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Review

Determination of organochlorine pesticide residues in fatty foods: A critical review on the analytical methods and their testing capabilities

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ABSTRACT

Organochlorine pesticide (OCP) residues in foods have been of concern for several decades. However, the analysis of some of the OCPs and their metabolites or derivatives, such as endrin aldehyde, endrin ketone, nonachlor, etc. in fatty foods (including foods of animal and plant origin), was not commonly included in routine monitoring programme. Recently, the Stockholm Convention introduced nine plus one new persistent organic pollutants (POPs) that included chlordecone and some other OCPs. Is there a method available that can analyze both traditional OCPs, together with their metabolites and derivatives in fatty foods? Furthermore, is there a suitable method that can monitor OCPs and the newly added POPs including chlordecone in fatty foods together in a pot? This review aims to provide some background information to answer these questions.

Contents

1. Introduction

Organochlorine pesticides (OCPs) were intensively used in agriculture to protect cultivated plants in mid-twentieth century. The use of pesticides in the USA doubled from 1960 to 1980. 1,1,1-Trichloro-2,2-bis(4-chlorophenyl)ethane (DDT), one of the common OCPs, was used to prevent spreading of malaria and other vector-borne diseases such as dengue, leishmaniasis and Japanese encephalitis through the prevention of growth of mosquito. Lindane, another example of the most widely used OCPs, had been used to treat head lice in children [1].

After OCPs were used widely in soil and plants for some years and due to their relative stability and bioaccumulation property, these persistent chemicals can be transferred and magnified to higher trophic levels through the food chain. Consequently, OCP residues are present in fatty foods, both foods of animal origin, such as meat, poultry, fish, eggs, and milk, and of plant origin, such as

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vegetable oil, nuts, avocado, sesame, oat and olives. Besides, these chemicals are widely distributed in the environment, which provides another route of unwanted intake in human. Nevertheless, human exposure occurs still primarily via low level food contamination. Since their mode of action is by targeting systems or enzymes in the pests which may be identical or very similar to systems or enzymes in human beings, these OCPs pose risks to human health [1] and the environment. Thus, monitoring of OCP residues in foods becomes a routine analysis of pesticides monitoring laboratories.

All US government pesticide residue datasets showed that persistent OCP residues were surprisingly common in certain foods despite being off the market for over 30 years [1]. Residues of dieldrin, in particular, posed substantial risks in certain root crops. About one quarter of the samples of organically labelled fresh produce contained pesticide residues, compared with about three quarters of conventional samples. Among the contaminated organic vegetable samples, about 60% of them were contaminated with OCPs [1].

The US Food and Drug Administration (FDA) categorize foods having ≥2% fat composition as fatty food, and non-fat foods as having <2% fat [2]. In 2005, Lehotay of USDA further explained in an article that foods divided into non-fat (<2% fat), low-fat (2–20%), and high-fat (>20%), the fat content being calculated on a wet weight basis [2]. According to Codex's classification, foods of animal origin would include edible offal, animal fat, milk, meat, eggs, and fish. After some OCPs were banned for use since the 80s, common daily food items such as eggs, milk, poultry, meat and fish have been used for monitoring the residual levels of OCPs. As regards food of animal origin, one efficient way to avoid large-scale contamination is to control and monitor the level of OCP residues present in animal feeds before being fed to the husbandry animals. At the same time, public health safety authorities should constantly monitor the OCP residue levels in animal food commodities as the major source of human background exposure to OCPs is through food of animal origin.

Most persistent organic pollutants (POPs) are OCPs, namely, aldrin, endrin, chlordane, DDT, heptachlor, mirex, toxaphene and hexachlorobenzene (HCB). They have been banned for agricultural or domestic uses in Europe, North America and many countries of South America in accordance with the Stockholm Convention in 1980s [3]. However, some OCPs are still used – e.g. DDT is used to control the growth of mosquito that spread malaria or as antifouling agent in some developing countries [3]. Besides, the most commonly used acaricide, dicofol, is made of DDT, its formulated products always contain small amount of DDT [4]. Residues of OCPs have been detected in breast milk (including DDT, HCB and HCH isomers) in contaminated areas. Recently, the scope of POPs was extended to include nine plus one chemicals. Among these new POPs, chlordecone, lindane (γ-hexachlorocyclohexane, γ-HCH), α-HCH, β-HCH, pentachlorobenzene (PeCB) and endosulfan, also belong to OCPs. In order to fulfil the requirements of the Stockholm Convention, the participating countries have to develop their own implementation plan to monitor the background level and collate exposure data. For the new pesticides in POPs, the HCH isomers have been commonly monitored, but not for chlordecone and PeCB.

During recent years, much research has been focused on the new POPs in the environment, food and human. Bocquene and Franco [5] reported that chlordecone was detected in nearly every water and sediment sample collected along the coastline of a Caribbean island called Martinique even after its ban for almost a decade. Contamination of river waters by chlordecone reflected the presence of residual levels of this compound in treated soils.

There are different reviews available which discuss different analytical aspects of fatty foods. For example, Molina-Díaz et al. [6] presented the development of multi-residue methods for the determination of pesticides in a new scope of matrix, fatty vegetables (i.e. edible oils and other fatty vegetables). They addressed the complicating issue of separation of pesticides and other chemical contaminants from high-fat vegetable matrices prior to subsequent steps in the analytical procedure. Another recent article written by LeDoux [7] reviewed published methods and research articles of the last two decades on the analysis of pesticides in foods of animal origin. Although a number of different classes of pesticides have been discussed in these review articles, limited information quoted therein had particular focus on OCPs.

In this review, the major focus is put on OCPs in all kinds of fatty foods, including both of animal and of plant origins. It will review the methodologies involved and explores all aspects in the methods developed for analyzing OCPs in fatty food matrices, including the advantages and disadvantages of different sample extraction, clean-up, instrumentation, performance criteria, etc., so that the readers could make an intelligent and informed choice based on their own equipment and the particular analytes and food matrices at hand. Besides, we aimed to provide background information whether all enlisted OCPs in the 22 POPs could be determined in fatty foods together with other traditional OCPs.

2. Definition of OCP residues

For monitoring purpose, maximum residue limit (MRL) would be set for a particular pesticide in a particular food matrix. Moreover, Codex has established extraneous maximum residue limits (EMRLs) for some of the OCP residues in foods. The EMRL refers to the maximum pesticide residue level arising from environmental sources (including former agricultural uses) other than the use of the pesticide directly or indirectly on the commodity itself. It is the maximum concentration of a pesticide residue that is recommended by the Codex Alimentarius Commission to be legally permitted or recognised as acceptable in or on a food, agricultural commodity or animal feed and is temporary, irrespective of the status of the Acceptable Daily Intake (ADI), until required information has been provided and evaluated.

Apart from MRL/EMRL which has to be considered before developing an appropriate method for routine monitoring, the residue definition has to be kept in mind. Table 1 summarizes the definitions of OCPs that have Codex's MRL/EMRL. However, some of the residue(s) have not been included in the list of monitoring chemicals of the Global Environment Monitoring System – Food Contamination Monitoring and Assessment Programme (GEMS/Food) of World Health Organization, especially in animal commodities. This may be a reason why only a limited number of laboratories would follow Codex's definition to monitor OCPs in foods.

3. Acid stability of OCPs

In order to remove fatty co-extracted interferents during cleanup stage, sulphuric acid treatment is a common technique employed. Although some OCPs are classified as persistent organic chemicals, it is noteworthy that some of them are not resistant to sulphuric acid treatment [8,9]. Some OCPs could be sulphonized completely upon contact with concentrated sulphuric acid. These sulphuric acid-sensitive OCPs include dieldrin, endrin, endrin aldehyde, chlordecone, endosulfan I, endosulfan II, *trans*-heptachlor epoxide and dicofol. In particular, dieldrin and endrin are the most sensitive and would degrade within a few minutes upon treatment of concentrated sulphuric acid. The other acid-labile OCPs would also degrade to different degrees within an hour. This explains why only limited monitoring data on these sulphuric acid-sensitive

Table 1
Summary of Codex definition of OCPs and targeted OCPs listed in GEMS/Food chemical list.

