be presented in relation to the known sources. The focus will be on the primary source, often the feed, since the congener patterns will be pharmacokinetically altered in animal derived food due to differences in absorption, distribution, metabolism and excretion (ADME). Primary patterns may also have been changed due to (repeated) heating or burning, or processing of contaminated oil by distillation or chemical treatment. A particular example is the dechlorination of OCDD during the hydrogenation of palm oil fatty acids, thereby increasing the levels of the more toxic congeners (Taverne-Veldhuizen et al., 2020).

Consistency of patterns due to analytical variation within and between laboratories is another important issue, but it remains to be ascertained as to whether this could actually result in misclassification of the source. The outcome of proficiency tests (PTs) and other interlaboratory trials with many participating laboratories may help to elucidate this impact.

2. Expression of patterns

When evaluating patterns, important aspects are the choice of congeners and whether congener patterns should be expressed as relative contribution to the sum of the measured concentrations, or as relative contribution to the TEQ. Concerning the first question, laboratories may analyse more PCDD/Fs and PCBs than the regulated 17 PCDD/Fs, 12 dl-PCBs and 6 ndl-PCBs. Inclusion of other congeners will certainly improve the comparison of the pattern with known patterns and narrow down the possibilities when similar patterns are found for different sources. However, most regulatory food laboratories do in general not quantify or even identify the other congeners in the chromatograms and only report on those included in the regulations. Furthermore, in food of animal origin, most e.g. the non-2,3,7,8-substituted PCDD/Fs will not be present due to metabolism. Therefore, it was decided to focus on the 17 PCDD/Fs and to some extent the 12 dl-PCBs and 6 ndl-PCBs. Nevertheless, the additional information can be used as confirmatory evidence to support any attribution made.

The expression of patterns, whether as contribution to the sum of measured levels or TEQ level, are complementary – both have advantages and limitations, as explained in the following paragraph In addition, it is probably best to deal with PCDD/Fs and dl-PCBs separately, since in many cases the contamination incident may only involve PCDD/Fs. However, even when PCBs are the source of the PCDD/Fs, expression of the relative contributions of PCDD/Fs and dl-PCBs to the total TEQ is unlikely to improve the confidence in identifying the source.

Expressing the pattern on an absolute concentration basis provides the reader with data as measured, but has the disadvantage that quite often samples of feed or feed ingredients contain relatively high levels of the octachlorinated PCDD/F, which dominate the pattern. This can be overcome by scaling (e.g. using a log scale to plot the data). However, basing the pattern on the TEQ-contribution also has significant advantages when comparing patterns in feed to animal derived animal products, as the pattern in food of animal origin will be changed in comparison to the pattern in the original source due to differences in absorption, distribution, metabolism and excretion. This can partly be overcome by applying the so-called transfer rates from feed to food (TRs, formerly called carry-over rates or CORs). However, in practice these TRs show a reasonable correlation with the TEFs, meaning that the lower chlorinated PCDD/Fs in general show higher TEFs and larger TRs than the higher chlorinated ones (EFSA, 2018). An exception are

TCDF and 1,2,3,7,8-PeCDF which show very low TRs and BCFs in e.g. cows and pigs (EFSA, 2018). This means that TEQ-based patterns in food and feed will be more similar for a specific source, as shown below for the case of citrus pulp (see 3.1). It was therefore decided to show the patterns for PCDD/Fs in the present paper as contribution to the PCDD/F-TEQ. However, the supplementary files (Fig. S2) shows both types of patterns for a number of incidents and sources.

For the PCBs, in almost all cases the TEQ-contribution of PCB 126 is 90 to 95% of the total, thereby dominating the pattern when expressed as TEQ contribution. As many laboratories nowadays determine both the 12 dl-PCBs and the 6 ndl-PCBs, it is worthwhile to include the latter in the pattern, giving a total of 18 PCB congeners. A possible disadvantage arises from the relatively low levels of the non-ortho PCBs which are considerably less prominent in the combined pattern. The relevant question is to what extent these non-ortho dl-PCBs can contribute to the identification of the type of PCB mixture present in the sample. More significant indications on e.g. the degree of chlorination can be derived from the pattern of the mono-ortho and ndl-PCBs.

3. Congener patterns related to different sources

In order to collect different patterns, the literature was reviewed for the various incidents in the food chain. Some additional patterns were obtained from laboratories contributing to this paper. In particular RIKILT (now WFSR) analysed samples from a large number of incidents using GC/HRMS-based methods (described in Hoogenboom et al., 2007), and in a number of cases these are shown rather than the ones published. In addition to PCDD/Fs some patterns observed in chlorinated pesticides were included, as these might still show up in the food chain due to past or current use. A number of different sources have been identified and these will be discussed in relation to the congener patterns. These sources are chemicals like ethylene dichloride (3.1), chlorophenols (3.2), chlorinated pesticides (3.3) and PCBs (3.4), burning of chlorine containing plastics in household waste and painted wood (3.5), certain types of clays (3.6) and minerals (3.7), and some unknown sources (3.8).

3.1. Pattern related to the production of ethylene dichloride

The production of citrus pulp pellets using lime from an industrial plant in Brazil producing polyvinylchloride (PVC) caused a major incident in 1998 (Malisch, 2000; Malisch and Kotz, 2014; Malisch, 2017). The contamination was discovered in Germany and affected 12 EU Member States, where a high fraction (generally around 25%) of citrus pulp pellets was included in feed for dairy cows. It is one of the best documented examples of the comprehensive forensic work which is required to identify the primary source. It started with the observation of elevated dioxin levels in milk and milk products in the South-West of Germany, and the consideration of a number of potential sources at a farm that was producing milk with high PCDD/F levels (including disinfectants, detergents, pesticides, drugs used in veterinary medicine, paints in silos and all kinds of feed). As a result, a compound feed was identified as possible source. From the five ingredients, citrus pulp was found to have caused the incident and this single component was considered as "source" of the milk contamination. As the citrus pulp pellets were produced in Brazil, the investigation of the "real" source continued there. From three hypothetical options (pesticides used for production of oranges; drying process; additives), lime which was added for pH neutralisation was found to be the origin of the contamination (Malisch et al., 1999; Carvalhaes et al., 2002). The contaminated lime came from one supplier who used the lime from a landfill which was used for the disposal of waste from a chlorine/organochlorine industry. This lime was heavily contaminated with by-products from a vinyl chloride monomer production process (for PVC production). As shown in Fig. 1A, OCDF was by far the most important congener in terms of absolute levels in both the citrus pulp pellets and feed prepared

