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Phthalate Sample Preparation Methods and Analysis in Food and Food Packaging: a Review

Nur Zatil Izzah Haji Harunarashid[1] · **Lee Hoon Lim**[1] · **Mohammad Hilni Harunsani**[1]

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Abstract A review on phthalate esters or phthalic acid esters (PAEs), chemicals of concern since a few decades ago that are widely used as plasticizers in food processing and packaging, is presented taking into account the background of such compounds, the metabolism, human exposure to PAEs, the sources and occurrence in food as well as the toxicological aspects and human health effects. In addition, 45 novel research articles that were published between 2002 and 2017 were identified and their results were tabulated showing the PAEs analysed, food matrix of PAEs, methods of sample preparation/extraction, methods of instrumental analysis and quantitation, percentage recovery and limit of detection (LOD) of the instrument for ease of comparison and referencing. In general, it was found that in the last 15 years, the number of PAEs analysed has increased from the commonly analysed 8 PAEs, namely dimethyl phthalate (DMP), diethyl phthalate (DEP), diisobutyl phthalate (DIBP), di-*n*-butyl phthalate (DBP), butyl benzyl phthalate (BBP), dicyclohexyl phthalate (DCHP), di-*n*-octyl phthalate (DNOP) and di-(2-ethylhexyl) phthalate (DEHP) to as many as 23 PAEs. The methods of sample preparation have also progressed from the simple liquid-liquid extraction using organic solvents to solid-phase microextraction techniques to the more recent head-space or direct immersion solid-phase microextraction methods. Whereas for the analysis of PAEs, gas chromatography and liquid chromatography are still the preferred methods with improved LOD of analysis ranging from approximately 10 ppm for fatty foods to 1–60 ppt for water, juices and cooking oil samples.

Keywords Phthalates · PAEs · Food packaging · Sample preparation · Gas chromatography · Liquid chromatography

Introduction

Food products are complex mixtures comprising of naturally occurring compounds such as lipids, carbohydrates, proteins, vitamins, organic acids and aromas and other different substances which generally originate from mechanical procedures, agrochemical treatments and packaging materials. They are produced and distributed around the world, hence prompting extremely stringent regulations to ensure the nourishment quality and safety in reference to food contaminants (Gallart-Ayala et al. 2013). Food contaminants may be referred to as the presence of an array of redundant chemical compounds other than accustomed ingredients or natural food constituents which can derive from field environmental pollutants. For instance, these contaminants may include but not limited to those derived from chemical industrial waste which may be waterborne or airborne, from leached pesticides or chemicals used in agricultural practices, those that are introduced through inattentiveness in transporting raw products or in the procedures during food transformation processes, as well as those that may arise from unsuitable packaging materials (Moret et al. 2012). Grob et al. (2006) reported that educated consumers had listed pesticides as the main source of

✉ Nur Zatil Izzah Haji Harunarashid
15M3002@ubd.edu.bn

Lee Hoon Lim
leehoon.lim@ubd.edu.bn

Mohammad Hilni Harunsani
hilni.sani@ubd.edu.bn

[1] Chemical Sciences, Faculty of Science, Universiti Brunei Darussalam, Tungku Link Road, Bandar Seri Begawan BE1410, Brunei Darussalam

food contamination, followed by environmental chemicals such as polychlorinated biphenyl (PCBs) and veterinary drugs and only a few would acknowledge food packaging materials in defiance of the fact that the measure of material migrating from food packaging into food may be 100 times more prominent than the contribution of pesticides and environmental pollutants (Moret et al. 2012).

Food packaging may contain chemical (organic or inorganic) food packaging contaminants that may be intentionally added for a technical purposes, the presence of impurities from starting materials or manufacturing by-products, or the presence of contaminants arising from packaging or material recycling. The migration of different types of chemicals particularly phthalates from the packaging into food is highly diverse depending on the type of packaging materials as summarized in Table 1. The physiochemical properties of the migrant such as the level of contamination of lipophilic substances in high-fat-content food, storage temperature and duration of storage, would also affect the extent to which the migration may occur. For non-inert materials such as plastics, elastomers, paper and board, chemical contaminants may migrate from the outside of the packaging or from the packaging material itself. Paper-based packaging materials tend to have large pore size that permits migration of small molecules from the outside into the food. For example, when beverage cartons or paper cups are stacked on top of each other, the outside layer comes into contact with its inside layer and thus transferring chemical contaminants, such as printing ink components, to the direct food contact side (Muncke 2014). Inert materials such as stainless steel, glazed ceramic or raw glass may contain heavy metals. These chemicals are often on the inside surface and hence are in direct contact with the food and can migrate into food by surface exchange. Furthermore, plasticizers like epoxidized soybean oil or phthalates can contaminate glass-packaged oily foods following migration of chemical contaminants from the closure's gasket and hence, attentive manufacturing is required. The migration of chemical contaminants into food may also occur when small-sized monomers are released from the degradation of polymer which is often the case of reusable food contact materials like plastic kitchenware. A polymer will degrade and subsequently release monomers under highly acidic or alkaline conditions (Muncke 2014). Another factor that may affect the migration of the contaminants is temperature as performed by Jeddi et al. (2015) in which she concluded that drinking water from polyethylene terephthalate (PET)-bottles stored at high temperature (>25 °C) would cause significant phthalates migration compared to low temperature.

Phthalates

Background

Phthalates, or commonly known as phthalic acid esters (PAEs), are derivatives of phthalic acid, the esters of 1,2-benzenedicarboxylic acid in which the acid groups are in the ortho-position (Gallart-Ayala et al. 2013; Muncke 2014; Van Holderbeke et al. 2014; Ventrice et al. 2013; Benson 2014; Cirillo et al. 2013). PAEs are synthetic organic chemicals that were introduced in the 1920s (Fasano et al. 2012). They were manufactured by reacting phthalic anhydride with various alcohols (Benson 2014) starting from methanol (MeOH) and ethanol (EtOH) for the smaller compounds, up to iso-decanol,

Table 1 Different types of food packaging materials with phthalates as possible contaminant (Muncke 2014; Jeddi et al. 2015; Bueno-Ferrer et al. 2010)

Packaging type	Materials	Contaminants
Plastic	Polyethylene terephthalate (drinking water plastic bottles)	Formaldehyde
		Acetaldehyde
		Antimony
		Ultraviolet (UV) stabilizers
		Phthalates
Plastic	Polyvinylchloride (PVC) (domestic films)	Vinyl chloride
		Phthalates
		Epoxidized soybean oil (ESBO: glass jar closures)
Carton (for dry food)		Mineral oils
		Phthalates
		Benzophenones
Glass	Glass container, closure with gasket	*Phthalates*
		Epoxidized soybean oil (ESBO: glass jar closures)
		Lead

straight chain or with some branching, producing a large variety of PAEs and thus providing a wide range of different properties for different possible uses (Moret et al. 2012). The physico-chemical characteristics of PAEs, and consequently their applications and uses, vary with the chemical structure of the side chains in which the PAEs can be classified into (1) low molecular weight PAEs with R and R side chains with up to six carbons and classified as very dangerous substances in Europe and in REACH (Registration, Evaluation, Authorization, and Restriction of Chemical substances) and (2) high molecular weight PAEs with side chains of more than six carbons but do not appear as substances that can cause problems to health (Moret et al. 2012; Ventrice et al. 2013). PAEs with shorter alkyl chain such as dimethyl phthalate, diethyl phthalate and dibutyl phthalate are commonly used in cosmetics and personal care products while longer branching alkyl chain such as butylbenzyl phthalate, dicyclohexyl phthalate, diethylhexyl phthalate and di-*n*-octyl phthalate are widely used as plasticizers (Cirillo et al. 2013). Figure 1 shows the general chemical structure of PAEs and the chemical structure, acronym, CAS number, molecular weight, boiling point, density and the uses of the most commonly used PAEs namely dimethyl phthalate, diethyl phthalate, diisobutyl phthalate, di-*n*-butyl phthalate, butyl benzyl phthalate, dicyclohexyl phthalate, di-*n*-octyl phthalate and di-(2-ethylhexyl) phthalate as listed in Table 2.