OCP	Codex residue definition	GEMS/Food monitoring targets	Codex MRL/EMRL (mg/kg on fat basis)		
			Milk	Meat	Poultry meat
Aldrin and Dieldrin	Sum of HHDN (aldrin) and HEOD (dieldrin)	Aldrin and dieldrin	0.006	0.2	0.2
Chlordane	Plant commodities: sum of cis- and trans-chlordane (fat-soluble) Animal commodities: sum of cis- and trans-chlordane and "oxychlordane"	Chlordane (α- and γ-, trans-nonachlor + oxychlordane)	0.002	0.05	0.5
DDT	Sum of p,p′-DDT, o,p′-DDT, p,p′-DDE and p,p′-TDE (DDD)	Sum of p,p′-DDT, o,p′-DDT, p,p′-DDE and p,p′-TDE (DDD)	0.02	5	0.3
Dicofol	Plant commodities: Dicofol (sum of o,p′ & p,p′ isomers) (fat-soluble) Animal commodities: Sum of dicofol and 2,2-dichloro-1,1-bis(4-chlorophenyl)ethanol (p,p′-FW152) calculated as dicofol	Dicofol (sum of o,p′ and p,p′ isomers)	0.1	3[a]	0.1
Endosulfan	For compliance with the MRL and for estimation of the dietary intake: sum of alpha-endosulfan, beta-endosulfan and endosulfan sulphate. This definition applies to plant and animal commodities	Endosulfan (sum of α- and β-isomers)	0.01[b]	0.2	0.03
Endrin	Sum of endrin and delta-keto-endrin	Endrin (sum of α- and β-isomers)	–	–	0.1
Heptachlor	Sum of heptachlor and heptachlor epoxide	Sum of heptachlor and heptachlor epoxide	0.006	0.2	0.2

[a] Cattle meat.
[b] On whole weight basis.

OCPs were collected around the world. Nevertheless, most OCPs have been found to be relatively stable in the presence of weak acid of low concentration.

4. Extraction methods

The selection of suitable solvent(s) and extraction method is critical for obtaining satisfactory recovery of OCPs from the food matrix. Of course, if co-extracted materials are minimized in the extract, the cleanup procedure would become simpler. Owing to the lipophilicity of OCPs, organic solvent(s) normally can extract OCPs from food efficiently but lipids are also co-extracted. In 1963, Mills et al. [10] used acetonitrile (MeCN) for extraction and liquid–liquid partitioning between MeCN–water mixture and petroleum ether. OCPs, non-polar in nature, were transferred to the petroleum ether phase for subsequent gas chromatographic (GC) determination. In 1970s, the Luke's method [11] was developed to extract residues of both OCP and organophosphorus pesticide (OPP) residues from food matrix. Sample was extracted with acetone and then both salt and non-polar solvent (dichloromethane (DCM), DCM-petroleum ether or cyclohexane-ethyl acetate) were added to induce phase separation of the acetone–water mixture. This type of solid–liquid extraction method was applicable for extracting OCPs from various types of food samples including vegetables, meat and its products [12,13], fish [14,15], eggs [16,17] and animal fats [18]. For liquid milk, liquid–liquid extraction is still the preferred method for extracting OCPs [18,19].

Several standardized methods, including AOAC 970.52, EN 1528 and EN 12393, have employed such solid–liquid or liquid–liquid extraction techniques for the determination of OCPs in both fatty and non-fatty foods. In some occasions, sonication [20,21] or Polytron® [22] was also applied to improve the extraction efficiency and recoveries. In general, solid–liquid extraction is an efficient extraction technique for OCPs except for those volatile compounds, such as HCB [12], which may be lost during solvent evaporation. However, the analysis is considered expensive and not environmentally friendly in terms of large volume of organic solvent(s) used. Furthermore, the process is labour-intensive and time-consuming and cannot be automated.

During solid–liquid or liquid–liquid extraction, it is quite common to add salts into the solution so that organic phase can be separated from aqueous phase more easily. Since 1980s, salting out effect with different salts or hydrophobic solvents has been applied in analysis of pesticides in food samples [23,24]. In 2003, Anastassiades et al. proposed a multiresidues method for analysis of pesticides in fruits and vegetables, which was called QuEChERS [25]. This procedure involves initial single-phase extraction with MeCN followed by salting-out extraction/partitioning by addition of $MgSO_4$ plus NaCl. The authors reported that using $MgSO_4$ alone gave the highest recoveries for the polar pesticides but resulted in poor selectivity because a large amount of water remained in the MeCN phase. The use of NaCl could result in less water in the MeCN phase and decrease the co-extraction of polar matrix components. This provided another benefit of salting out effect. Up till present, QuEChERS has only demonstrated its good performance in determining a few OCPs in mainly non-fatty food such as fruits and vegetables.

Recently, application of this extraction approach has also been experimented in other food types of higher fat contents. Cunha et al. have evaluated the QuEChERS sample preparation approach for the analysis of pesticide residues in olives and olive oil [26]. In that article, a direct sample introduction device was employed in GC–MS analysis to avoid nonvolatile coextractives from contaminating the instrument. However, among the 16 pesticide analytes studied, only one OCP, namely p,p′-DDE was included. This indicates that the application of QuEChERS for the extraction of lipid-soluble analytes from fatty matrices awaits further development.

Soxhlet extraction is another traditional techniques used for extracting OCPs from meat [17,27–29], fish [29–33] and eggs [27]. Here, less solvent(s) is required. The drawbacks are that it is time-consuming with normally 12–20 h of extraction, and recoveries of a few pesticides were reported to be below 70% [22].

In recent years, there are other different fast techniques developed for the extraction of OCPs in food. Supercritical fluid extraction (SFE) has been attempted by several researchers as SFE has the advantage of efficiency, selectivity, short extraction time and low solvent volume [34–36]. However, SFE extraction is difficult to optimize for different matrices [37]. Large amount of fatty substances could completely clog the solid-phase trap of certain models [38]. Moreover, large amount of unwanted matrix substances are also co-extracted and some unstable OCPs such as endrin ketone and chlordecone cannot be recovered under the high extraction temperature used. To improve the extraction effectiveness, solvent modifier could be added to overcome analyte–matrix interactions.

For samples of high lipids content, fluoroform had also been used as the extractant [39]. Further, additional cleanup steps could be incorporated with the SFE procedure either by on-line sorbents (e.g. alumina, silica) in the extraction vessel, or by off-line SPE trapping column [36]. Snyder et al. compared the extraction efficacies of SFE and conventional solvent extraction [40], their results indicated that recoveries of OCPs from chicken tissues obtained by SFE were equivalent to those by conventional solvent extraction. Moreover, recoveries by SFE of the liver tissue were higher than those obtained by solvent extraction. This was explained by the superior mass transport property exhibited by supercritical fluids against conventional organic solvents.

Pressurized liquid extraction (PLE) is another fast extraction technique which uses a high-temperature and pressurized liquid extraction conditions to extract the target analytes. PLE has been applied to analyze OCPs in animal internal organs, muscles as well as fish [22,41–43]. The efficiency of PLE is normally higher when compared to other extraction techniques, especially Soxhlet [42]. Research had been conducted to optimize the effects of extraction temperature, number of extraction cycles and various extraction solvent mixture compositions on the extraction effectiveness and recoveries of certain OCPs from fish samples [42]. Besides, cleanup sorbent material(s) can also be imbedded in the extraction cells so that cleanup can also be processed simultaneously with extraction. Though it has the advantages of low solvent consumption and short extraction period, the initial cost is high, large amount of unwanted matrix substances are co-extracted and some unstable OCPs including endrin [35], endrin aldehyde [41] and PeCB [41] yielded low recoveries.