from it. This pattern is characteristic for the production of ethylene dichloride, produced by an oxychlorination process (Torres et al., 2013). This was the "real" primary source of the contamination found in milk. This example with three comprehensive parts on two continents (from milk to citrus pulp; from citrus pulp to lime; from lime to EDC (ethylene dichloride, an intermediate in the production of PVC) shows the complexity of tracing the origin of a contamination and different meanings of "source".

However, as shown in Fig. 1A, in milk from an affected farm, the pattern based on absolute levels was quite different from that in the pellets and feed. When expressed on relative contribution to the TEQ level, 2,3,7,8-TCDD and 1,2,3,7,8-PeCDD were the most important congeners in the milk, but also in the feed, as well as in the pulp (Fig. 1B). This demonstrates that TEQ-based patterns allow a better comparison between the primary source and the animal derived products due to ADME aspects. Interestingly, Torres et al. (2013) noticed a discrepancy between this TEQ based pattern and the one in the EDC source, and came up with a number of possible explanations related to the heat treatment of the lime and the presence of other PCDD/F precursors.

3.2. Patterns related to chlorophenols

Chlorophenols are man-made chemicals used for various applications, like pesticides and fungicides. Probably the most well-known incident with chlorophenols is the accident in Seveso, Italy in 1976, where a cloud of chemicals escaped from a chemical company during the production of the herbicide 2,4,5-trichlorophenoxyacetic acid (2,4,5-T) and contaminated the adjacent area. TCDD is a known by-product in the synthesis of 2,4,5-T and was by far the most important PCDD/F congener discovered in the blood of exposed people. TCDD was also a major congener in Agent Orange (a mixture of equal parts of 2,4,5-T and 2,4-D (2,4-dichlorophenoxyacetic acid)), that was used as a defoliant in the Vietnam war. It can still be detected in food stuffs in certain areas, like the U.S. Air Force base Bien Hoa, where the defoliant chemicals were handled (Schecter et al., 2003; Hoang et al., 2014).

Another well-known source of, in particular, higher chlorinated PCDDs is pentachlorophenol (PCP), widely used as an antifungal agent including preservation of wood.

The first known incident with chlorophenols in the food chain occurred in the late fifties in the US when a large number of chickens became diseased (hepatic necrosis leading to oedema), or died (Sanger et al., 1958; Firestone, 1973). It took a decade to identify PCDD/Fs as the cause, being present in fat scrapings from cow hides, that had been treated with a mix of trichloro-, tetrachloro- and pentachlorophenols. The pattern in this "toxic fat", described by Hayward et al. (1999), is shown in Fig. 2 and is characterized by a high contribution of PeCDD and HxCDDs to the TEQ.

Several other food-related incidents with chlorophenols have since occurred. The use of PCP treated wood in stables was the most likely source of PCDD/Fs in chicken and pork samples in a Canadian survey (Ryan et al., 1985). PCP treated wood in a stable seriously affected the outcome of a study on the transfer of PCDD/Fs in beef cattle (Feil et al., 2000) and a follow-up study on other experimental stations showed that this was a more common source (Huwe et al., 2004). Wood chips, prepared from contaminated wood and used as bedding material, caused the contamination of eggs on a farm in Italy (Diletti et al., 2005; Brambilla et al., 2009). Mixing with PCP contaminated saw dust caused the contamination of choline chloride, a widely used feed ingredient (Llerena et al., 2003). Fig. 2 includes the pattern in this contaminated material. In 2007, PCP turned out to be the source of contaminated industrial grade guar gum, used for food production (Fig. 2) (Wahl et al., 2008), again showing the high TEQ contribution of HpCDD.