Metabolism of Phthalates

The metabolism and elimination of phthalates are rather complex, requiring three distinct steps, for example the metabolism of DEHP as illustrated in Fig. 2. The first step occurs at different parts of the body, for instance the mouth or skin, stomach, intestines or blood where the phthalate diester is cleaved into respective hydrolytic monoesters. In the second step, modification of the alkyl chain of the resulting hydrolytic monoester by various oxidation reaction takes place, in which the extent of the oxidative modification increases as the alkyl chain length of the phthalate monoester increases. This therefore decreases their water solubility as oxidative metabolites

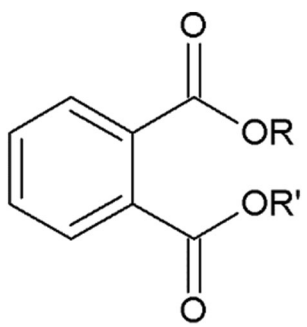


Fig. 1 Generic chemical structure of PAEs where R and R′ groups can be linear, branched or cyclic rings

are more water soluble than the corresponding hydrolytic monoester. The low molecular weight phthalates are often metabolized to their hydrolytic monoesters (primary metabolites) whereas the high molecular weight phthalates of 8 or more carbons in the alkyl chain are metabolized to their hydrolytic monoesters, which are then transformed into oxidative products (secondary metabolites). Finally in the third step, conjugation of both the hydrolytic monoester and the oxidized secondary metabolites with glucuronic acid occur which are eventually excreted in urine (Yen et al. 2011; Koch and Calafat 2009).

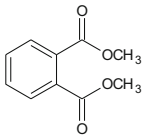
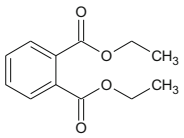
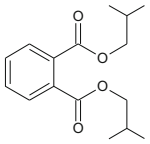
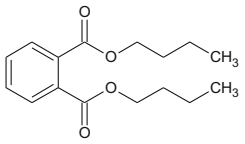
Human Exposure to Phthalates

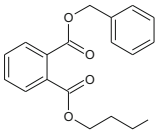
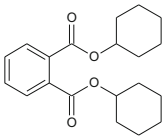
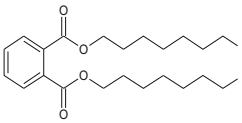
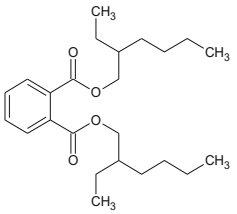
PAEs are primarily used as plasticizers and solvents as well as stabilizers for colour and fragrances (Duty et al. 2005a). They are also present in printing inks, lacquers, building materials (flooring, furniture and electric cables) (Ni et al. 2016; Butte and Heinzow 2002), paints, pesticides, baby toys, personal care and cosmetics (deodorants, perfumes and hair products), pharmaceutical products as well as medical devices (Fig. 3) (Du et al. 2016; Del Carlo et al. 2008; Shen 2005; Cinelli et al. 2013; Gómez-Hens and Aguilar-Caballos 2003; Sathyanarayana et al. 2008; Vera et al. 2011). Extensive industrial applications of PAEs in these many products have caused widespread exposure to human mainly through ingestion, inhalation, dermal contact (Cirillo et al. 2013; Adibi et al. 2003; Rudel et al. 2003) and medical devices (He et al. 2015; Zeman et al. 2013; Jeddi et al. 2015; Schecter et al. 2013; Swan 2008). It is possible to find PAEs in the environment (Rudel et al. 2003; Staples et al. 2008) as they are easily released into water, air and soil and are released slowly from worn down manufactures without PAEs being chemically bound in plastics or other products (Gómez-Hens and Aguilar-Caballos 2003). Although PAEs can be easily degraded in atmosphere by oxygen and UV radiation, they may persist for a long time in solution.

Ingestion

PAEs ingestion may occur through food, water and from the uses of their packaging particularly DEHP (Schettler 2006). In fact, the main source of PAEs exposure in the general population is from dietary intake (Cirillo et al. 2013; Fasano et al. 2012; He et al. 2015; Sioen et al. 2012; US Agency for Toxic Substances and Disease Registry 2012; Fromme et al. 2007; Wormuth et al. 2006). PAEs are mainly used as plasticizers due to their ability in increasing flexibility, workability and durability. However, Jeddi et al. (2015) and supported by Dewalque et al. (2014) have reported that children are more exposed than adults as they consume more food and water such as breast milk, infant formulas and plastic-packed food per unit body weight. In addition, they are also exposed by

Table 2 Name, chemical structure, acronym, CAS number, molecular weight, boiling point, density (retrieved from MSDS of Chem Service Inc) and the uses of commonly used PAEs

Compound	CAS no.	MW/gmol^{-1}	Bp/°C	ρ/g mL^{-1}	Uses
Dimethyl phthalate (DMP) 	131-11-3	194.20	283.7	1.194	Plasticizers, additives in plastics (Wang et al. 2004)
Diethyl phthalate (DEP) 	84-66-2	222.24	295	1.118	Personal care products, cosmetics (Heudorf et al. 2007), perfume and fragrance products (Romero-Franco et al. 2011, Api 2001), medicine coatings (Hauser et al. 2004)
Diisobutyl phthalate (DiBP) 	84-69-5	278.35	296.5	1.04	Similar properties as DBP and can be used as substitute of it (Koch et al. 2012)
Di-n-butyl phthalate (DBP) 	84-74-2	278.35	340	1.047	PVC plastics, latex adhesives, cosmetics, personal care products, solvent for dyes (Heudorf et al. 2007), medicine coatings (Hauser et al. 2004)

Compound (Acronym)	CAS no.	MW/gmol^{-1}	Bp/ °C	ρ/g mL^{-1}	Uses
Butyl benzyl phthalate (BBP) 	85-68-7	312.39	370	1.11	Vinyl tiles, artificial leather, traffic cones (Heudorf et al. 2007), hairspray (Romero-Franco et al. 2011; Houlihan et al. 2002)
Dicyclohexyl phthalate (DCHP) 	84-61-7	330.42	224	1.383	Printing ink on plasticizer (Castle et al. 1989)
Di-n-octyl phthalate (DnOP) 	117-84-0	390.56	242	0.982	Garden hoses, pool liners, flooring tiles, toys (Schettler 2006), bottle cap liners, and as an indirect food additive (Heudorf et al. 2007)
Di-(2-ethylhexyl) phthalate (DEHP) 	117-81-7	390.56	384	0.981	Building products (wallpaper, wire and cable insulation), car products (vinyl upholstery, car seats), clothing (footwear, raincoats), food packaging, children's products (toys, grip bumpers) (Heudorf et al. 2007), nail polish and perfume (Romero-Franco et al. 2011; Koo and Lee 2004), medical devices (Romero-Franco et al. 2011; Schettler 2006)

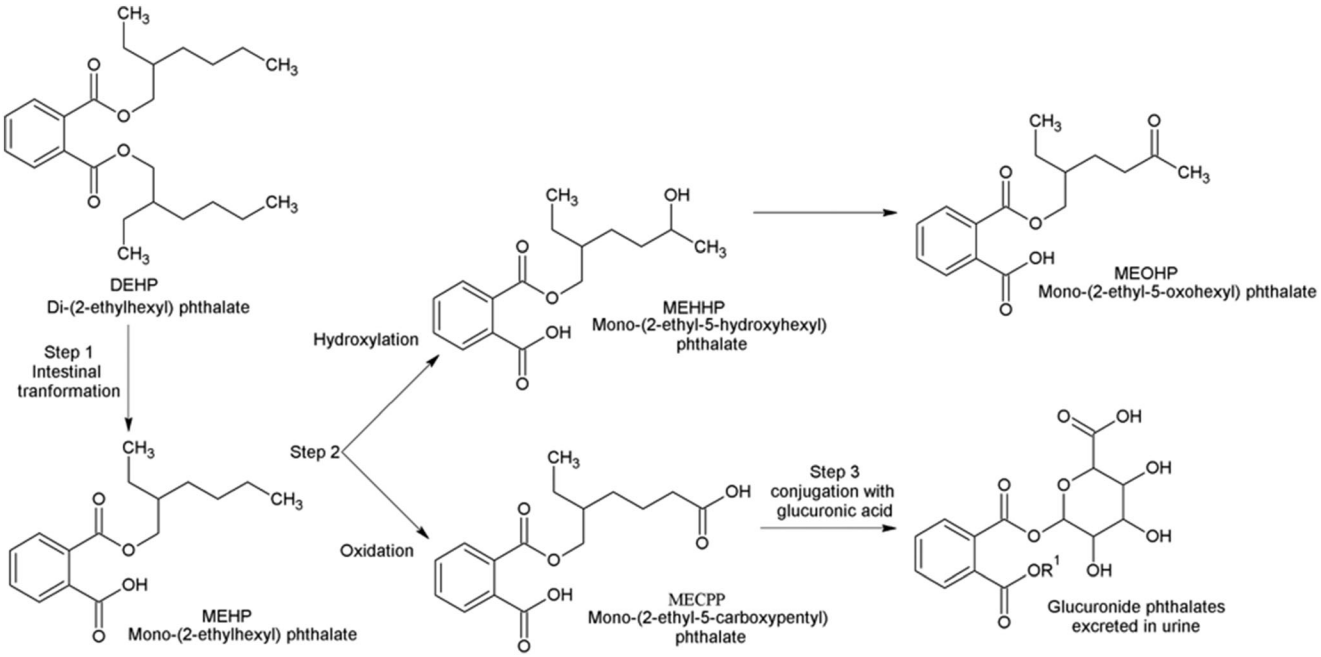


Fig. 2 Metabolism of DEHP

indoor dust and by sucking plastic teats, toys and mouthing contaminated hands and other objects (Sathyanarayana et al. 2008; Jeddi et al. 2015; Clark 2003; Calafat et al. 2004; Mortensen et al. 2005). Other than that, human are also exposed to PAEs by ingestion of dust from floor and carpet tile and products used in automotive interiors (Benson 2014).