Microwave-assisted extraction (MAE) is another recent technique that can also be applied for extracting OCPs from food [43–46]. By applying microwave energy to the extraction solvent, the highly localized temperature and pressure cause heating of the matrix and migration of target analytes from the sample material to the surrounding solvent rapidly. Both focused open-vessel and closed-vessel MAE have been assayed and compared with the PLE method. The three approaches gave similar results in terms of recovery, but closed-vessel MAE is less convenient for samples with high water content [43]. However, Barriada-Pereira et al. also showed that endrin aldehyde could not be fully recovered, although its recovery was already improved when compared with PLE [47]. Similar to PLE, research had also been conducted to investigate the effects of extraction temperature, extraction time and various extraction solvent mixture compositions on the extraction effectiveness and recoveries of certain OCPs from fish samples [46].

Matrix solid-phase dispersion (MSPD) is based on the solid phase dispersion of the sample matrix for the subsequent isolation of various analytes [48]. By blending a liquid [49–52] or solid food sample [53–56] with irregular shaped particles (silica- or polymer-based solid support) with lipids solubilising capacity of a support-bound polymer (octadecylsilyl (C_{18}) [53–55] or other materials [51,52,56]), a semi-dry material is obtained. It is used as a pre-column packing from which OCPs can be isolated by elution with organic solvents of different elution powers and polarities. The main advantages of this technique are that it is simple and rapid, and it allows several steps to be performed in the sample preparation simultaneously. MSPD is applicable to most food samples regardless of the contents of water and lipids. It is suitable for solid, semi-solid and viscous sample matrices, which might cause problem in other sample preparation procedures [48]. It can be easily adapted and modified for any multiresidue isolation from food.

Since MSPD involves the dynamic interactions of solid support, bonded phase, sample matrix, analytes and eluting solvent, the success of this kind of extraction can only be attained through trials and errors. For instance, in using C_{18} as the MSPD sorbent for the simultaneous extraction of OCPs and OPPs from milk, Schenck and Wagner [51] discovered that C_{18} must be moistened with methanol prior to the addition of milk. However, washing C_{18} with water or petroleum ether after wetting with methanol would result in very low recoveries (<20%) for OCP residues. On the contrary, the addition of some MeCN to the C_{18}/milk mixture would improve the recoveries of OCPs by about 20%, while having no effect on OPPs. It was believed that MeCN could disrupt the binding between the lipophilic OCPs and fat globules that existed in the cream phase of the milk.

Generally speaking, except for SFE, PLE and MAE which cannot extract endrin, endrin aldehyde and/or chlordecone with satisfactory recoveries, other techniques are likely suitable for the purpose of extracting most OCPs including their metabolites/derivatives as well as those OCPs listed under the new POPs.

5. Cleanup methods

The success of the analysis of OCPs in fatty food critically relies on the efficiency of the cleanup step(s), especially when mass spectrometric technique is not used for quantitation. Even though 60-meter capillary GC column is quite commonly used for separating co-extracted materials from the target analytes, overlapping of co-extracted substances with analytes cannot be easily avoided, especially for foods of complexed matrices. Besides, these co-extracted substances might induce matrix enhancement/suppression effect and shorten the lifetime of the GC column. Since OCPs are fat soluble, other fatty substances would be co-extracted from the sample at the same time. These fatty substances are highly soluble in organic solvent and tend to absorb in the GC system resulting in poor chromatographic performance. Therefore, lipids removal is a must and is normally the first cleanup step for fatty foods sample preparation.

5.1. Removal of lipids

The simplest approach to remove the fatty co-extracted interferents is by freezing centrifugation. The logic behind is that fatty substances (mainly lipids) have lower melting points than the solvent so that frozen lipids can be removed by centrifugation or filtering while OCPs remain dissolved in the solvent. Different freezing temperatures ranged from −24 to −70 °C have been used [20,57]. However, the solubility of lipids in solvent not only depends on the temperature but also the solubility product, Ksp. Therefore, this technique can remove significant amount of lipids for some food matrix but not for every matrix. Certain amount of lipids would remain in the solvent after the freezing centrifugation step and hence further cleanup is required.

Another simple approach is by partitioning between different organic solvents. Argauer et al. [38] extracted OCP residues from milk with an acetone–MeCN mixture and then partitioned the extract with DCM. Practically speaking, since OCPs are also slightly soluble in polar solvent loss of OCPs and thus lower recovery is expected. Therefore, limited number of publications could be found for analyzing OCPs using solvent partitioning as lipids removal approach.

Using materials with large surface area for absorption of lipids have been employed since early 1970s. These materials include, Florisil®, Lipid Removal Agent (LRA) media from Supelco, micro Cel-E and Calflo E® from Johns-Manville. Micro Cel-E [58], Calflo E® [59] and LRA media [60] are synthetic calcium silicate while Florisil® [61,62] is magnesium silicate with high specific surface area. They can be applied to remove lipids either in sample preparation, solid phase extraction step or during sample cleanup step, with minimal adverse effect on non-lipid chemicals. When food sample is mixed with these lipids absorbing materials, edible fat could be removed.

After gel permeation chromatography (GPC) was applied to the cleanup of OCP residues analysis in late 1970s, this technique almost became the most frequently employed and unavoidable step for lipids removal of fatty foods [15,22,63]. This technique separated low molecular mass (up to several hundreds) compounds such as OCPs from high molecular mass compounds such as lipids of 600–1500 mass units. If applied properly and without exceeding the maximum loading of the GPC column (e.g. about 500 mg of lipids per run), the residual lipids remained after GPC cleanup normally falls less than 1% of the initial amount. Most authors used Bio-beads SX-3® column of 200–400 mesh as the GPC phase for OCPs analysis. Envirogel® and Envirosep-ABC® GPC packed columns have also been used in meat products. The advantage is that the runtime could be reduced to half of Bio-beads SX-3® column.

In brief, if treatment of concentrated sulphuric acid is not used for lipids removal, the targeted OCPs would likely survive after the fat removal step using any of the above-mentioned approaches, albeit with probably less clean sample extract as the sulphuric acid-treated one.

5.2. Solid-phase cleanup

None of the above-mentioned approaches can completely remove lipids from the extract of fatty foods. Besides, other interfering co-extracted substances could not be removed by the lipids removal procedure. Therefore, it is common to conduct a second cleanup step by solid-phase extraction (SPE) nowadays. Both conventional glass column packed with sorbent(s) and ready-to-use cartridges have been utilized and the common used phases are silica, Florisil®, alumina and C_{18}-bounded silica.

Ghidini et al. [18] used Florisil® or GPC as the second cleanup step for liquid milk after extraction by MSPD with Chem Elut® as solid support. Similarly, Schenck and Wagner [51] advised that Florisil® cartridge cleanup was required when MSPD extraction was used for extraction of OCPs from liquid milk. Doong and Lee [29] compared the cleaning efficiency of ready-to-use cartridge filled with three different adsorbents for shellfish extract. Their results demonstrated that out of the 14 OCPs tested, two were retained in the C_{18}-cartridge. As for alumina and Florisil® SPE, though all 14 tested OCPs could be recovered, Florisil® provided better results in terms of recoveries, repeatability and removal of interfering substances. Similarly, Hong et al. [20] also showed that Florisil® had better cleaning efficiency of fatty acids in fish extract when compared with C_{18}. Besides, recoveries of some OCPs were poor with hexane as eluent and these more polar OCPs could be eluted out from the column with acetone.