At the end of 2010, PCDD/Fs were detected in fatty acids intended to be used for deinking of paper, but which were illegally used for production of animal feed in Germany (Abraham et al., 2011). RIKILT (now
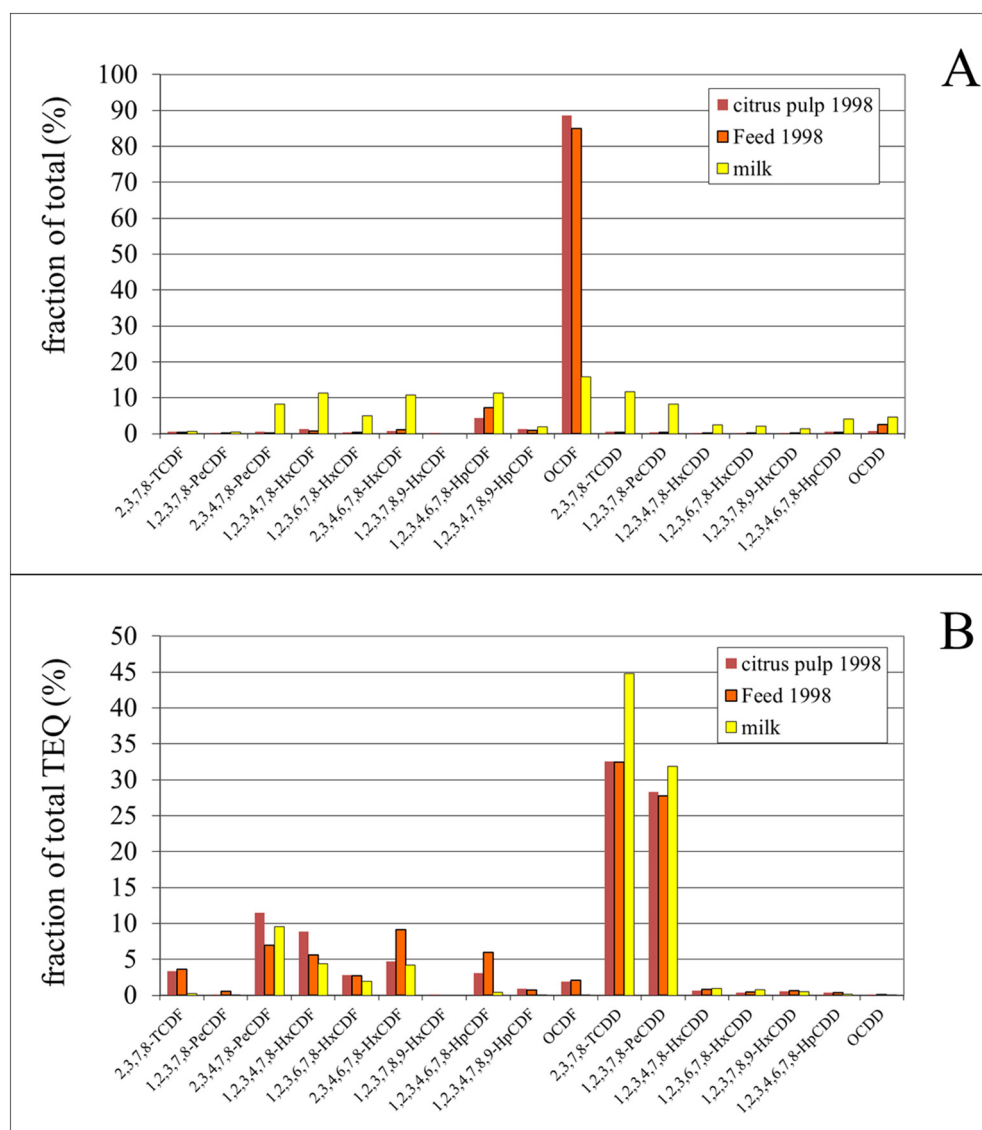
Fig. 1. Congener patterns for PCDD/Fs (contribution to A: absolute level and B: TEQ) in citrus pulp, feed prepared with citrus pulp and milk from cows fed with this feed (Malisch, 2000). The incident was caused by the use of contaminated lime from a PVC production plant, the high OCDF contribution being typical for the oxychlorination process used for the production of ethylene dichloride.

WFSR) observed PCDD/F levels up to 181 pg TEQ/g fat in a number of fatty acid samples (unpublished). The highest contaminated sample was analysed with GC-TOFMS and was shown to contain indicative levels of 700 ng/g tetrachlorophenols (TeCP, 3 isomers), 30 ng/g trichlorophenol and 475 ng/g PCP. The real source of the chlorophenols in the fatty acids was never disclosed. The pattern (Fig. 2) showed the typical high TEQ contribution of certain hexachlorinated PCDDs.

3.3. Patterns related to other agricultural chemicals

In addition to chlorophenols, also a number of other chlorinated chemicals applied in agriculture, may be contaminated with PCDD/Fs, like the herbicides 2,4-dichlorophenoxy-acetic acid (2,4-D) (Holt et al., 2010; Liu et al., 2013), and pentachloronitrobenzene (PCNB), and the insecticide lindane (Holt et al., 2010). Fig. S1 (supplementary files) shows congener patterns for these 3 compounds and a mixture 2,4,5-T/2,4-D, reported by Holt et al. (2010). For lindane, 1,2,3,6,7,8-HxCDD contributed most to the TEQ level, whereas for PCNB, this applied to a mixture of 4 congeners, being 1,2,3,6,7,8-HxCDF, 1,2,3,4,6,7,8-HpCDF, and to a smaller extent HpCDD and OCDD. The pattern for the 2,4,5-T/

2,4-D mixture shows the high TEQ contribution of TCDD (96%), whereas for 2,4-D this is primarily PeCDD. The absence of PeCDD in this mixture is in line with the much higher PCDD/F levels in 2,4,5-T. Masunaga et al. (2001) analysed different batches of the herbicide chloronitrophen (CNP) and also observed a high contribution of PeCDD to the TEQ levels in this compound. Proper control of the production process has been found to prevent the formation of these contaminants, based on the analysis of batches produced in later years.

3.4. Patterns related to PCBs

There are a number of food and feed related incidents shown to be caused by PCBs. The most publicised of these were the two incidents with rice oil (Kuratsune et al., 1972; Hsu et al., 1985), the first of which was locally called "Yusho" and occurred in northern Kyushu in Japan in 1968. This was followed just over a decade later, in 1979, by a similar incident called "Yu-Cheng" in Taiwan. Both incidents had similar causes, i.e. contaminated cooking oil that was purified by steam distillation in a device using PCB-oil in the coils of the heating system. A large number of people were exposed during these incidents and they
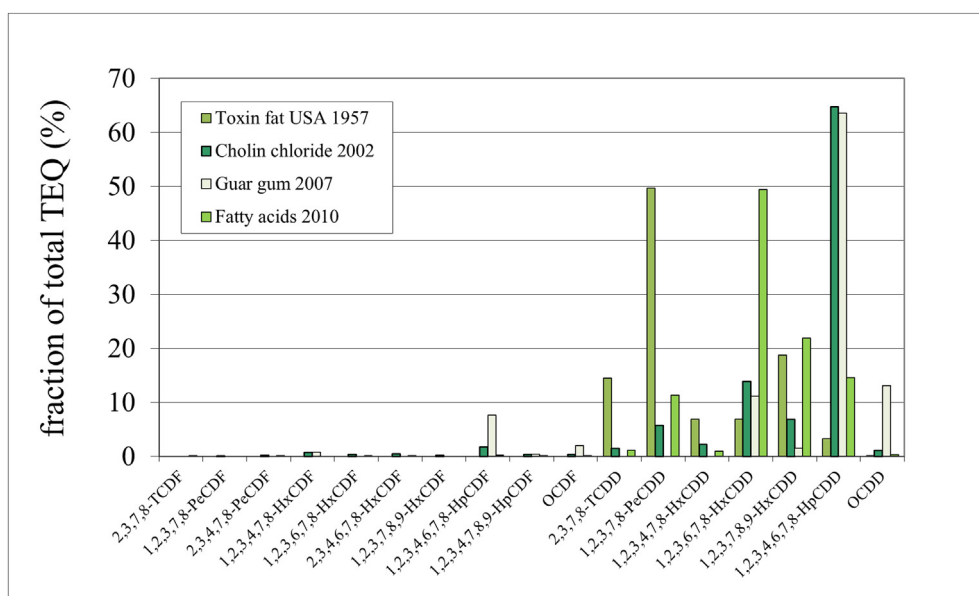
Fig. 2. PCDD/F congener pattern for a number of incidents related to chlorophenols, — as a mix used on cow hides (1957), PCP in saw dust mixed with choline chloride and in industrial guar gum (2002, 2007) or fatty acids intended for deinking of paper but used in feed (2010).