Inhalation

Inhalation of PAEs can occur mainly from house dust and indoor air including inside automobiles where PAEs release from plasticized components can occur. However, PAEs exposure through dust and indoor air depends on the PAE sources such as building materials, PVC flooring and furnishing and PVC accessories. A study by Oie et al. (1997) reported a mean total PAE content of 960 μg/g of dust in 38 homes in Norway with DEHP as the main compound. Another study by Rudel et al. (2001) has reported a total PAEs concentration ranged from 0.3 to 524 μg/g dust and from 0.005 to 28 $\mu g/m^3$ indoor air from 120 US homes with DEHP ranging from 20 to 114 ng/m^3 and DBP ranging from 101 to 431 ng/m^3. Hobbies such as clay modelling may also represent as a source of PAEs exposure by inhalation in which polymer clay is reported as a major source of air-dispersed PAEs. This material is softened by various PAEs and can be dispersed in air during the firing of the modelled clay. Another source for the PAEs inhalation is from the use of perfumes and hairsprays (Cirillo et al. 2013; Blount et al. 2000).

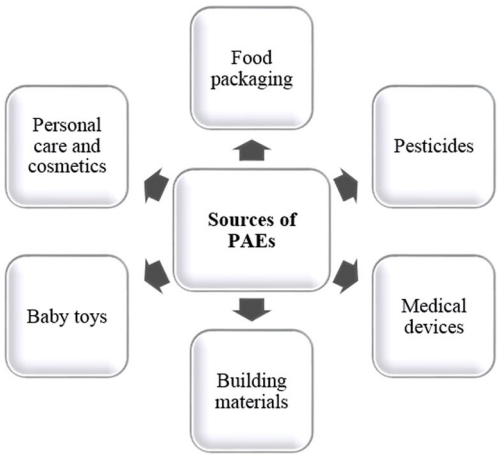


Fig. 3 Sources of PAEs

Dermal Contact

Direct contact with clothing, personal care products, synthetic modelling clay, cleaning products, insecticides and denture materials that contain PAEs may lead to absorption of PAEs through the skin. In terms of frequency of use, Blount et al. (2000) has considered personal care products such as cosmetics as the main exposure source for women. A study by Duty et al. (2005b) suggested that the main source of exposure for men was from using eau de cologne and aftershave. This is due to the uses of PAEs as lubricants in cosmetics and personal care products. In the case of infants, PAEs exposure

is mostly from their mothers who use lotions, powders and shampoo as studied by Sathyanarayana et al. (2008).

Medical Devices

Medical devices have been shown to expose human to PAEs via ingestion mainly from the use of PVC bags which are softened by DEHP that are employed in enteral nutrition. The leaching of the plasticizer may be caused by the lipid content of the enteral/nutritional formulas (Cirillo et al. 2013). In addition, many drugs and medicines such as antibiotics, antihistamines, laxatives, herbal preparations and nutritional supplements are coated with synthetic polymers containing PAEs that can leach into the gastrointestinal tract during drug release and thus become an important source of PAEs ingestion (Hauser et al. 2004; Hernández-Díaz et al. 2009). Furthermore, exposure from medical devices such as intravenous exposure may also occur. DEHP which is often the main PAE is released from PVC devices that are normally employed for intravenous therapies such as transfusion of blood and blood products, extracorporeal membrane oxygenation and dialysis (Lee et al. 1999). As reported by Calafat et al. (2004) and Green et al. (2005), premature babies undergoing intensive medical care in neonatal intensive care units were found to be exposed to higher concentration of DEHP than adults.

Medical devices may also be a source of human exposure to PAEs by inhalation with regard to respiratory therapy. DEHP may transfer into respiratory gases passing through tubes that are made of PVC plasticized by PAEs (Cirillo et al. 2013).

Sources and Occurrence of PAEs in Food

Between 2009 and 2011, by the order of Belgian Federal Public Service of Health, Food Chain Safety and Environment, a Belgian research project PHTAL (acronym for phthalate) was conducted whose main objectives were to obtain data of phthalates in all kinds of food products and packaging materials sold in the Belgian market (Fierens et al. 2012), to understand possible contamination pathways of phthalates in the Belgian food market (Van Holderbeke et al. 2014) and to estimate dietary exposure to phthalates of the Belgian population (Sioen et al. 2012). Contamination of PAEs in food is found to be most likely due to their transfer from materials in contact with the food during processing, handling or transportation (Wormuth et al. 2006; Sakhi et al. 2014; Cao 2010). As the PAEs are not chemically bonded to polymers but remain present as a freely mobile and leachable phase, they can potentially leach and easily migrate (Ni et al. 2016; Moskovkin 2002) into food and beverages from the enclosing materials (Gómez-Hens and Aguilar-Caballos 2003). This has therefore made food as a major source of exposure of phthalates in humans (Fasano et al. 2012; Fromme et al. 2007; Wormuth et al. 2006; Clark et al. 2011; Rudel and Pevorich 2009). In addition to this, this project also found that PAEs were illegally substituted for food grade emulsifiers in formatting clouding agents that are meant to provide turbidity to selected food products, mainly beverages (Self and Wu 2012; Espachs-Barroso et al. 2005), and were also used to give a characteristic colour, flavour and mouth-feel in beverages (Jasentuliyana et al. 1998).

Toxicological Aspects and Human Health Effects

The toxicity of PAEs to human being has been reported over 20 years ago (Chronic Hazard Advisory Panel 1985; Ventrice et al. 2013; Moret et al. 2012; Ni et al. 2016; Martino-Andrade and Chahoud 2010; Okamoto et al. 2011) prompting concerns on the development of reproductive systems (He et al. 2015; Martino-Andrade and Chahoud 2010; Matsumoto et al. 2008; Kamrin 2009; Fisher 2004; Scholz 2004). PAEs have been categorized as a "chemical of concern" by the United States Environmental Protection Agency (EPA) (Cao et al. 2016; U.S. EPA 2012) and are classified by most countries as carcinogenic, mutagenic and toxic to reproductive health (Gallart-Ayala et al. 2013). PAEs are considered to be potential endocrine-disrupting chemicals (EDC) (European Union Risk Assessment Report 2003; Cariou et al. 2016; Chauvigné et al. 2009; Eveillard et al. 2009) which are compounds of known toxicity even at low concentrations that are able to mimic or block the action of natural hormones affecting the normal biology function in animals and humans and are able to interfere with androgen signalling and production (Cacho et al. 2012; Laws et al. 2000).

Exposure in male adults, mainly to DEHP, may cause alterations in pulmonary functions and sperm properties resulting in reduced sperm counts and mobility in such a way that it can cause seminiferous tubule atrophy, decreased testis weight, decreased sperm production and decreased testicular zinc level, in which testicular effects can lead to infertility (Ventrice et al. 2013; Foster et al. 1980; Li et al. 2012a). With regard to women, it was observed that the target of PAEs toxicity was in ovaries and in particular steroid hormone production (Ventrice et al. 2013).

Even though PAEs are rapidly hydrolysed into their corresponding monoesters and then metabolized and eventually excreted with urine and faeces (Itoh et al. 2005), they have been detected in serum, amniotic fluids and breast milk (Ghisari and Bonefeld-Jogersen 2009) and hence showing a negative relationship between high PAEs exposure and children's intelligence and behaviour as reported by several epidemiological studies (Nelson 1991; Ventrice et al. 2013; Cho et al. 2010). Human exposure to PAEs (mainly DEHP) can

begin in utero, resulting in a shorter pregnancy duration (Yen et al. 2011; Latini et al. 2003). In addition to this, from the recent epidemiological studies, PAEs exposure have also been associated with shorter gestational age (Whyatt et al. 2009; Adibi et al. 2009), shorter anogenital distance (Suzuki et al. 2011; Marsee et al. 2006), precocious puberty (Lomenick et al. 2010), pubertal gynecomastia (Durmax et al. 2010), premature thelarche (McKee 2004), low birth weight (Zhang et al. 2009), attention deficit hyperactivity disorder (Kim et al. 2009; Engel et al. 2010), low intelligence quotient (Cho et al. 2010), thyroid dysfunction and growth retardation (Boas et al. 2010) and hypospadias (Ormond et al. 2009) in infants and children.