Yagüe et al. developed a multiresidue method to analyze 22 OCPs in liquid milk based on MSPD extraction and neutral alumina SPE cleanup [49]. Average recoveries were between 74 and 106% for all analytes, except β-HCH, β-endosulfan and endosulfan sulphate, which were believed to retain on the alumina cleanup column. Although the recoveries for these three OCPs were improved a little by increasing the degree of inactivation of alumina from 2% up to 8%, the recoveries were still not considered satisfactory without sacrificing the cleanup power of the alumina column. This same situation was encountered again in Yagüe et al.'s another article describing a multiresidue method for the analysis of 19 OCPs in yoghurt [50]. The neutral alumina cleanup employed significantly diminished recoveries of dieldrin and a-endosulfan (<60%), and did not allow recoveries of β-HCH and β-endosulfan.

To extend the SPE cleanup concept further, combining two or more columns of different adsorbents in series has been used for maximizing the recoveries of OCPs while minimizing matrix co-extractive. Wang et al. used silica gel and activated carbon to separate OCPs from polychlorinated naphthalenes. Long et al. [54,55] used a combination of C_{18} and Florisil® to cleanup the extract from milk with MeCN as the elution solvent. Stefanelli et al. [12] combined Extrelut NT3, C_{18}-bonded silica and Florisil® to cleanup the extract before GC–MS analysis.

Schenck et al. [52] evaluated Florisil® solid-phase extraction cartridges for cleanup of 24 OCP residues in food extracts, in terms of elution patterns and recoveries. A range of elution solvents was evaluated. A 2% ethyl ether-petroleum ether eluant gave the optimized overall recoveries while minimizing interferences from co-extractants. Bazulic et al. [64] reported that the quality of Florisil® was important in avoiding possible interference and misinterpretation of results. Even though GC–MS was employed as the detection system, poor quality Florisil® could introduce false positive results for lindane and dieldrin. Recently, Beyer and Biziuk have evaluated the efficiency of different sorbents used during clean-up of extracts of OCPs in low fat food [65]. The Florisil, alumina and NH_2 columns were found to provide the most effective cleanup, removing the greatest amount of interfering substances, and simultaneously ensuring analyte recoveries higher than 70% for most compounds. Though combination of common additional SPE columns provided benefit in effectiveness of cleanup, it also increases the cost of analysis and solvent consumption.

Instead of using ready-to-use cartridges, Rosenblum et al. [66] used diatomaceous earth as solid support to prevent the formation of emulsions during cleanup of the extract of composite diet food sample. After Soxhlet extraction and alumina column cleanup, the extract was analyzed by temperature-programmable large-volume injector with pre-separation column. This set-up allowed splitless transfer of target analytes to the analytical GC column and purged 99% of high molecular weight interferents. Hence, a cleaner baseline was obtained in the late-eluting region and maintenance of the GC column could be minimized.

In QuEChERS procedure, dispersive SPE is used in the cleanup step [25]. Here, different sorbent powders such as C_{18}, PSA and GCB are added into the initial sample extract solution to remove the interferents. After shaking and/or vortexing, and subsequent centrifugation, the supernatant could be subject to instrumental analysis. Though the dispersive SPE procedure is easy and fast, it is less effective to remove interfering compounds when compared to SPE. Moreover, when GCB is used as one of the cleanup sorbent material, the recoveries of HCB and PeCB would generally be reduced, unless toluene is added in the sample extract medium or in the eluent [67].

Another simple cleanup approach called disposable pipette extraction (DPX) has also been applied in pesticide residues analysis, sometimes in an automated set up. Guan et al. [68] reported the use of disposable pipette extraction (DPX) for rapid cleanup followed by GC–MS to analyze OCP residues in corn muffin mix and cocoa beans. The DPX method in this study was based on the weak anion exchange (WAX) mechanism to remove the major sample matrix interferent, i.e. fatty acids, from the chromatographic analyses. There are now several kinds of DPX products available, including RP, CX and WAX. Among these, WAX was claimed to be suitable for the determination of OCPs in fatty food.

A two-pronged approach was adopted by Zhu [33] to cleanup sample extract depending on the susceptibility of the OCPs of concern to acid and base. In their method, an extract containing acid-stable OCPs was cleaned up by a sulphuric acid-impregnated silica column, whereas an extract containing non-acid stable OCPs was cleaned up by a 3-in-1 column (composing of silica, alumina and Florisil materials) impregnated with 15% potassium hydroxide-methanolic solution.

In addition, cleanup using reverse phase liquid chromatography (LC) [69] or normal phase HPLC (NPLC) [70] has been reported. In the latter case, fat was dissolved in n-hexane and fractionated on silica gel HPLC using DCM/hexane as solvent. Recently, Diaz-Plaza

et al. reported on-line coupling of reversed phase liquid chromatography and gas chromatography using the through oven transfer adsorption–desorption interface with subsequent electron-capture detector to determine OCP residues in olive oil [71].

Attempts had also been conducted to combine extraction, enrichment and sample introduction into one single step by using "solid phase micro-extraction (SPME)". Although moderate success was achieved in the application on certain food matrices, extraction efficiencies were found to drop drastically (from more than 70% to less than 40%) when the lipids content of the samples was increased [32]. This demonstrated that the matrix and thus lipids content of the sample extract in the sample vial would have significant effect on the adsorption dynamics of the OCP compounds to the SPME fiber.

To sum up, the combination of sorbent(s) and eluting solvent(s) have to be chosen very carefully. Otherwise, some OCPs or their metabolites/derivatives would be lost during the cleanup step. These OCPs could either break down or adhere to the sorbent material, leading to low or even no recovery. Finding of the optimal cleanup conditions is an art itself. As the targeted OCPs might cover a wide range of polarities, it is quite difficult to find the best combination of SPE column material and eluting solvent, which permits recovering the polar OCPs (but leaving the polar interferents behind on the column), as well as recovering the non-polar OCPs (without eluting any residual oil present in the extract from the column).

6. Separation and detection techniques

6.1. GC separation

As most of the OCPs are non-polar in nature and easily vaporized, GC is the most common technique for chromatographic separation. Nowadays, capillary column instead of packed column is normally used. Stationary phase including 100% dimethylpolysiloxane, methylpolysiloxane containing 5, 35 or 50% phenylpolysiloxane or 14 or 50% cyanopropylphenylpolysiloxane have been used for the separation of OCPs.

However, overlapping of peaks may occur if the number of target analytes gets bigger, e.g. more than 20, especially when isomers of BHC, endosulfan I, chlordecone, *trans*-nonachlor and α-chlordane are involved. Previously, column with stationary phase of 14% cyanopropylphenylpolysiloxane (1701) was commonly used as second confirmation column as only α-chlordane, trans-nonachlor, p,p′-DDE, p,p′-DDD and endosulfan II could not be well separated from each other [72]. Rtx-CLPesticides and Stx-CLPesticides columns (by Restec) were introduced in early 2000 which claimed to allow complete separation of around 20 OCPs commonly found in reference standard mix. Recently, another model of capillary columns, Zebron-MultiResidue, i.e. ZB-MR1 and ZB-MR2 (by Phenomenex) claimed to suitable for separation of OCPs was available commercially. It should be emphasized that the choice of a suitable GC column would depend on the list of target OCPs in mind. In any case, GC running conditions have to be optimized.

6.2. GC selective detectors

A number of different selective detectors can be coupled with GC for analyzing OCPs, including electron capture detector (ECD), halogen specific detector (XSD), electrolytic conductivity detector (ELCD) or Hall detector and atomic emission detector (AED).

GC-ECD is the most commonly used detection method with low detection limits. It is particularly useful for detecting halogen-containing molecules. However, other organic molecules, such as aromatic compounds, would also give positive signal. Users have to confirm the presence of OCPs by another confirmative technique. Unlike other detectors, ECD contains a radioactive source (normally ^{63}Ni) to ionize the analytes.