developed typical symptoms of chloracne, an early sign of acute organo-chlorine contamination, as well as a host of other biological effects. Also a large number of chickens died in the Yusho incident due to the use of a fatty acid by-product in chicken feed (Kuratsune et al., 1972).

In the case of the Yusho incident, the PCB oil that leaked into the crude rice-oil was Kanechlor-400, with a high contribution of tri-, tetra- and, to a lesser extent, pentachlorinated PCBs (Takasuga et al., 2005). However, in the contaminated rice oil, high amounts of PCDFs were also observed, with a high contribution of 2,3,4,7,8-PeCDF (58%) and 1,2,3,4,7,8-HxCDF (22%) to the PCDD/F-TEQ level (Yao et al., 2002). The most important dl-PCB, in terms of the TEQ level, was PCB 126 but overall dl-PCBs contributed only around 25% to the TEQ-level of the rice oil (Yao et al., 2002). Much less suitable data are available for the rice oil in the Yu-Cheng incident, although also in this case, PCDFs were detected at high levels. In addition, the rice oil in both cases contained polychlorinated quaterphenyls (PCQs). Both the PCDFs and PCQs are thought to be formed during the repeated heating of the PCB-oil, resulting in a much higher PCDD/F-TEQ-level of the PCB-oil than normally observed in Kanechlors. A ratio of around 1500 between the ndl-PCB level and the PCDD/F-TEQ was estimated from the various reports for the rice oil in the Yusho incident.

Several decades later, in 1999, a major incident in chicken and pig feed was uncovered in Belgium, where a PCB-oil with a pattern typical for a mixture of Aroclors 1254 and 1260 contaminated recycled fat used for feed production (Bernard et al., 1999). Based on the levels in feed and the fat content, a 30% contribution of the seven indicator PCBs to the total amount of PCBs in such a mixture, and the 60 t of con-taminated fat used for feed production, Hoogenboom et al. (2004a) es-timated that 160 kg of PCB-oil entered the food chain. The PCDD/F pattern, included in Fig. 3A, shows the dominance of PCDFs and in par-ticular 2,3,4,7,8-PeCDF in terms of contribution to the TEQ-level (based on WHO-TEFs from 2005). Fig. 3B shows the congener pattern for the PCBs, both dioxin- and non-dioxin-like. The PCB-pattern contained rel-atively high levels of the higher chlorinated PCBs, 138, 153 and 180. In this particular case the ratio between the level of the ndl-PCBs and the PCDD/F-TEQ was around 50,000, a ratio that was used to set a limit for the ndl-PCBs, used as an alternative for the analysis of PCDD/Fs.

Another large incident with PCBs as the origin of the PCDD/Fs, oc-curred in Ireland in 2008 (Heres et al., 2010; Tlustos et al., 2012). The PCDD/F pattern (Fig. 3A), was quite similar to that from the Belgium

incident. In this case the contamination occurred during the drying of bakery waste products with diesel oil that contained PCBs. Due to the burning of the oil, PCBs were converted to PCDFs. This conversion was probably the cause for a relatively low ratio of ndl-PCBs to the PCDD/F-TEQ, being less than 2000 in the contaminated bread crumbs. The PCB-pattern (Fig. 3B) showed a relatively large contribution of higher chlorinated congeners, indicating a somewhat higher contribution of Aroclor 1260, as compared to the mixture in the Belgium incident. In pork, the pattern changed considerably due to the almost complete me-tabolism of TCDF and 1,2,3,7,8-PeCDF by the pigs (Heres et al., 2010). Cows metabolise the compounds in a similar way (Hoogenboom et al., 2015b).

In 2010, free-range eggs in the Netherlands were contaminated with PCDD/Fs and some PCBs (Traag et al., 2010). Since a number of different farms were contaminated and all exhibited the same congener pattern, it became clear that feed was the source of contamination, rather than soil. Eventually the problem was traced back to organic corn imported from the Ukraine. The PCDD/F pattern (Fig. 3A), showed a relatively high TEQ contribution of TCDF. The PCB pattern (Fig. 3B) shows a rela-tively high contribution of lower chlorinated PCBs, which concurs with the PCDD/F pattern. Since this incident, there have been two fur-ther notifications in the European Rapid Alert System for Food and Feed (RASFF), one with pea seeds (2013.0600) and one with rapeseed (no 2013.1308), both from the Ukraine and showing rather similar con-gener patterns for both PCDD/Fs and PCBs (data not shown).

PCBs have also been widely used in paints and sealants, and as such are widely spread in old buildings. Willett and Hess (1975) described the contamination of feed stored in silo's due to PCB-containing paint, resulting in elevated levels in milk of dairy cows. Hoogenboom et al. (2014) described a number of incidents on farms with free ranging lay-ing hens, due to either the use of granulate from old buildings in the courtyard, or the wash-off from coated asbestos roof plates.