As mentioned above, PAEs are considered to be carcinogenic in which they are responsible in causing cancer due to the peroxisome-proliferator-activated-receptor-α (PPARα) activated by the ability of PAE monoesters that increases as the chain length increases (Cirillo et al. 2013; Bility et al. 2004). Studies in rodents have shown that PAEs can cause hepatic cancer, liver tumours, testicular Leydig cell and pancreatic acinar cell tumours (Ventrice et al. 2013; Cirillo et al. 2013).

Other health effects caused by PAEs exposure also include airway remodelling causing asthma, allergies (Ventrice et al. 2013; Jaakkola et al. 1999; Jaakkola and Knight 2008) and respiratory symptom (Cirillo et al. 2013; Polakoff et al. 1975; Falk and Portnoy 1976; Brooks and Vandervort 1977; Eisen et al. 1985; Markowitz et al. 1989; Nielsen et al. 2007) obesity and diabetes due to low testosterone level (Ding et al. 2006; Selvin et al. 2007) and autism spectrum disorders (ASDs) (Weintraub 2011) as PAEs can also interfere with neurological development. Several animal studies have also revealed that their effect on the dopamine system in the central nervous system in which a low dose of PAEs can impair tyrosine hydroxylase immunoreactivity (Ishido et al. 2004) causing the loss of mid-brain dopaminergic neurons and thus decreasing tyrosine hydroxylase biosynthetic activity (Tanida et al. 2009).

Analysis Approach

It is particularly difficult to perform an effective measurement of PAEs content in food as food samples can be easily contaminated within laboratory environment and activities as glassware, solvents and reagents used may contain traces of PAEs. Hence, analysis of PAEs contamination in/from food packaging migrating into food products represents a challenging task that will necessitate suitable precautions to avoid any contamination. Due to the complexity of matrices and low concentration levels expected in samples, assessment of PAEs contamination would thus require efficient preconcentration and clean-up procedures to ensure the quality of analytical determination results. Other typical steps required in the analysis procedures for food sample preparation are sampling, homogenization and extraction (Cirillo et al. 2013).

Sample preparation is a more or less complex procedure in accordance to the characteristics of the food matrix. In parallel to assessing the migration of chemicals from packaging into food, determining the migration of chemicals from packaging into food simulants (extractant used as food substitutes for analysis; solvents, oil or polymeric resin that can be used to mimic chemical properties of food to simplify the chemical analysis of migrants from food contact materials) may also be of interest as they represent a different group of food. Food simulants vary depending on their chemical properties as shown in Table 3 in which they may migrate variably depending on migration test conditions such as temperature and period of exposure. However, chemical migration into actual food is expected to be lower than the migration into food simulants; hence, food simulants are believed to overestimate the real migration. In contrast, all food simulants can be used for overall migration testing such as in assessing a mixture of chemicals that can migrate from the entire packaging into food. The use of distilled water as food simulant is also common for this purpose (unspecific analysis) (Muncke 2014).

Blank Problems

Due to the widespread use of products containing PAEs, PAEs have become ubiquitous environmental contaminants. They therefore have become the main cause of blank problems as well as increasing the risk of secondary contamination that may occur during sampling, sample preparation, extraction and/or instrumental analysis and therefore leading to overestimated contamination levels. As PAEs are commonly present in laboratory environment, Frankhauser-Noti and Grob (2007) reported the presence of DBP and DEHP in the laboratory air to be 3 and 2.4 μg/m^3 respectively; in organic solvents and chemicals for instance 100 μg/L of DBP and DEHP were found in commercially available hexane (Grob et al. 2006), which are adsorbed on glassware and other devices used for the analysis. PAEs are also present in materials commonly used in laboratory activities such as tubing, caps, stoppers, glass wool, filter paper or fibres, cartridges and stir bar used in specific sample preparations. In addition, a 1.5-mL autosampler vial was also estimated to contain 10 and 4 ng of DBP and DEHP, respectively (Frankhauser-Noti and Grob 2007).

It is best to keep PAEs analysis to be as quick and as simple as possible by keeping the sample preparation to minimum, with minimal extraction steps and pre-concentration of the extracts, which can be done by minimizing the use of solvents and chemicals, glassware and the exposure of sample in air. In order to reduce the primitive contamination in solvents,

Table 3 List of food simulants based on studies published by Muncke (2014)

Food simulant	Abbreviation	Use
10% ethanol	Food simulant A	Aqueous food
3% acetic acid	Food simulant B	Aqueous and/or acidic (pH <4.5) food
20% ethanol	Food simulant C	Aqueous, alcoholic (≤20% ethanol) and/or fatty food
50% ethanol	Food simulant D1	Fatty food, alcoholic (>20% ethanol) and/or emulsions (oil-in-water)
Vegetable oil	Food simulant D2	Fatty, with free fats contacting the food contact material surface
Tenax (poly(2,6-iphenyl-*p*--phenylene oxide), particle size 60–80 mesh and pore size 200 nm	Food simulant E	Dry foods (for specific migration testing)
Distilled water	–	Overall migration testing

redistilling the solvents can be done even though Frankhauser-Noti and Grob reported redistilling solvent is not efficient enough and is not always possible in routine analysis laboratories as contamination during and after distillation is still possible. However, they reported that the best solution was to perform a dispersive solid-phase extraction (SPE) in distilled solvent such as adding active aluminium oxide to reservoir which is able to absorb the presence of all polar materials in the solvent, taking into account the amount of aluminium oxide added and the time of shaking to allow aluminium oxide to absorb PAEs present in the solvent. However, this alternative is only applicable for organic solvents and not in more polar solvents as PAEs would be extracted from aluminium oxide instead of being purified. The solvent bottles then should be closed after use to avoid contact with air.

With regard to the glassware used, removal of more than 90% of DBP and DEHP (Frankhauser-Noti and Grob 2007) can be achieved by solvent rinsing followed by heating at 400 °C for 1–2 h (David et al. 2003) or heated in the oven at 400 °C for several hours or overnight and then kept in a desiccator containing aluminium oxide or covered with aluminium foil to avoid adsorption of PAEs from the air. For materials that cannot be cleaned by heating, they should be rinsed with purified solvent drawn from a bottle containing aluminium oxide. In conclusion, it is best not to expose any solvents and materials used to the air during the preparation, extraction steps until the end of the analysis determination (Moret et al. 2012).

Water and Beverages

In general, PAEs from non-fatty liquid samples such as water, beverages and alcoholic solution can be extracted commonly by liquid-liquid extraction (LLE) in which the sample is mixed with organic solvents with higher affinity for PAEs in order to change the equilibrium in favour of the organic solvent with no additional clean-up required. Different extraction solvents can be used as proposed by several researches for instance dichloromethane (CH_2Cl_2) (Shelton et al. 1984; Bošnir et al. 2007; Fierens et al. 2012; He et al. 2015; Paz Otero et al. 2015), *n*-hexane (Holadová and Hajšlova 1995), cyclohexane (Tienpoint et al. 2005), diethyl ether (Ejlertsson and Svensson 1995) and ethyl acetate (Jonsson and Borén 2002). However, in comparison with conventional LLE (Ostrovský et al. 2011), Rezaee et al. (2006) has proposed using dispersive liquid-liquid microextraction (DLLME) of better efficiency, simplicity and rapidity in 2006. Later on in 2011, ultrasound DLLME using carbon tetrachloride (CCl_4) as extractant was applied to extract six PAEs in bottled milks. In 2013, ultrasound-vortex-assisted extraction was established by Cinelli et al. (2013) to extract PAEs in wine. Despite the advantages of DLLME, its main drawback is the use of chloro-containing organic extractants that could lead to environmental pollution. Therefore, recyclable ionic liquids (salt in liquid state for example sodium chloride), which are non-volatile and non-toxic were used as green extractants and were combined with DLLME to extract PAEs from alcoholic beverages (Fan et al. 2014). However ionic liquids are unstable and tend to decompose when in touch with metallic catalysts. In addition a few toxic solvents and extremely complex purification process are required to synthesize an ionic liquid and thus leading to high cost limiting their wide application (Yang et al. 2015). In 2016, Pérez-Outerial et al. determined PAEs in liquid samples by UA-DLLME (ultrasound-assisted-dispersive liquid-liquid microextraction) followed by solidification of floating organic drop by using n-hexadecane as extracting solvent.