For ELCD, OCPs eluting from a GC column form combustion products as they are mixed with hydrogen gas over a nickel catalyst at around 1000 °C in a quartz tube furnace. Hydrogen chloride (HCl) is formed. The hydrogen gas stream containing HCl is diverted into a flowing stream of liquid, often propanol. HCl readily ionizes in the liquid, the electrolyte solvent, and changes in its electrolytic conductivity are measured by the ELCD. Therefore, ELCD is a more selective detector but with around an order less in sensitivity when compared with ECD. A number of different researchers have applied such detector for the determination of OCPs in food [73,74].

XSD runs in different principles with ELCD and its operating principle is based mainly on halogen-induced thermal electron emission. OCPs eluting from a GC column are mixed with oxygen gas at 800–1000 °C in a tube furnace. These OCPs are then converted into their oxidation products through combustion. When these halogen-containing compounds enter the detector, the current increases and a signal is registered. Therefore, XSD is also a halogen selective detector. XSD has a key advantage over ECD with respect to selectivity. Although it possesses worse sensitivity for OCPs than ECD, it sometimes achieves lower detection limits in real samples due to reduced chemical noise from the matrix [75]. However, in general, due to the drifting baseline and interferences, XSD gives highly variable quality of results depending on the analyte of interest. The linear dynamic range is comparatively less than other detectors. Both ELCD [73,74] and XSD [75] produce molar response to chlorine in principle and have been used for organohalogen pesticide analysis.

The strength of the AED lies in the detector's ability to simultaneously determine the atomic emissions of several elements in analytes that elute from a GC capillary column (eluants). As eluants come off the capillary column, they are fed into a microwave powered plasma (or discharge) cavity where the compounds are destroyed and their atoms are excited by the energy of the plasma. The light that is emitted by the excited particles is separated into individual lines via a photodiode array. The associated computer then sorts out the individual emission lines and can produce chromatograms made up of peaks from eluants that contain only a specific element. Thus, AED is another selective GC detector for OCPs at sub part-per-million level [76–78].

Ting and Kho [78] commented that AED is easy to perform, simple to maintain, and its chromatograms can be interpreted by analysts without much prior training. The detection technique's capability of acquiring multi-elements selectively and accurately renders AED a powerful alternative method for qualitative confirmation in OCP analysis. As for quantitative determination, recovery studies showed that satisfactory results were obtainable except for certain sample matrices such as citrus fruits [78] and other notorious problematic matrices like onion, garlic and leek, that have sulphur-containing volatiles [79]. In theory, signal responses of AED should be independent of the molecular structures, and therefore, quantitation can be simplified by the use of universal calibration. However, on a practical level, the signal responses are affected to some extent by the molecular structure and any interpretation should be carried out with caution.

6.3. GC mass spectrometric detection

Even though the above-mentioned selective detector can be used for quantification, it is unlikely to fulfil the European Commission's stringent requirements as set for pesticide analysis. Confirmation with GC-hyphenated with mass spectrometric (MS) detector is normally required. Single quadrupole MS detector running in electron ionization (EI) mode with target analytes monitored by selective ion monitoring (SIM) becomes a routine

monitoring tool for OCPs nowadays [12,13,20,66]. Argauer et al. [80] quantified a number of OCPs and pyrethroids with ion-trap MS. Since some of the OCPs are electronegative in nature, GC–MS detector under negative chemical ionization mode with methane as reagent gas could provide better sensitivity [41].

To further increase confidence in confirmative analysis, GC coupled with tandem MS is one of the suitable techniques. Besides providing a more definitive detection tool, tandem MS also decreases matrix interferences, improves selectivity and achieves higher signal-to-noise ratio and subsequently improves the detection limit. Both tandem-in-time (ion-trap) [80] and tandem-in-space (triple quadrupoles) [15,22,81] detectors have been applied for OCP residues analysis in different matrices.

6.4. Two-dimensional GC separation

Two-dimensional or comprehensive GC (GC × GC) involves the separation of target analytes by two orthogonal capillary columns in which the second column is normally of much smaller diameter and shorter in length. The resulting peaks are much sharper with smaller peak width and higher in peak intensity. Besides, the co-eluting peaks from the first column could be separated by the second column. In addition, it also offers enhancement in sensitivity of around one order in terms of peak height. GC × GC coupled to time-of-flight MS [82,83] or other detectors [84] has been applied to pesticide residues analysis in food. To obtain the best separation of all the OCP analytes, the GC × GC conditions have to be optimized by varying the modulation period and the hot/cold-pulse duration [83].

Khummueng et al. demonstrated the use of GC × GC with dual detectors (NPD and ECD) to analyze 41 pesticide residues. Here, identification was based on the comparison of the retention times of two detectors, as well as the relative response ratio of the signals obtained in the two different detector channels, with those of the standards [84].

6.5. LC separation

There are limited reports on the separation of OCPs using liquid chromatography (LC). In 1976, Dolphin et al. first reported the use of the combination of LC with a normal phase partisil column with n-hexane as mobile phase and electron capture detector to analyze OCPs in milk [85]. Till 1997, Bauza et al. reported similar finding of separating DDT isomers with a nitrile column and n-heptane as mobile phase [86]. In 2005, Grice et al. reported the use of a reversed phase C_{18} column with a gradient solvent system of acetonitrile-water and photodiode array detector to determine five OCP residues in medicinal plant samples [87].

6.6. LC mass spectrometric detection

Liquid chromatographic mass spectrometric (LC/MS) system is commonly used for polar, non-volatile and/or thermally labile pesticides. However, OCPs are basically nonpolar compounds and normally not ionized efficiently with atmospheric chemical (APCI) or electrospray ionization (ESI) mode of LC/MS. However, Chusaksri et al. reported that endosulfan, heptachlor and their metabolites could be detected by LC-APCI–MS/MS in negative ionization mode [88] while Famiglini et al. reported that OCPs could also be detected when LC coupled to a direct electron ionization mass spectrometer [89].

The development of atmospheric pressure photoionization (APPI) technology has expanded the range of compounds amenable to LC–MS to include nonpolar compounds [90,91]. Two approaches towards utilizing APPI have emerged: dopant-assisted (DA) APPI [90] and direct APPI [91]. The practical application of DA-APPI has outpaced the development. The charge exchange ionization pathway utilized for nonpolar compounds has only become efficient under restrictive conditions, mainly because the usual charge exchange reagent ions (the dopant photoions themselves) tend to be consumed in proton transfer reactions by solvent and/or dopant neutrals. Osaka et al. [92] have used LC/APPI/MS with toluene as dopant to achieve the simultaneous analysis of HCB and pentachlorophenol at ppb levels and found to be more effective than by APCI as ionization source. Besides, Osaka et al. also showed chlordecone has much better sensitivity in LC-ESI–MS/MS analysis than GC–MS/MS.

Up till present, all OCPs including their metabolites/derivatives can be analyzed by GC coupled with selective detector or MS detector. However, chlordecone has been found to be quite problematic and insensitive, even with NCI mode or GC–MS/MS. Therefore, LC–MS/MS could be considered when sensitivity of detecting chlordecone is critical. Otherwise, most other OCPs should be analyzed simultaneously by gas chromatographic technique.

7. Method performance

Nowadays, methods developed for the determination of pesticide residues would likely to follow the SANCO's "Method Validation and Quality Control Procedures for Pesticide Residues Analysis in Food and Feed" [93] for validation data compilation. Before that, researchers would adopt the single laboratory validation guideline issued by IUPAC [94], AOAC [95], Nordic Committee [96], etc. However, some of the papers published in the old days did not contain sufficient method performance characteristics as required by modern standards. For illustration and ease of reference, some selected methods with details and their method performance characteristics are summarized in Table 2.

Among the method performance characteristics, spike recovery at known level with a blank matrix was always provided. Regarding to the acceptance criteria set in SANCO's procedure [93], the average recovery should be within the range of 70 and 120%. For some multiresidue methods, some of the targeted pesticide residues had low recovery rates. Such loss of OCPs could relate to the effectiveness of extraction, partition coefficients of analytes in the solvents, rate of evaporation together with solvent(s), adsorption properties on cleanup sorbent material(s), thermal stability in the GC injector and liner, and/or matrix enhancement/suppression effect in GC analysis.