3.5. Combustion sources related to burning municipal waste and improper drying

The burning of certain waste is a well-known source of PCDD/Fs. Various countries reported the contamination of agricultural production areas surrounding municipal waste incinerators (Olie et al., 1977; Rappe et al., 1987; Liem et al., 1991; Lovett et al., 1998). Fig. 4 shows a typical
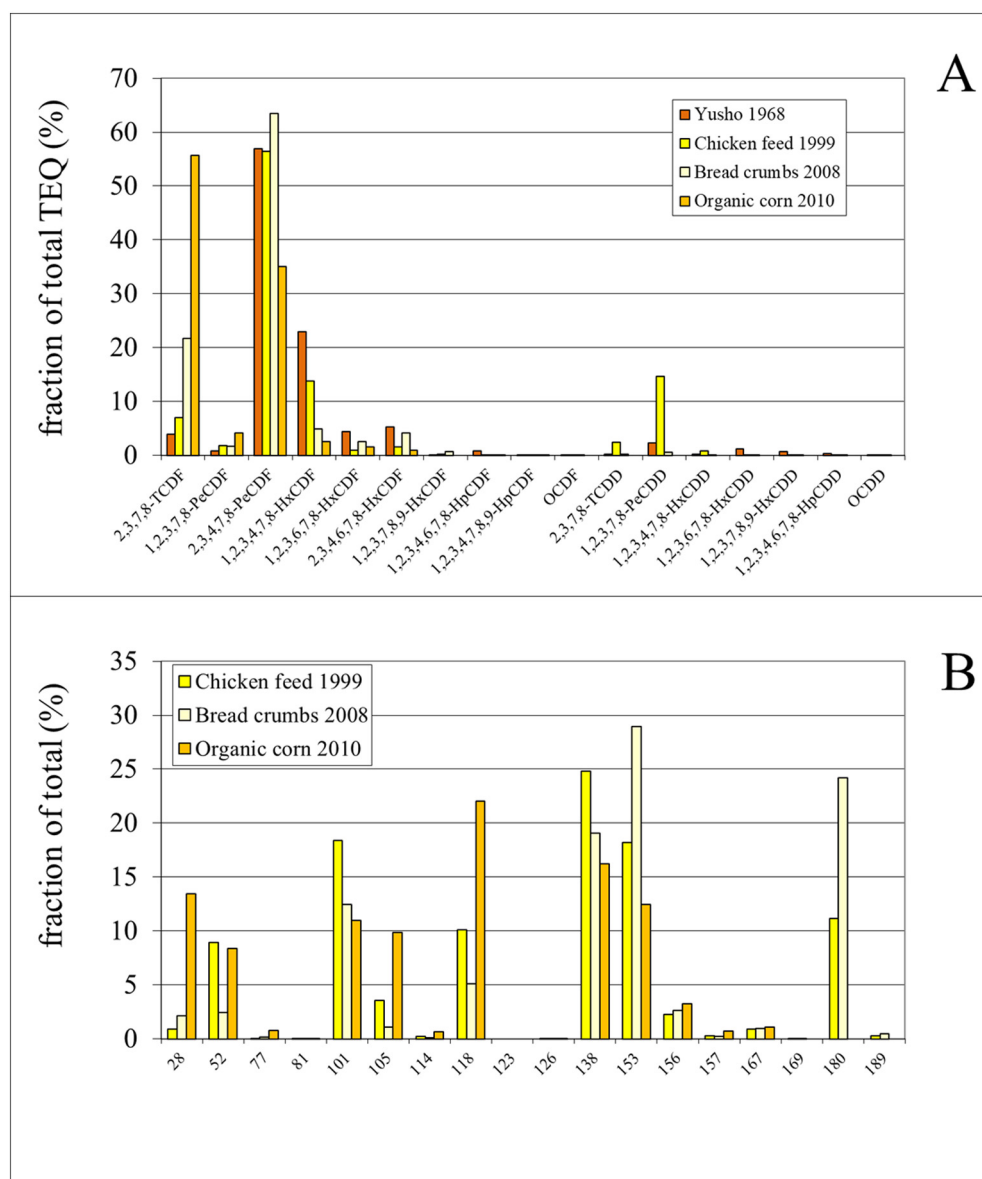
Fig. 3. Congener patterns for PCDD/Fs (A, contribution to TEQ) or ndl- and dl-PCBs (B, contribution to sum), for four incidents related to PCBs. For the rice oil (Yusho) no congener pattern for the ndl-PCBs was retrieved.

PCDD/F pattern observed on grass near a municipal waste incinerator in the Netherlands (Slob et al., 1995). The pattern is very similar to that obtained with vegetation during accidental fires in the Netherlands, including one with silos produced from PVC (Hoogenboom et al., 2012, 2015b). Proper control and operation of municipal waste incinerators has been shown to be effective in preventing the formation of these contaminants.

In 2003, the use of painted wood for drying of bakery waste in Germany caused an incident in Germany and the Netherlands (Hoogenboom et al., 2004b). The pattern is included in Fig. 4, showing the relatively high TEQ contribution of the lower chlorinated congeners.

A RASFF notification reported an elevated level of PCDD/Fs in *Tagetes erecta*, which is used as a dye in feed stuffs for laying hens. Although not disclosed, the most likely source may again be drying.

At the end of 2011, the use of beet pulp imported from Germany resulted in elevated milk levels on some farms in the Netherlands (Hoogenboom et al., 2015b). The beet pulp had been dried with coal, containing plastic debris from a roof shattered by a hail storm. The pattern is included in Fig. 4 and shows a pattern that is quite similar to that in the dried bread crumbs.