Other than LLE, solid-phase extraction (SPE) is also a commonly used method where SPE columns use polar stationary phase such as C18 (Khedr 2013), C8, polystyrene, XAD-2 adsorbents (Cinelli et al. 2014) and multiwall carbon nanotubes (MWCNTs) (Casajuana and Lacorte 2003; Cai et al. 2003; Mohamed and Ammar 2008; Del Carlo et al. 2008) to selectively adsorb PAEs while polar compounds that are not of interest are eluted and separated from analytes of interest. Even though this technique allows the use of solvents to be reduced and hence improving extraction efficiency and yielding more purified extracts, it is time consuming and it often requires extensive sample handling and treatment of sample prior to analysis, which then lead to high blank values. In addition to the conventional SPE, magnetic solid-phase extraction (MSPE) using magnetic nanosorbents

incorporating multiwall carbon nanotubes (MWCNTs) (Guan et al. 2010), single-walled carbon nanotubes (SWCNTs) (Rastkari et al. 2010) and graphene (Wu et al. 2011) have been employed. In 2011, analysis of PAEs in water was performed using a newly synthesized polypyrrole-coated Fe_3O_4 magnetic microsphere (Meng et al. 2011) and later on in 2013, it was applied to analysis of PAEs in soybean milk (Wang et al. 2013). In the same year, Tahmasebi et al. (2013) has successfully synthesized a novel type of polythiophene-coated Fe_3O_4 supermagnetic nanosorbent as a new sorbent for SPE in analysis of PAEs in water.

In contrast to SPE, solid-phase microextraction (SPME) is more efficient, simple and solvent-free and does not require any prior sample preparation. The conventional SPME device looks like a syringe composed of fused silica fibre coated with a thin layer of sorbents which plays an important role in its high selectivity and fixed with a needle that usually employs a miniature automatic device to integrate sampling, extraction, purification, concentration and injection in one procedure (Moret et al. 2012). This technique permits simpler sample preparation and reduce the risk of secondary contamination. The extraction of target analytes from liquid samples can be performed either by direct immersion SPME (DI-SPME) or headspace SPME (HS-SPME) in which both techniques were used in several studies for determination of water since late 1990s (Peñalver et al. 2000, 2001; Luks-Betlej et al. 2001; Polo et al. 2005; Montuori et al. 2008; Cao 2008). In recent years, Carillo et al. (2007, 2008) have developed a method based on HS-SPME to extract PAEs from wine samples using PDMS/DVB (polydimethylsiloxane/divinylbenzene) fibre. However, the fibres showed tendency to break and are relatively expensive.

Another approach of analysing liquid samples is stir bar sorptive extraction (SBSE) in which PDMS is also used as a coating for the stir bar, which is usually immersed in sample solution to extract the target analytes and then thermally desorbed for separation and detection. This method allows a higher performance resulting in higher sample capacity and recovery, thus giving better sensitivity than LLE and SPE. In the case of liquid samples, no clean-up procedure is necessary when using this approach.

Oils and Fatty Extracts

When extracting PAEs from fatty matrices, it is crucial to apply clean-up procedures due to the co-extraction of the lipid components mostly represented by triacylglycerols. The two commonly clean-up procedures applied are liquid-liquid partition with acetonitrile (ACN) (Sørensen 2006) and gel permeation chromatography (GPC) both of which involve liquid-liquid partition to remove fats and oils in fatty extracts that is often performed by size exclusion chromatography (SEC), where extracts are injected onto a column packed with Biobeads SX3 or PLgel and eluted with CH_2Cl_2/cyclohexane (Tsumura et al. 2001; Castle et al. 1988, 1990) or ethyl acetate/cyclohexane (Blüthgen and Heeschen 1998; Petersen and Breindahl 2000) or pentane/methyl *tert*-butyl ether (MTBE) (Hogberg et al. 2008). In addition to this, the column may be packed with Florisil, silica gel or other phases to perform the clean-up.

With regard to liquid fatty matrices, extraction methods will be briefly described in the solid foods section below. In the case of vegetable oils, PAEs determination can be analysed by conventional LLE technique usually performed by using ACN followed by clean-up using different SPE phase such as silica or Florisil. Treatment with aluminium oxide prior to clean-up step was proposed by Mariani et al. (2006) to remove co-extracted free fatty acids that may cause interference in the chromatographic analysis.

New approach for the extraction of PAEs from virgin oil samples has been developed in López-Feria et al. 2009 by López-Feria et al. using surfactant-coated carbon nanotubes as extractant where the phase containing the extract analytes is transferred into a headspace vial and added with sodium chloride to facilitate the release of the target analytes to the headspace. Other more recent approaches to further simplify sample preparation are SPME and the analysis with PTV injection system (programmed temperature vaporizer). Frankhauser-Noti and Grob (2006) have described PTV injection technique as a very useful method as it allows direct injection of a diluted oily solution without prior extraction and clean-up steps in which the injector is kept below the solvent evaporation temperature during the injection of sample and is then rapidly heated. The analytes present in the sample are subsequently evaporated as characterized by different volatilities and then compounds of interest are transferred into the separation column leaving high-boiling components in the inlet to avoid their entrance in the analytical column. A system known as backflush system will then allow the cleaning of the pre-column and the inlet. Although PTV injector and the convention split/splitless injector are rather similar in injecting the sample into a liner place inside the volatilizing chamber where it is evaporated, the difference between the two is that the PTV injector can be rapidly heated and cooled during the injection and analysis, whereas the conventional split/splitless injector only works in isothermal conditions. Therefore, the PTV injection technique is able to simplify sample preparation and eliminate problems of secondary contamination.

Solid Foods

The commonly used method of extraction of PAEs from non-fatty solid foods after homogenization such as fruits and vegetables is LLE by direct extraction with ACN or mixtures of ACN and water in which some cases need to be followed up by a further extraction with 1:1 mixtures of *n*-hexane/CH_2Cl_2

or cyclohexane/CH_2Cl_2 (Page and Lacroix 1995; Lau and Wong 1996). A less common technique of Soxhlet liquid extraction (SLE) is also used which has been proposed by Sablayrolles et al. (2005) where frozen, lyophilized and ground samples are extracted with *n*-hexane. The extract can then be purified using a Florisil SPE cartridge after concentration and finally target compounds are eluted by a 9:1 mixture of *n*-hexane/acetone.

In the case of fatty solid foods such as dairy products, meat products, chocolates and retail products, it is necessary to extract the lipid fraction first as PAEs may be co-extracted with it. This is then followed by LLE with a mixture of solvents such as of acetone/*n*-hexane as proposed by Page and Lacroix (1995), Castle et al. (1988) and MAFF (1996a, b, 1998), MeOH/*n*-hexane by Sharman et al. (1994) and Castle et al. (1990), *n*-hexane/CH_2Cl_2 by Yano et al. (2002), MeOH/*n*-hexane/MTBE by Sørensen (2006), pentane/acetone/*n*-hexane/MTBE by Hogberg et al. (2008), ACN/*n*-hexane by Page and Lacroix (1995), Tsumura et al. (2001, 2002, 2003) and Yano et al. (2005) or with singly solvent such as *n*-hexane as proposed by Guo et al. (2010) and Jarošová (2006), CH_2Cl_2 by Page and Lacroix (1995), pentane by Petersen and Breindahl (2000) and ACN by Cariou et al. (2016).

In addition to the LLE step, Guo et al. (2010) proposed the addition of aluminium oxide and sodium chloride solution to decrease interference from proteins, fats and other components whereas Tsumura et al. (2001, 2002, 2003) has proposed the addition of sodium chloride to eliminate water for PAEs analysis in fresh foods. On the other hand, Page and Lacroix (1995), Yano et al. (2002) and Petersen and Breindahl (2000) proposed treatment with potassium hydroxide, potassium oxalate or other destabilizing agents to damage the phospholipid-protein membrane of the fat globules in PAEs analysis of cheese, milk, infant foods and other dairy products. Likewise, sodium sulphate is also used to remove water from the extract followed by evaporation to concentrate the sample extract under nitrogen flow and finally redissolving the residue with various solvents. PAEs analysis in fatty extracts should undergo clean-up procedures such as gel permeation chromatography (GPC) (Fierens et al. 2012) and gas-purge microsyringe extraction (GP-MSE) (He et al. 2015). Other extraction methods include the use stir bar sorptive extractive (SBSE) (Cacho et al. 2012), direct analysis in real time–standardized voltage and pressure (DART-SVP) (Self and Wu 2012) and ultrasonic extraction (UE) (He et al. 2015; Cacho et al. 2012).

Packaging Materials

In the analysis of PAEs determination in food packaging materials, it is necessary to apply migration tests using food simulants and standardized migration test conditions depending on the type of food. Fasano et al. (2012) has performed two extraction methods to analyse PAEs which are incubation for 10 days at 40 °C and ultrasonic extraction in which the food simulants are extracted by SPE. In the same year, Cacho et al. (2012) has proposed a method in determining PAEs in vegetables and migration studies from their packages by SBSE with prior extraction with ethanol.