Park et al. [57] also attributed the low recoveries for the three DDT metabolites to their high solubilities in n-hexane during the partitioning step. Bennett et al. [19] described the optimization of elution of OCPs from SPE with different solvents and concluded that loss of some pesticides could not be avoided. Stefanelli et al. [12] suspected that the low recovery of HCB was due to its high volatility and loss during solvent evaporation. One possible way to circumvent this is by adding some "high-boiling" solvent into the sample to be concentrated. This could serve as a trapping agent to minimize the loss of those highly volatile OCPs like HCB and PeCB.

DDT and its metabolites show typical examples of degradation in the GC injector. When the injector temperature is higher than 150 °C, these OCPs would start to degrade significantly [66]. Another commonly encountered problematic analyte in OCPs analysis is dicofol. It has been shown that whereas the o,p′-dicofol and p,p′-dichlorobenzophenone could still be detected by GC analysis. The other isomer, namely p,p′-dicofol, found to degrade significantly during GC analysis even the solution was prepared freshly. Hence, this compound is likely degraded at the injector or inside the column.

Garrido-Frenich et al. [81] reported the corrected spike recoveries were close to 100% after matrix-matched calibration was

Table 2
Summary of published methods and their performance characteristics for the determination of OCPs in fatty foods.

Food matrix	OCPs tested	Extraction	Clean-up	Quantification	Recovery	LOQ	Ref.
(a) Bovine milk and dairy products							
Bovine milk	22	MSPD: Si-C_{18} n-Hexane	SPE: Neutral-Alumina column Elute: n-Hexane	GC-ECD Column: Quandrex 007-2 50 m Injector: 210 °C ECD: 300 °C	NR-109%	0.02–0.62 μg/L	[49]
Bovine milk	5	MSPD: C_{18} MeCN	SPE: Florisil® Elute: Pet ether:diethyl ether	GC-ECD Column: DB-608 30 m Injector: 250 °C ECD: 300 °C	76–98%	0.5 ng/g	[51]
Bovine milk	24	MSPD: C_{18} MeCN	SPE: C_{18} Elute: MeCN SPE: Florisil® Elute: Ether:Pet ether (2:98)	GC-ECD Column: DB-5 or DB-1701 30 m Injector: 250 °C ECD: 300 °C	42–94%	n.s.	[52]
Bovine milk	20	LLE: EtOH:EtOAc (9:95) Freezing	SPE: C_{18} Elute: MeCN SPE: Aminopropyl Elute: MeOH:DCM (7:93)	GC-ELCD Column: DB-608 30 m Injector: 230 °C	72–128%	2–3 ng/g	[19]
Milk	22	SLE: Acetone:EtOAc:cyclohexane (2:1:1)	GPC: S-X3 EtOAc:cyclohexane (1:1) SPE: PSA/GCB (500/250 mg) Elute: 75% acetone/toluene	GC × GC-TOFMS Column: VF-5MS 30 m BPX-50 2.2 m Injector: 40–280 °C (prog.) MS: SCAN	43–119%	0.2–1 ng/g	[82]
Dairy products	16	LLE: MeCN (saturated with petroleum ether)	SPE: Florisil® Elute: DCM:petroleum ether (2:8)	GC-ECD Column: HP-5 30 m Injector: 280 °C ECD: 300 °C	79–104%	4–5 ng/g (LOD)	[98]
Yogurt	21	SLE: Acetone	SPE: C_{18} Elute: n-Hexane SPE: deactivated alumina Elute: n-Hexane	GC-ECD Column: 007-2 50 m Injector: 210 °C ECD: 300 °C	NR-102%	0.02–0.58 ng/g	[50]
(b) Eggs							
Eggs	6	SLE: MeCN	SPE: GCB/Aminopropyl Elute: Acetone:Toluene (3:1) SPE: Florisil® Elute: Petroleum ether:diethyl ether (98:2)	GC-ECD Column: DB-225 30 m Injector: 250 °C ECD: 350 °C	86–108%	n.s.	[16]
Eggs	20	MSPD: Florisil® DCM:hexane (1:1)	Con. sulphuric acid	GC-ECD Column: DB-5MS 30 m Injector: 240 °C ECD: 300 °C	82–99%	0.7–2.2 ng/g	[56]
Eggs	16	SFE: (CO_2)	SPE: Florisil® Elute: Acetone:hexane (1:9)	GC-ECD Column: SGE BPX5 30 m Injector: 220 °C ECD: 260 °C	82–108%	1 ng/g (LOD)	[36]
(c) Fish tissue and cod liver							
Fish tissue	10	Soxhlet: n-Hexane	Treated with con H_2SO_4 SPE: Silica Elution: n-Hexane Freezing: −20 °C	GC-ECD Column: DB-608 30 m Injector: 250 °C ECD: 300 °C	94–103%	1 ng/g	[30]
Fish tissue	9	Soxhlet: n-Hexane	SPE: 2% deactivated Florisil® Elution: n-Hexane/n-Hexane:DCM (42.5:7.5)	GC-ECD Column: DB-5 30 m Injector: 220 °C ECD: 280 °C	70–102%	0.12–3.1 ng/g	[31]
Fish tissue	8	ASE: Hexane:DCM (1:1) or hexane:acetone (4:1)	GPC: SX-3 Cyclohexane:EtOAc (1:1)	GC-ECD Column: DB-5 or DB-7 60 m Injector: 250 °C ECD: 300 °C	n.s.	n.s.	[42]

Table 2 (*Continued*)

Food matrix	OCPs tested	Extraction	Clean-up	Quantification	Recovery	LOQ	Ref.
Fish tissue	24	SLE (sonication): n-Hexane:acetone (2:5)	Freezing: −24 °C SPE: Florisil® vs silica Elution: Acetone:n-Hexane (1:9)	GC-MS Column: DB-5MS 30 m Injector: 270 °C MS: SIM	78–115%	0.5–20 ng/g	[20]
Fish tissue	9	MSPD: C_{18} MeCN	SPE: Florisil® Elute: MeCN	GC-ECD Column: DB-5 25 m Injector: 200 °C ECD: 300 °C	82–97%	n.s.	[55]
Fish	8	MAE: MeCN:H_2O (95:5)	SPE: Florisil® Elute: Acetone:hexane (1:9)	GC-ECD Column: ZB5-MS 30 m Injector: 80 °C (on-column) ECD: 350 °C	78–108%	5–10 ng/g	[46]
Fish	16	Soxhlet: n-Hexane:Acetone (1:1)	SPME: polydimethylsiloxane	GC-ECD Column: RTX-CLPesticides 2 30 m Injector: 260 °C ECD: 300 °C	70–104%	LOD: 0.1–0.7 ng/g	[32]
Fish muscle	20	MSPD: ENVI™-Carb Hexane:EtOAc (8:2)	SPE: ENVI™-Florisil Elute: Hexane:EtOAc (8:2)	GC-ECD Column: DB-35MS 30 m Injector: 300 °C ECD: 350 °C	53–352%	5–94 ng/g	[99]
Fish muscle	21	PLE: Hexane:acetone (1:1) MAE: Hexane:acetone (1:1)	SPE: ENVI™-Carb Elute: Hexane:EtOAc (8:2)	GC-ECD Column: DB-35MS 30 m Injector: 300 °C ECD: 350 °C	PLE: 14–131% MAE: 70–150%	PLE: 80–736 ng/g MAE: 6–130 ng/g	[47]
Mackeret fillet, cod liver	2	MAE: EtOAc:Cyclohexane (1:1)	GPC: SX-3 Cyclohexane:EtOAc (1:1) SPE: Silica n-Hexane	GC-ECD Column: CP-Sil 8/C_{18} and CPSil-2 50 m each Injector: 220 °C ECD: 300 °C	93–99%	n.s.	[45]
Fish fillet, cod liver	14	MAE or ASE: EtOAc:Cyclohexane (1:1)	GPC: SX-3 Cyclohexane:EtOAc (1:1) SPE: Silica Elute: n-Hexane	GC-ECD Column: CP-Sil 8/C_{18} and CPSil-2 50 m each Injector: 250 °C ECD: 300 °C	n.s.	n.s.	[43]
(d) Meat and poultry							
Beef meat	22	MAE: MeCN:n-hexane (1:1)	Freezing: −70 °C Centrifugation	GC-ECD Column: SPB-608 30 m	45–96%	1.04–4.25 ng/g	[57]
Beef meat	18	SLE: Petroleum ether	SPEs: NT3/C_{18}/Florisil® Wash: n-Hexane Elution: MeCN	GC–MS Column: HP-5MS 30 m Injector: 240 °C MS: SIM	49–110%	8–75 ng/g	[12]
Beef meat	5	SLE: Isooctane	SPE: Florisil® MeCN	GC-ITMS Column: DB-5 30 m Injector: 50–230 °C (prog.) MS: MS/MS	52–77%	2–24 ng/g (LOD)	[80]
Chicken, lamb & pork meat	21	Polytron, ASE or Soxhlet: EtOAc	GPC: Envirogel Cycloexane:EtOAc (1:1)	GC–MS^2 Column: VF-5MS 30 m Injector: 200–300 °C (prog.) MS: MS/MS	Polytron: 69–106% ASE: 64–87% Soxhlet: 62–93%	0.06–7.14 ng/g	[22]
Meat	3	Polytron: EtOAc	GPC: Envirogel EtOAc:cyclohexane (1:1)	GC–MS/MS Column: VF-5MS 30 m Injector: 200–300 °C (prog.) MS: MS/MS	70–110%	n.s.	[81]
Pork & meat products	24	SLE: DCM	GPC: SX-3 DCM:Cyclohexane (15:85)	GC–MS Column: HP-5MS 30 m Injector: 250 °C MS: SIM	65–120%	2–25 ng/g (on lipid basis)	[13]