In practice, the pattern observed for burning, is also the most abundant pattern seen in various animal derived products. This is an indication that burning processes contributed most to the current background levels in grass, animal feed but also soil which may contribute significantly to the intake of PCDD/Fs by animals foraging outside, such as free-ranging poultry (Hoogenboom et al., 2016). In general dl-PCBs seem not to be formed during the incineration of household waste in MWIs. This is particularly relevant for PCB 126, which often contributes for more than 50% to the TEQ at background levels in edible products of foraging animals. The source for this PCB is unclear.

3.6. Patterns related to inorganic chlorine sources - clays

In 1997, it was discovered that Mississippi ball clay was responsible for elevated levels of PCDD/Fs in chicken and catfish in the US (Hayward et al., 1999). The clay was used for the homogeneous mixing of minerals into the feed. The pattern in processed ball clay was characterized by the presence of only PCDDs (Fig. 5). Ferrario et al. (2000) reported that part of the TCDD present in the raw clay was lost during the processing. Similarly, in 1999, Jobst and Aldag (2000) showed that kaolinic clay from a
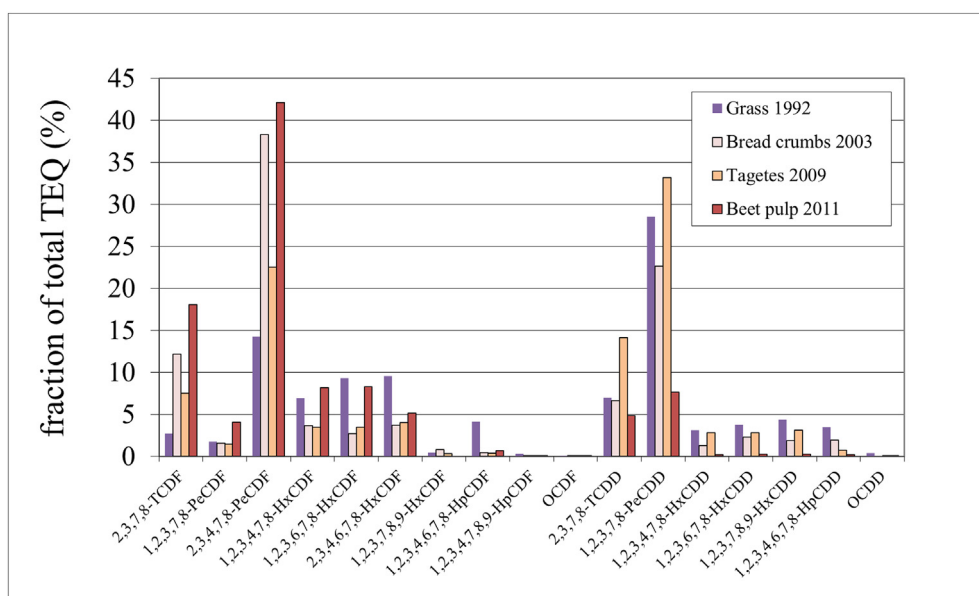
Fig. 4. Congener patterns for PCDD/Fs (contribution to TEQ) in grass near a waste incinerator, dried bread crumbs and beet pulp, as well as Tagetes, also likely to result from drying.

German mine, used for similar reasons in feed production, contained high levels of, only PCDDs. This was confirmed by analysis of the same type of clay sampled in the Netherlands (Fig. 5). In 2004, a very similar congener pattern was discovered in potato peel fed to cows that showed strongly increased PCDD/F-TEQ levels in milk. As already mentioned, the similarity in the patterns helped in tracing the source of the contamination, being the use of kaolinic clay in a nearby company producing potato products.

The use of this type of clay was abandoned in the feed and food industry, but clays are also traditionally used during pregnancy by women of certain African countries and ethnic minorities in the Netherlands (Reeuwijk et al., 2013). Various clays, both purchased in the Netherlands and African countries, were examined, part of them showing high levels of PCDD/Fs. In most cases, the pattern was similar to that in the kaolinic clay (like the Mabele clay shown in Fig. 6), but in one sample (termed Mabele sale), it clearly differed. This clay, showed a relatively high contribution of 1,2,3,7,8,9-HxCDD and small contribution of PeCDD to the TEQ level.

The source of the PCDDs has long been debated, whether industrial or produced in nature. However, the latter seems the case as it was shown that they might be formed under high pressure and temperature, conditions present in specific layers in the earth (Holmstrand et al., 2006; Horii et al., 2008; Gu et al., 2008).

3.7. Patterns related to inorganic chlorine sources - minerals

Certain batches of minerals used in animal feed were shown to be contaminated with quite high levels of PCDD/Fs. So-called sequestered minerals, produced by mixing and heating various minerals with kelp, is an example. For one of these products, carbosan-Cu, Ferrario et al. (2003) reported levels of PCDD/Fs, which would add up to 1.2 μg WHO_{2005}TEQ/kg. RIKILT (WFSR) analysed a series of these minerals with levels of 0.03 to 0.5 μg WHO_{2005}TEQ/kg for those with Zn, Mg, Fe and Mn, but around 2 μg WHO_{2005}TEQ/kg for two samples of carbosan-Cu (not published). The pattern for carbosan-Cu showed a