Another method for PAEs analysis from packaging is ultrasonic method with *n*-hexane as the extracting solvent as performed by Fierens et al. (2012) and later on by Van Holderbeke et al. (2014). However, Van Holderbeke has employed modifications from the original method by Fierens which include adding a step where exchanging the sample extracts was done with CH_2Cl_2 followed by purification with GPC.

Nevertheless, a direct analysis of the sample extracts from paper and board packaging was performed by Nerin et al. (2002) with supercritical fluid extraction (SFE) using ethanol that did not require pre-treatment of the samples. In addition, Soxhlet extraction using hexane is also applied to analyse PAEs in polymer-coated sample cup. A more recent approach of PAE determination is the development of magnetic dummy molecularly imprinted dispersive solid-phase extraction (MAG-MIM-dSPE) (Qiao et al. 2014) for selective determination of PAEs in plastic bottled beverages using DINP (diisononyl phthalate) as a template mimic resulting in a successful analysis of 5 PAEs.

Other Extraction Methods

In 2012, dispersive SPE (d-SPE) approach was performed for clean-up of 17 PAEs in fatty food after being extracted with organic solvents (Li et al. 2012b). In 2013, 15 PAEs were analysed in vegetable juices by using hollow fibre-liquid phase microextraction (HF-LPME) (Zhu et al. 2013). Later on, a new extraction method based on membrane filtration-enrichment using nylon membrane as solid-phase support was proposed by Chen et al. (2014).

As proposed by Anastassiades et al. (2003), a method known as QuEChERs (quick, easy, cheap, effective, rugged and safe) was first used to extract pesticides from foods in which the procedures include homogenization of sample, extraction with ACN, dehydration with magnesium sulphate followed by removal of impurity with primary secondary amine (PSA) and finally analysis using GC-MS or LC-MS. Later on in 2014, QuEChERs was successfully applied in extracting 23 PAEs from grape jelly, seasoning powder, egg noodles and grapefruit sauce (Xu et al. 2014, Yang et al. 2015).

Instrumental Determination

The most common quantitative methods used for PAEs determination are mainly gas chromatography (GC) and liquid

Table 4 Instrumental methods for analysis of PAEs arranged chronologically

Article	Analyte	Matrix	Sample preparation/ extraction	Analytical instrument; column (column dimension)	Injection mode/ temperature
Nerin et al. (2002)	DEP, DIBP, DBP, DEHP, etc.	Paper and board packaging	Extraction with ethanol; Supercritical fluid extraction using CO_2	GC-MS; SGL-5 (60 m × 0.25 mm × 0.25 μm)	260 °C
Casajuana and Lacorte (2004)	DMP, DEP, DBP, BBP, DEHP	Milk	Solid-phase extracted (C18), dichloromethane/hexane 4:1 *v*/*v*, methanol, water	GC-MS; EI; HP-5MS (5% phenyl and 95% methyl polysiloxane) (30 m × 0.25 mm × 0.25 μm)	Splitless (250 °C)
Serôdio and Nogueira (2006)	DMP, DEP, DBP, DEHP, etc.	Water	Stir bar sorptive extraction (20 mm × 0.5 mm PDMS)	LVI-GC-MS; TRB-5MS (30 m × 0.25 mm × 0.25 μm)	–
Bonini et al. (2008)	DMP, DEHP, DEP, DnBP, BBP, DCHP, etc.	Cling films	Soxhlet extraction using ethyl acetate	GC-FID, MDN-5 (95% dimetil-5% diphenyl silicone) (30 m × 0.25 mm)	Splitless mode (250 °C)
Leivadara et al. (2008)	DBP, DEHP	Drinking water	Liquid-liquid extraction using MTBE (DBP), liquid-liquid extraction using dichloromethane and methane (DEHP)	DBP: GC-ECD; fused silica DB-1 (30 m × 0.32 mm × 0.25 μm), DEHP: GC-MS; fused silica DB-5MS (30 m × 0.32 mm × 1.8 μm)	Split/splitless (DBP; 175 °C, DEHP; 200 °C)
Gärtner et al. (2009)	DiBP, DEHP, DOP, BBP, DnBP	Infant food in paperboard	Accelerated solvent extraction with iso-octane	GC-MS; EI; HP-5MS (30 m × 0.25 mm × 0.25 μm)	Splitless (250 °C)
He et al. (2010)	DMP, DEP, DBP, DNOP, etc.	Soybean milk	Molecularly imprinted solid-phase extraction (MISPE)	GC-MS; DB-5MS (30 m × 0.25 mm × 0.25 μm)	Splitless
Rios et al. (2010)	DMP, DEP, DIBP, BBP, DEHP, DOP, etc.	Olive oil	Headspace solid-phase microextraction	Ion-trap (IT); MS; ZB-5MS (30 m × 0.25 mm × 0.25 μm)	–/260 °C
Xu et al. (2010)	DMP, DEP, BBP, DBP, DEHP, DOP, etc.	Cooking oil, water	Solid-phase extraction by nylon 6 nanofibers mat	HPLC C18 (150 mm × 4.6 mm, 5 μm)	–
Amiridou and Voutsa (2011)	DMP, DEP, DBP, BBP, DEHP, DnOP	Water	Liquid-liquid extraction with dichloromethane	GC-MS; Rtx-5MS Crossbond 5% diphenyl-95% dimethyl polysiloxane column (30 m × 0.25 mm × 0.25 μm)	(280 °C)
Meng et al. (2011)	DMP, DEP, DiBP, DBP, BBP, DEHP, DnOP	Water	Polypyrrole-coated magnetic particles solid-phase microextraction	GC-MS; HP-5MS (30 m × 0.25 mm × 0.25 μm)	Splitless (250 °C)
Ostrovský et al. (2011)	DMP, DBP, DEP, DEHP, etc.	Fatty food	Liquid-liquid extraction chloroform/methanol mixture 2:1 *v*/*v*; NaCl	GC-FID and MS; DB-5 MS (30 m × 0.25 mm × 0.25 μm)	Splitless (280 °C)
Yan et al. (2011)	DMP, DEP, DBP, BBP, DNOP, etc.	Bottled milks	Ultrasound-assisted dispersive liquid-liquid microextraction	GC-FID; KB-1 (30 m × 0.25 mm × 0.25 μm)	Split ratio of 10 (290 °C)
Zhang et al. (2011)	DMP, DEP, DBP	Water	Ionic liquid cold-induced aggregation dispersive liquid-liquid microextraction	HPLC-VWD; C-18 (250 mm × 4.6 mm, 5 μm)	–
Cacho et al. (2012)	DMP, DEP, DBP, BBP, DEHP, DOP	Vegetables	Stir bar sorptive extraction (10 mm × 0.5 mm; 24 μL PDMS)	GC-MS DB-17 MS (30 m × 0.25 mm × 0.25 μm)	Splitless (PTV)
Farajzadeh and Mogaddam (2012)	DMP, DEP, DiBP, DBP, DEHP	Aqueous samples; water and vinegar	Air-assisted liquid-liquid microextraction		Splitless (300 °C)

Table 4 (continued)