Table 2 (*Continued*)

Food matrix	OCPs tested	Extraction	Clean-up	Quantification	Recovery	LOQ	Ref.
(e) Shellfish and mollusca							
Shellfish	13	Soxhlet: n-Hexane:acetone (3:1)	SPE: Alumina/silica/Florisil® treated with 15% KOH methanolic solution Elution: n-Hexane:DCM (3:1)	GC-ECD Column: DB-5 30 m Injector: 220 °C ECD: 300 °C	78–89%	0.1–0.6 ng/g (LOD)	[33]
Shellfish	14	MSPD: C_{18} MeCN:MeOH (9:1)	SPE: Florisil® Elute: MeCN:MeOH (9:1)	GC-ECD Column: DB-5 30 m Injector: 200 °C ECD: 300 °C	66–84%	n.s.	[53]
Crab meat	24	SLE: MeCN Centrifugation	SPE: C_{18}/Florisil® Wash: Toluene:Pet ether (3:97) Elute: Ether:Pet ether (2:98)	GC-ECD Column: DB-5 or DB-1701 30 m Injector: 250 °C ECD: 300 °C	48–105%	n.s.	[52]
Mollusc, crab	8	Saponified with NaOH Soxhlet: n-Hexane:acetone (1:1) and repeat with n-hexane	SPE: Florisil® Elute: n-Hexane Clean with 10% sulphuric acid	GC-ECD Column: DB-1701 30 m ECD:	60–116%	0.1–0.6 ng/g (LOD)	[100]
(f) Animal fat, vegetable oil and seeds							
Fish oil, vegetable oil & pork fat	19	SLE: EtOAc:Cyclohexane (1:1)	GPC: Envirosep-ABC Cychohexane:EtOAc (1:1)	GC–MS^2 Column: VF-5MS 30 m Injector: 250 °C MS: MS/MS	63–116%	6 ng/g	[15]
Animal fat	16	SLE: Cyclohexane:EtOac (1:1)	GPC: SX-3 Cyclohexane:EtOAc (1:1) SPE: Silica (Hypersil) Elute: Toluene:Acetone:n-Hexane (10:2:88)	GC-ECD Column: CPSil-8CB or CPSil-18CB 60 m Injection program: 100–270 °C	77–90%	n.s.	[101]
Animal fats	3	SLE: DCM:cyclohexane (1:1)	GPC: Biobeads SX-3	GC-ECD Column: DB-608 30 m Injector: 230 °C ECD: 325 °C	58–103%	n.s.	[63]
Bovine fat	9	MSPD: C_{18} MeCN	SPE: Florisil® Elute: MeCN	GC-ECD Column: DB-5 25 m Injector: 200 °C ECD: 300 °C	71–110%	n.s.	[54]
Edible oil	8	LLE: MeCN (saturated with n-hexane)	SPE: Florisil® Elute: Hexane then DCM:hexane (1:9) Clean with con. H_2SO_4	GC-ECD Column: HP-35 15 m Injector: 230 °C ECD: 300 °C	n.s.	n.s.	[102]
Oil and poultry fat	15	MSPD: Extrelut-3 MeCN saturated with hexane	SPE: C_{18} Elute: MeCN saturated with hexane; Florisil, n-hexane:benzene:EtOAc (180:19:1)	GC-ECD Column: DB-1701 or DB-1 60 m Injector: 93–283 °C (prog) ECD: 300 °C	57–103%	n.s.	[103]
Olive oil	15	LLE: MeCN saturated with hexane	GPC: Envirogel EtOAc:cyclohexane (1:1)	GC Column: CP-SIL 5CB 30 m Injector: 270 °C ECD: 300 °C ITMS: MS/MS	ECD: 91–124% MS^2: 90–102%	ECD: 2–20 ng/g MS^2: 0.5–20 ng/g	[104]
Olives	3	MSPD: Aminopropyl MeCN	SPE: Florisil® MeCN	GC-NCI-MS Column: ZB-5MS 30 m Injector: 250 °C MS: SIM	73–119%	30–40 ng/g	[105]
Vegetable oils or oil seeds	15	Soxhlet: Light petroleum	SPE: Florisil® + Extrelut (with sulphuric acid treatment) Upper phase of light petroleum:MeCN:EtOH (100:25:5)	GC-ECD Column: RTX-35 30 m or RTX-5, 25 m Injector: 290 °C ECD: 350 °C	NR-111%	1–10 ng/g	[106]

Table 2 (*Continued*)