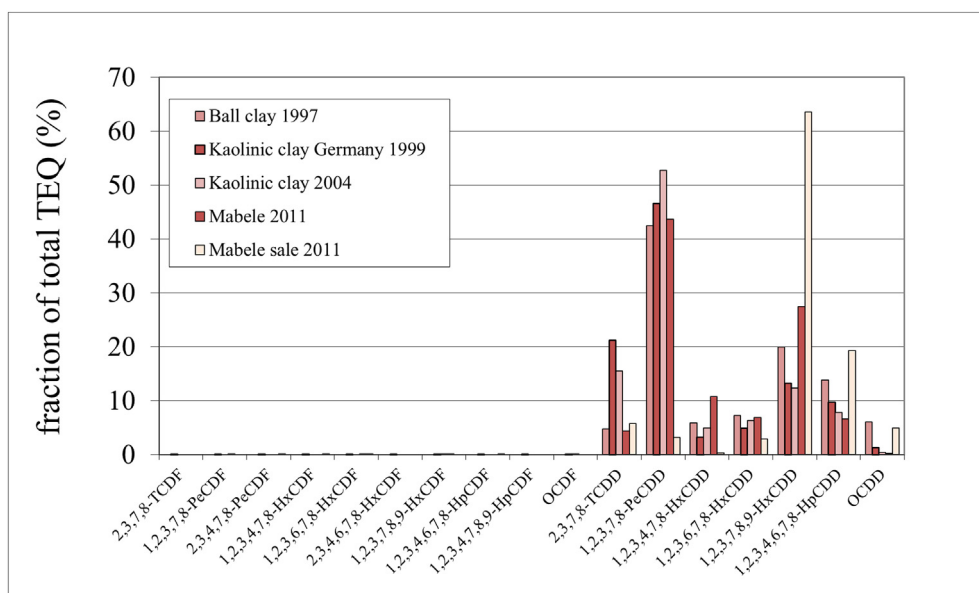**Fig. 5.** Congener patterns for PCDD/Fs (contribution to TEQ) in clays used in the feed and food industry and African clays used by pregnant women.
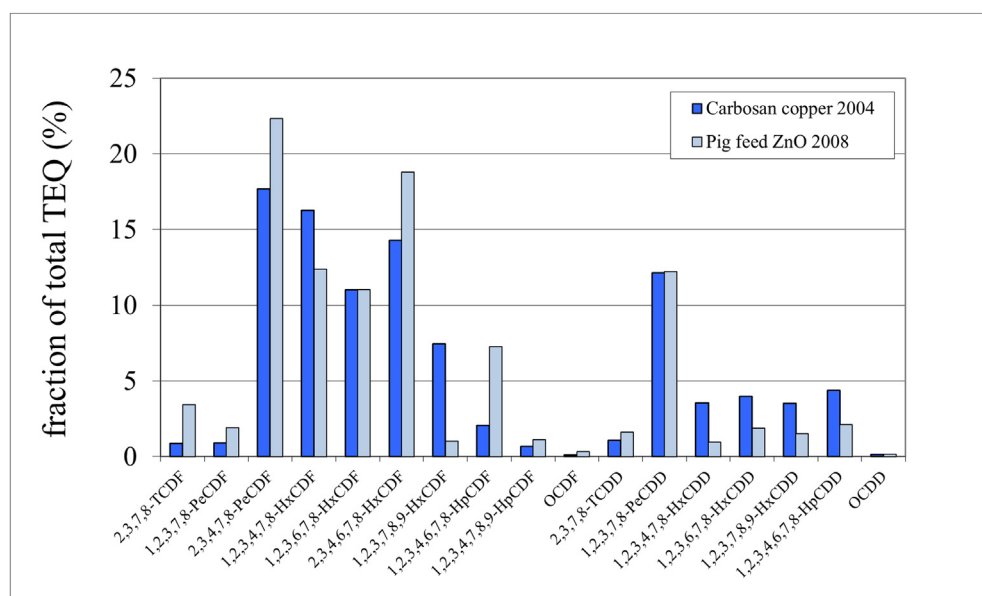
Fig. 6. Congener patterns for PCDD/Fs (contribution to TEQ) in sequestered copper (carbosan copper) and pig feed prepared with contaminated zinc oxide.

relatively high contribution (71%) to the TEQ level of a large number of different PCDFs but also various PCDDs, in particular PeCDD (Fig. 6).

In 2008, the use of a recycled zinc oxide caused an incident in Chile with elevated levels in pork meat, detected in South Korea (Kim et al., 2011). A sample of premix showed a level of 5.7 μg WHO$_{2005}$TEQ/kg, a sample of pig feed a level of 12 ng WHO$_{2005}$TEQ/kg. Remarkably, the pattern was quite similar to that observed for the sequestered minerals, with an 80% contribution of the PCDFs to the TEQ (Fig. 6).

3.8. Patterns related to unknown sources

A typical pattern was observed during an incident with fat coming from the production of gelatine, and used for feed production (Hoogenboom et al., 2007). The pattern was dominated by PeCDD and small amounts of TCDD (Fig. 7). The source was traced back to the use of contaminated HCl that is used for the production of gelatine from pig bones, but the pathway leading to the HCl contamination was never confirmed. However, it appears that the chemical synthesis of a specific compound, as in the case of certain chlorinated agrochemicals, could best explain this pattern.

Another incident occurred in Chile in 2013, where 4 samples of chicken taken at a slaughterhouse at different time points, showed a pattern not reported before (Fig. 7), although it resembled the one from the gelatine incident. A more detailed study of chromatograms showed that certain non-2,3,7,8-PeCDDs were actually present at much higher levels than 1,2,3,7,8-PeCDD. This pattern was less pronounced in the gelatine incident, clearly indicating a different source. The actual source and site of the contamination was never discovered.