Article	Analyte	Matrix	Sample preparation/ extraction	Analytical instrument; column (column dimension)	Injection mode/ temperature
			(AALLME) with 1,1,2,2-tetrachloroethane	GC-FID; SPB-1 (100% dimethyl siloxane) (30 m × 0.25 mm × 0.25 μm)	
Fasano et al. (2012)	DMP, DBP, BBP, DEHP	Food packaging	Solid-phase extraction	GC-MS DB-5 MS (30 m × 0.25 mm × 0.25 μm)	Splitless (290 °C)
Fierens et al. (2012)	DMP, DEP, DiBP, DnBP, BBP, DEHP, DCHP, DnOP	Food products and packaging	Solvent extraction with acetone/*n*-hexane 1:1; (aqueous) liquid-liquid extraction with dichloromethane; (fatty food) ultrasonic extraction with *n*-hexane (packaging)	GC-MS; EI; DB-XLB (60 m × 0.25 mm × 0.25 μm)	Splitless (250 °C)
Guo et al. (2012)	DMP, DEP, DBP, DIBP, BBP, DEHP	Food	Liquid-liquid extraction with hexane	GC-MS DB-5 MS (30 m × 0.25 mm × 0.25 μm)	–
Luo et al. (2012)	DMP, DEP, DiBP, DBP, BBP, DCHP, DEHP, DnOP, etc.	Water and beverages	Magnetic multi-walled carbon nanotubes solid-phase microextraction	GC-MS; Fused silica (30 m × 0.25 mm × 0.25 μm)	Splitless (250 °C)
Ranjbari and Hadjmohammadi (2012)	DMP, DEP, BBP, DBP	Water	Magnetic stirring-assisted dispersive liquid-liquid microextraction (MSA-DLLME)	HPLC-UV C18 (250 mm × 4.6 mm, 10 μm)	–
Self et al. (2012)	BBP, DBP, DiBP, DEHP, DnOP, etc.	Food and nutraceutical products	Direct analysis in real time (DART)	MS; positive ion mode	–
Ting et al. (2012)	DMP, DEP, DBP, DIBP, etc.	Fatty food	Dispersive solid-phase extraction	GC-MS HP-5MS (30 m × 0.25 mm × 0.25 μm)	Splitless (250 °C)
Cinelli et al. (2013)	DMP, DEP, DBP, BBP, DIBP, DEHP	Wine	Ultrasound-vortex-assited dispersive liquid-liquid microextraction	GC-FID and IT/MS; SE-54 (30 m × 0.25 mm × 0.25 mm)	Splitless (from 110 °C to 130 °C at 80 °C/min)
Khedr (2013)	DEHP	Soft drinks, milk powder	Solid-phase extraction	HPLC-ESI-MS/MS XDB-C8 (150 mm × 4.6 mm, 5 μm)	–
Tahmasebi et al. (2013)	DBP, DEHP	Water	Polythiophene-coated Fe_3O_4 superpara-magnetic nanoparticles solid-phase extraction	GC-FID; HP-5 (30 m × 0.32 mm × 0.25 μm)	Splitless (260 °C)
Wang et al. (2013)	BBP, DEHP, etc.	Soybean milk	Magnetic solid-phase extraction	HPLC-UV/VIS 225 nm; C18 (200 mm × 4.6 mm × 5 μm)	–
Yang et al. (2013)	DMP, DEP, DBP, DEHP, DOP	Edible oil	Solid-membrane extraction	HPLC-UV/VIS 230 nm; C18 (25 cm × 4.6 mm × 5 μm)	–
Zhang and Lee (2013)	DMP, DEP, DBP, BBp, DEHP, DnOP	Water	Low density solvent-based vortex-assisted surfactant-enhanced-emulsification liquid-liquid microextraction with toluene (extractant) and cetyltrimethyl ammonium bromide (surfactant)	GC-MS; DB-5MS (30 m × 0.25 mm × 0.25 μm)	Splitless (250 °C)

Table 4 (continued)

Article	Analyte	Matrix	Sample preparation/ extraction	Analytical instrument; column (column dimension)	Injection mode/ temperature
Zhu et al. (2013)	DMP, DEP, DCHP, DBP, DEHP, DIBP, BBP, etc.	Vegetable juices	Hollow fibre-liquid phase microextraction	GC-MS; DB-5MS (30 m × 0.25 mm × 0.25 mm)	Splitless (250 °C)
Cinelli et al. (2014)	DMP, DEP, DBP, BBP, DIBP, DEHP	Hydro-alcoholic food beverages	Solid-phase extraction with Amberlite XAD-2 adsorbent	GC-FID and IT/MS SE-54 (30 m × 0.25 mm × 0.24 μm)	Splitless (PTV)
Fan et al. (2014)	DIBP, DBP, BBP, DEHP	Alcoholic beverages	Conventional ionic liquid dispersive liquid-liquid microextraction	HPLC-DAD 240 nm; C18 (15 cm × 4.6 mm × 5 μm)	–
Hayasaka (2014)	DMP, DEP, DIBP, DNBP, BBP, DEHP, DOP, etc.	Wine	Filter (0.2 μm)	HPLC-MS/MS; C18 (75 mm × 2 mm × 4 μm)	–
Qiao et al. (2014)	BBP, DEP, DBP, DNOP, etc.	Plastic bottled beverages	Magnetic dummy molecularly imprinted dispersive solid-phase extraction (MAG-MIM-dSPE)	GC-FID KB-1 (30 m × 0.25 mm × 0.25 μm)	Split/splitless (290 °C)
Xu et al. (2014)	DMP, DEP, DBP, DCHP, DNOP, etc.	Milk, liquor, wine, grain, beverage, meat, biscuit, oil, canned food	QuEChERS Glass-based solid-phase extraction	HPLC-MS/MS; C18 (100 mm × 4.6 mm × 2.7 μm)	–
He et al. (2015)	DMP, DEP, DBP, BBP, DEHP, DNOP	Food	Ultrasonic extraction and liquid-liquid extraction (aqueous) with dichloromethane	GC-MS DB-5 (30 m × 0.25 mm × 0.25 μm)	Splitless (280 °C)
Hosaka et al. (2015)	DMP, DEP	Polymer-coated cup	Soxhlet extraction with hexane	TD-GC-MS 5%diphenyl 95% dimethylpolysiloxane (30 m × 0.25 mm × 0.25 μm)	–
Jeddi et al. (2015)	DBP, BBP, DEHP	Water	magnetic solid-phase extraction with PDMS/MWCNTs-OH	GC-MS HP-5 MS (30 m × 0.25 mm × 0.25 μm)	Splitless (290 °C)
Lin et al. (2015)	DMP, DEP, DIBP, BBP, DBP, DCHP, DEHP, DNOP, etc.	Milk	Extraction with ethyl acetate	GC-MS DB-5 (30 m × 0.32 mm × 0.25 μm)	Splitless (280 °C)
Makkliang et al. (2015)	DBP, DEHP	Chicken soup	Magnetic micro solid-phase extraction	GC-FID; DB-5 (30 m × 0.32 mm × 0.25 μm)	–
Otero et al. (2015)	DEHP, BBP, DBP, DCHP, DEP, DIBP, DMP, DNOP, etc.	Water and the packaging	Liquid-liquid extraction with dicholoromethane Packaging extracted by water-bath sonication	GC-MS; EI; DB-5 MS (30 m × 0.25 mm × 0.25 μm)	Splitless
Amanzadeh et al. (2016)	DBP, DEHP, etc.	Drinking water, vegetable oil	Graphene/polyvinyl chloride nanocomposite fibre headspace solid-phase microextraction	GC-FID; CP-Sil 8 CB (30 m × 0.32 mm × 0.25 μm)	Splitless (230 °C)
Du et al. (2016)	DMP, DEP, DBP, DIBP, DEHP	Tea	Simultaneous distillation extraction (SDE)	GC-MS; HP-5MS (60 m × 0.32 mm × 0.25 μm)	Splitless (300 °C)
Li et al. (2016)	BBP, DBP, DEHP, etc.	Disposable tablewares	Hexafluoro-isopropanol induced sodium dodecyl sulphate/ dodecyltrimethyl-ammonium-bromide cataionic surfactant coacervate extraction	HPLC; C18 (250 mm × 4.6 mm, 5 μm)	–

Table 4 (continued)

Article	Analyte	Matrix	Sample preparation/ extraction	Analytical instrument; column (column dimension)	Injection mode/ temperature
Pérez-Outerial et al. (2016)	DBP, BBP, DEHP, DNOP, etc.	Food, Water	Ultrasound-assisted dispersive liquid-liquid microextraction followed by solidification of floating organic drop	GC-FID; HP-5 (30 m × 0.25 mm × 0.25 μm)	Splitless (300 °C)

Article	Oven temperature	Quantification method	Recover %/RSD %	LOD (LOQ)
Nerin et al. (2002)	65 °C (2 min) to 300 °C (5 °C/min, 6 min)	External standard	–	–
Casajuana and Lacorte (2004)	60 °C (1 min) to 175 °C (6 °C/min, 1 min) to 280 °C (3 °C/min) to 300 °C (7 °C/min)	Internal standard (deuterated DEHP)	73–119	0.06–0.36 μg/kg
Serôdio and Nogueira (2006)	70 °C (25 °C/min, 2 min) to 150 °C (25 °C/min) to 170 °C (3 °C/min) to 185 °C (3 °C/min) to 195 °C (3 °C/min) to 255 °C (60 °C/min) to 280 °C (8 °C/min) (held during 4 min) in a 24.50 min	–	5.1–98.5/2.2–4.8	3–40 ng/L
Bonini et al. (2008)	50 °C (2 min) to 150 °C (40 °C/min, 1 min) to 310 °C (8 °C/min,5 min)	Internal standard (methylmargarate)	–	13.88–141.41 mg/L
Leivadara et al. (2008)	DBP; 35 °C (9 min) to 40 °C (1 °C/min, 3 min) to 220 °C (6 °C/min, 10 min), DEHP; 50 °C (4 min) to 170 °C (20 °C/min) to 270 °C (8 °C/min) for 10 min	External standard	–	–
Gärtner et al. (2009)	70 °C (3 min) to 280 °C (40 °C/min, 20 min)	Internal standard (deuterated PAEs)	88.7–105.2	0.005–0.095 μg/g (0.016–0.295 μg/g)
He et al. (2010)	150 °C to 170 °C at 30 °C/min, to 300 °C (40 °C/min, 3 min)	External standard	75.8–107.5/1.82–10.11	0.013–0.022 μg/mL
Rios et al. (2010)	70 °C (2 min), to 200 °C (6 °C/min, 5 min), to 295 °C (4 °C/min, 8 min)	Internal standard (benzylbenzoate)	–/<20	0.02–0.05 mg/kg
Xu et al. (2010)	–	External standard	<88.37/>6.92 (water) <85.92/>7.03 (oil)	0.001 μg/L (water) 0.020 μg/L (cooking oil)
Amiridou and Voutsa (2011)	60 °C (1.5 min) to 180 °C (20 °C/min) to 230 °C (5 °C/min) to 310 °C (20 °C/min, 5 min)	Internal standard (DnOP-d_4)	70–94/–	2–30 ng/L
Meng et al. (2011)	60 °C (1 min) to 280 °C (15 °C/min, 4 min)	External standard	91.9–113.4/3.4–11.7	0.006–0.068 μg/L
Ostrovský et al. (2011)	40 °C (20 °C/min) to 320 °C	External standard	–/<15	0.4 (1.2) μg/g
Yan et al. (2011)	150 °C (2 min) to 285 °C (25 °C/min, 10 min)	External standard	93.2–105.7/<4.0	0.64–0.79 ng/g
Zhang et al. (2011)	–	External standard	69.9–84.8/2.2–3.7	0.68–1.36 ng/mL
Cacho et al. (2012)	75 °C (0.5 min) to 200 °C (25 °C/min) to 275 °C (50 °C/min, 5 min)	Internal standard (anthracene)	83–118.5/<3.2–5.5	15.8–106 pg/g
		External standard	89–102/<4.0	0.12–1.15 ng/mL (0.85–4 ng/mL)