Food matrix	OCPs tested	Extraction	Clean-up	Quantification	Recovery	LOQ	Ref.
Sesame seeds	16	MAE: Water:MeCN (5:95)	SPE: Florisil® Elute: Hexane:EtOAc (8:2)	GC–MS Column: DB-5MS 30 m Injector: 250 °C MS: SIM	84–105%	5–10 ng/g	[107]
(g) Miscellaneous and mixed food types							
Fish feed	6	Soxhlet: Petroleum ether	DSPE: Envi-Carb and sulphuric acid (90%) n-Hexane	GC-ECD Column: AT-5 30 m Injector: 240 °C ECD: 300 °C	61–134%	3 ng/g (LOD)	[108]
Muscle & liver	12	Soxhlet: n-Hexane	SPE: Silica Elution: n-Hexane Clean with con. H_2SO_4	GC-ECD Column: DB-608 30 m Injector: 250 °C ECD: 300 °C	94–103%	1–5 ng/g	[17]
Meat, fish, egg	21	SLE: Petroleum ether	GPC: SX-3 n-Hexane:EtOAc (1:1)	GC-ECD Column: Quandrex 007-2 or 007-608 50 m	80–110%	1–18 ng/g or μg/L (on lipid basis)	[14]
Composite diet sample	15	Soxhlet: Sample mixed with diatomaceors earth n-Hexane:acetone (1:1)	SPE: Alumina Elution: DCM:n-hexane (7:3)	GC–MS Column: HP-5MS 30 m Injector: 65–375 °C (prog.) MS: SIM	NR-199%	0.2–5.3 ng/g	[66]
Egg, poultry meat & liver	10	Soxhlet: Acetone:DCM (2:8)	SPE: Silica Wash: n-Hexane Elution: n-Hexane:DCM (3:2)	GC-ECD Column: HP-5 30 m Injector: 220 °C ECD: 280 °C	50–123%	0.01–0.3 ng/g	[27]
Cattle adipose tissue & swine liver	19	ASE: DCM:acetone (1:1)	GPC: SX-3 DCM:acetone (1:1) SPE: Silica Elution: n-Hexane:DCM (95:5) then MeOH:DCM (1:9)	GC–MS Column: DB-5MS 30 m Injector: 280 °C MS: SIM	24–122%	n.s.	[41]
Shellfish, meat, Fish	14	Soxhlet: n-Hexane	SPE: Florisil® Elute: Pet ether:diethyl ether (95:5)	GC-ECD Column: PTE-5 30 m Injector: 250 °C ECD: 300 °C	61–135%	0.5–4.8 ng/g (LOD)	[29]
Pork, fat & liver	6	Soxhlet: n-Hexane:acetone (3:1)	SPE: acidified silica Elution: n-Hexane then DCM	GC-ECD Column: HT-8 50 m Injector: 290 °C ECD: 320 °C	72–80%	0.2 ng/g (on lipid basis)	[28]
Liver and brain	4	SLE: Chloro-form:Acetone (1:1)	GPC: SX-3 n-Hexane:$CHCl_3$:acetone (75:20:5) SPE: Silica Elute: n-Hexane:$CHCl_3$:acetone (75:20:5)	GC-ECD Column: BP-5 25 m Injector: 250 °C ECD: 350 °C	86–105%	0.04–0.26 μg/g (LOD)	[21]
Organ tissue	21	ASE: DCM:Acetone (1:1)	GPC: S-X3 DCM:hexane (1:1) SPE: activated silica Elution: 5%DCM/hexane, 10% methanol/hexane	GC–MS Column: DB-5MS 30 m Injector: 280 °C MS: SIM	24–122%	n.s.	[41]
Milk, pork fat, animal feed and cod liver oil	10	SLE: Hexane	LC: Silica n-hexane	GC-ECD Column: SE-54 30 m Injector: 290 °C ECD: 350 °C	62–110%	0.1–50 ng/g	[70]
Animal fat, liver and kidney	8	ASE: n-Hexane:DCM (1:1)	SPE: acidified silica Elution: n-hexane SPE: silica/activated carbon Elution: n-hexane:DCM (10:4)	GC–MS^2 Column: ZB-1 60 m Injector: 280 °C MS: MS/MS	45–95%	0.7–1.9 pg/g	[109]

Abbreviations: ASE, accelerated solvent extraction; DCM, dichloromethane; ECD, electron-capture detector; GC, gas chromatography; GPC, gel permeation chromatography; ITMS, ion-trap mass spectrometry; LC, liquid chromatography; LLE, liquid–liquid extraction; LOD, limit of detection; LOQ, limit of quantitation; MeOH, methanol; MS, mass spectrometry; MSPD, matrix solid-phase dispersion; NR, Not recovered; n.s., not specified; SIM, selective ion monitoring; SLE, solid–liquid extraction; SFE, supercritical fluid extraction; SPE, solid-phase extraction.

applied which indicated that the lower recoveries arose from matrix suppression effect. In contrast, Schenck and Donoghue [16] reported matrix enhancement effect for DDT metabolites when analyzing OCPs in eggs with GC-ECD.

However, Argauer et al. [80] reported that much lower and variable recoveries of p,p′-DDT from spiking in meat was likely due to degradation. With reference to the recovery table listed in the Codex Alimentarius Commission's guidelines, the spiked recovery should be more or less the same in the range of 10 μg/kg to 100 mg/kg, unless the spiked level is close to the LOQ. Therefore, it is still a challenge for a researcher to fulfil the international requirements when developing a method for multiresidue OCP analysis.

Some of the MRL/EMRL of OCPs as set by Codex are listed in Table 1, most of them are on lipid basis. For liquid milk sample with around 3–4% lipid, the quantitation limit has to be around 30 times lower when whole weight basis is applied. Furthermore, Codex also provides guidelines which specify that the limit of detection (LOD) and the limit of quantitation (LOQ) should be equal to or lower than 1/5 and 2/5 of the MRL/EMRL respectively for analyte level not more than 0.1 mg/kg [97]. Therefore, the LOQ for DDT in milk should be lower than 0.4 μg/kg on whole weight basis. Owing to the fact that DDT refers to the sum of 4 isomers, the LOQ for each individual isomer should be better than 0.1 μg/kg on whole weight basis. This demanding low level poses another challenge for the researchers working in the field of OCP analysis.

8. Conclusions

The determination of OCPs and the newly added POPs in fatty foods is necessary to protect human public health. In this connection, a reliable method with sufficiently low detection limit is certainly required to support the background monitoring and regulatory enforcement. Codex has already issued the method performance guidelines which mentions that the LOD and LOQ should be equal to or lower than 1/5 and 2/5 respectively of the specified MRL/EMRL level (for analyte level not more than 0.1 mg/kg). In addition, for the developed analytical method to be sound, i.e. the recoveries should be in the specified acceptable range [97].

Some fast extraction methods, such as SFE and PLE, have been proved not always suitable for the determination of OCPs in fatty foods as those unstable compounds, such as endrin aldehyde and chlordecone, would be lost. Another fast extraction technique, MAE, has not been thoroughly evaluated in this area. Other traditional methods, including solid–liquid, liquid–liquid, Soxhlet, MSPD, are still providing promising approaches for the extraction of OCPs in fatty foods. Given the current situation and the importance of extraction in the overall OCP analysis, an ideal extraction method which is both fast and effective is yet to be developed.

As regards sample cleanup methods, a more efficient and effective way of removing lipids in fatty food samples other than traditional GPC approach would greatly alleviate the problem in subsequent cleanup steps as well as instrumental analysis. Although Florisil® column or SPE cleanup is the most commonly used cleanup approach, other suitable sorbents, either in column or SPE cartridge form, could still be considered for their sample cleanup capabilities. Attention should be paid to the quality of Florisil® or any other sorbents used in the cleanup steps. Similarly, the qualities of extraction solvents and all materials (e.g. centrifuge vessels, SPE column, etc.) that come into contact with the sample or extract must also be checked to avoid possible interferences. One typical example is the presence of manufacturing by-products like quinines and alkyl phthalates in SPE cartridges [52]. These compounds may be extracted from the polypropylene housing or the frit. Even with the use of GC–MS or GC–MS/MS, these interferences might not be discernable and lead to false positive results. This becomes more crucial when requirements for the lowest detection limit achievable in this type of trace analysis entails. In addition, loss of volatile OCPs (e.g. HCB and PeCB) during solvent evaporation should be minimized.

As new GC columns have been introduced into the market in recent years, baseline separation of targeted OCPs is now obtainable. Besides, comprehensive GC provides an alternative to separate the co-eluting analytes. Regarding GC–MS, its sensitivity is around an order poorer than GC-ECD or GC–MS/MS. In comparison, GC–MS/MS has provided better sensitivity and much lower chance of false positive results than other selective GC detectors. Except for chlordecone, which has better response in LC-ESI-MS/MS, GC–MS/MS is probably the best detection technique for other OCPs. In conclusion, up to now, only very few reported methods that determine some of the OCPs in fatty foods could fulfil all the required method performance criteria as set by the Codex. More research is needed to make progress in this relatively slow evolving field as compared with other pesticide residues analysis such as OPPs and carbamate pesticides.

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