4. Conclusions

The list of examples presented in the current paper is by no means exhaustive, but does cover the major incidents of food and feed contamination with PCDD/Fs and PCBs that have occurred over the last few decades, and should provide a good initial source of information for
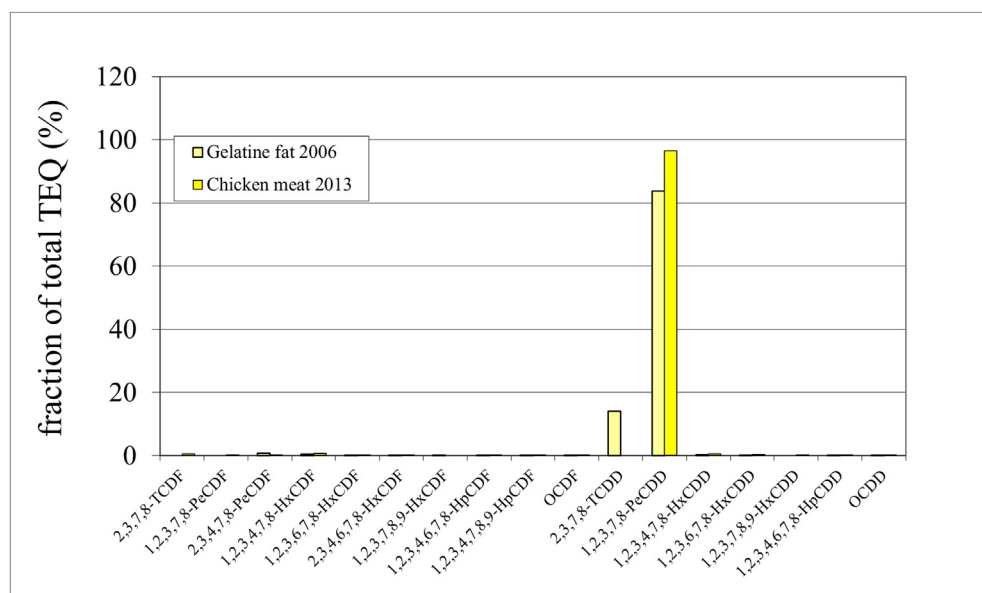

Fig. 7. Congener patterns for PCDD/Fs (contribution to TEQ) in fat derived from gelatine production using contaminated HCl, and in chicken meat samples from Chile (source unknown).
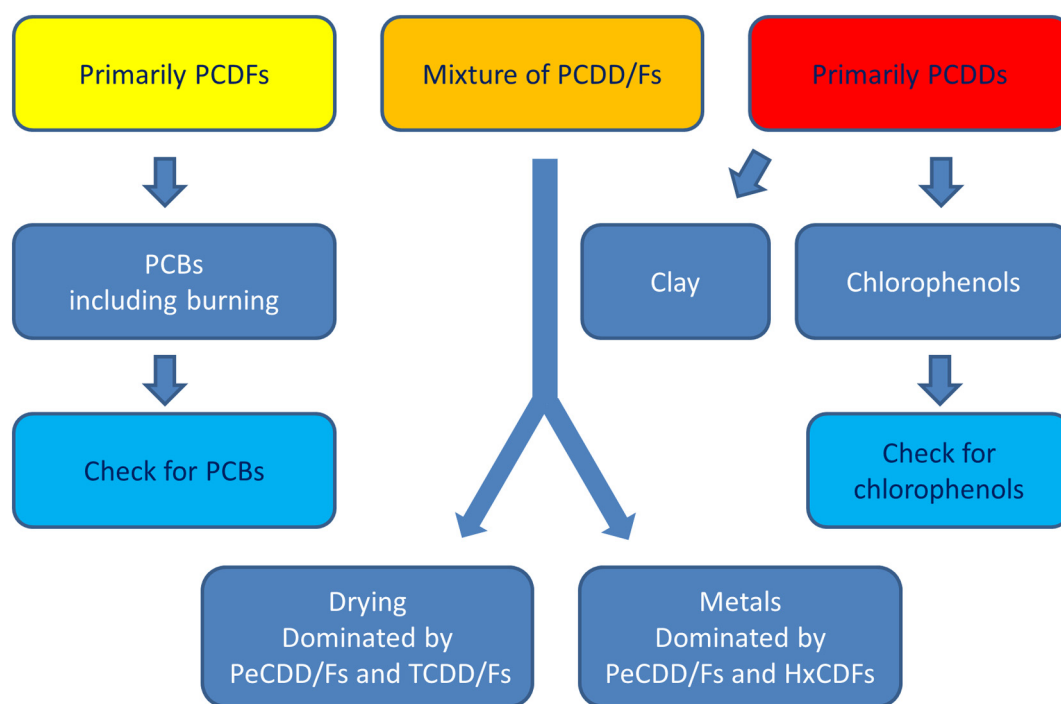
Fig. 8. Decision tree for pointing out the most likely source of the PCDD/Fs discovered in a sample, based on the TEQ contribution.

analytical chemists, regulators, risk assessors and managers. The specific congener patterns that arise from PCDD/F and PCB contamination incidents, in some cases at least, appear to re-occur with a similarity that may make them amenable to elucidation from earlier recorded data. Even where not completely matched, similarities in the patterns may provide a useful clue to the source. The strong predominance of PCDFs e.g. indicates some form of PCB mixture as the source (either processed – as in the case of the Irish incident, or directly as in the case of the rice oil and Belgian incidents) (Fig. 8). The presence of mainly PCDDs points to either certain clay materials or chlorophenols, with higher chlorinated PCDDs indicating PCP as the source. A more mixed pattern indicates either burning of waste materials (including painted wood), or metal containing minerals (e.g. recycled zinc oxide). Although similar, there are still some differences between these patterns that might help to discriminate them. Some patterns observed could thus far not be linked to a specific source.

When attempting to elucidate the source of contaminants, it is also important to understand the potential transformation of congener patterns from the original source to the targeted food. This transformation is an integration of the initial weathering process within the environment, followed by uptake and metabolism by the animal. The potential uptake by the plant crop used as feed may act as an intermediate, although this seems limited. The resulting transformation may be described by transfer rates (TRs) or bioconcentration factors (BCFs) which could be used in conjunction with the observed patterns, and this will be the subject of further work on this topic. Source identification could be improved by the inclusion of data on other congeners, such as non-2,3,7,8-substituted PCDD/Fs, regulated PCBs and in particular, other PCB congeners, some of which are similarly persistent in animal tissues (e.g. PCB-99). These data are produced but often lost, due to non-reporting, as the congeners are not part of a regulatory limits. If data on other contaminants were available, this could also be included.

A database containing the various patterns and allowing a quick comparison with levels of concern in new samples would be helpful and is under development (Malisch et al., 2017). At this stage an Excel sheet that allows a rapid visual comparison of an analytical result with known patterns is available at WFSR. Future work will also be directed towards a decision support tool to speed up the comparison of patterns and identification of sources.

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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2020.141098.

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