Table 4 (continued)

Article	Oven temperature	Quantification method	Recover %/RSD %	LOD (LOQ)
Farajzadeh and Mogaddam (2012)	90 °C (2 min) to 190 °C (20 °C/min) to 210 °C (10 °C/min) to 290 °C (15 °C/min, 4 min)			
Fasano et al. (2012)	65 °C (2 min) to 160 °C (15 °C/min) to 170 °C (3 °C/min) to 310 °C (10 °C/min, 10 min)	Internal standard (DPP D4, anthracene D10)	61–143/2–23	18–451 ng/L for EC[a]; 13–368 ng/L for UE[b]
Fierens et al. (2012)	50 °C (1 min), to 320 °C (15 °C/min, 15 min)	Internal standard (deuterated PAEs)	82–104/<14	(1–230 μg/kg) high fat; (0.1–20 μg/kg) low-fat; (0.01–0.03 μg/kg) aqueous; (0.1–1.5 μg/kg) packaging
Guo et al. (2012)	–	Internal standard (deuterated PAEs)	56–101/3–25	(0.002–762 ng/g)
Luo et al. (2012)	60 °C (1 min) to 220 °C (20 °C/min, 1 min) to 280 °C (5 °C/min, 4 min)	External standard	64.6–125.6/<16.5	4.9–38 ng/L
Ranjbari and Hadjmohammadi (2012)	–	External standard	26.54 (DMP), 82.67–98.92/<2.61	0.13–0.38 μg/L (0.43–1.27 μg/L)
Self et al. (2012)	–	External standard	–	0.5–1.0 μg/mL (food), 0.5–50 μg/g (nutraceutical)
Ting et al. (2012)	60 °C (1 min) to 220 °C (20 °C/min, 1 min), to 280 °C (5 °C/min, 4 min)	Matrix-matched standard	70.9–125.4/<9.8	100–800 μg/kg
Cinelli et al. (2013)	10 °C/min	Internal standard (anthracene)	85–100.5/<8.2	≥0.022 μg/L (≥0.075 μg/L)
Khedr (2013)	–	Internal standard (propyl-paraben)	97.0–102.8/≤2.2–3.9	water, soft drink: 13 (46) ng/L; milk powder: 650 (2300) ng/kg
Tahmasebi et al. (2013)	150 °C (1 min) to 215 °C (15 °C/min) to 260 °C (8 °C/min) to 280 °C (20 °C/min, 3 min)	External standard	85–92/<3.2–12.2	0.2–0.4 μg/L
Wang et al. (2013)	–	Matrix-matched standard	87.2–103.4/3.1–6.2	0.52–50.9 ng/mL
Yang et al. (2013)	–	External standard	85.92–101.03/<5.3–7.0	0.02–0.15 ng/mL
Zhang and Lee (2013)	100 °C to 280 °C (10 °C/min, 4 min)	External standard	73.5–106.6/<11.7	8–25 ng/L
Zhu et al. (2013)	60 °C (1 min), to 220 °C (20 °C/min, 1 min), to 280 °C (5 °C/min, 4 min)	External standard	71.8–90.1/2.1–18.9	0.0001–0.01 mg/L
Cinelli et al. (2014)	100 °C to 300 °C at 10 °C/min	Internal standard (anthracene)	94–103/6.5–13.7	1.21–2.51 pg/μL (2.42–5.03 pg/μL)
Fan et al. (2014)	–	External standard	88.5–104.6/<8.0	1.5–4.2 ng/mL
Hayasaka (2014)	–	Deuterium-labelled internal standard	94.6–105.7/2.1–6.7	1.6–26.6 μg/L (0.5–8.8 μg/L)
Qiao et al. (2014)	150 °C (2 min) to 285 °C (25 °C/min, 10 min)	External standard	89.5–101.3/3.1–6.9	0.53–1.2 μg/L (1.8–4.0 μg/L)
Xu et al. (2014)	–	External working calibration	75.7–115.2/3.2–18.9	0.8–15 μg/kg (10–100 μg/kg)
He et al. (2015)	70 °C to 120 °C (15 °C/min) to 280 °C (10 °C/min) for 5 min	Internal standard (phenantherene)	85.7–102.6/<10	0.14–0.38 ng/g (solid), 0.0021–0.0096 ng/mL (liquid)
Hosaka et al. (2015)	100 °C to 320 °C (20 °C/min) to 320 °C for 5 min	External standard	–/<3	–
Jeddi et al. (2015)	50 °C (1 min) to 280 °C (30 °C/min) to 310 °C (15 °C/min, 4 min)	Internal standard (benzyl benzoate)	–	0.01–0.025 μg/L (0.025–0.05 μg/L)
Lin et al. (2015)	120 °C (4 min) to 220 °C (5 °C/min) to 300 °C (20 °C/min) for 6 min	External standard	79.1–110.3/<8.6	0.09–0.36 ng/g
Makkliang et al. (2015)	–	Matrix-matched standard	70–118/<4.6–10.2	26.3,36.4 ng/mL (88, 121 ng/mL)
Otero et al. (2015)		Internal standard (benzyl benzoate)	87.13 ± 3.54/<10.2	

Table 4 (continued)

Article	Oven temperature	Quantification method	Recover %/RSD %	LOD (LOQ)
	Method 1. 180 °C (0.5 min) to 280 °C (20 °C/min) for 7 min Method 2. 50 °C (1 min), to 280 °C (30 °C/min) to 310 °C (15 °C/min) for 4 min			16.08–114.67 ng/mL (17.58–125.32 ng/mL)
Amanzadeh et al. (2016)	100 °C (1 min) to 190 °C (7 °C/min) to 260 °C (10 °C/min) to 280 °C (30 °C/min, 5 min)	External standard	87–112/<8.3	0.06–0.08 μg/L
Du et al. (2016)	60 °C, to 120 °C (5 °C/min, 2 min), to180 °C (2 °C/min, 5 min), to 250 °C (6 °C/min, 12 min)	External standard	79.83–116.67 (tea samples) 78.22–101.64 (tea infusions)/<20	0.24–3.72 μg/kg
Li et al. (2016)	–	External standard	82.4–123.6/0.4–7.4 (intra-day) 0.6–7.8 (inter-day)	1.0–2.6 ng/mL
Pérez-Outerial et al. (2016)	160 °C for 1 min, to 200 °C (10 °C/min), to 255 °C (2 °C/min)	External standard	–/2.7–9.3	0.64–2.82 μg/L

[a] Extreme condition

[b] Ultrasonic extraction

chromatography (LC). PAEs have low molecular weight, relatively low polarity, thermally stable and sufficiently volatile to be analysed by GC methods. GC-MS equipped with a DB-5MS column coated with 5% phenyl-95% dimethylpolysiloxane carried out in selected ion monitoring (SIM) mode is one of the most widely used techniques for the analysis (Casajuana and Lacorte 2003; Blüthgen and Heeschen 1998; Petersen and Breindahl 2000; Frankhauser-Noti and Grob 2006; Yang et al. 2015; Gärtner et al. 2009). Even though low detection limit is strongly influenced by the secondary contamination problems, GC techniques however can allow low detection limits to be achieved especially by splitless injection. Other than GC-MS, electron ionization (EI)-MS, chemical ionization (CI)-MS using methane as the reagent gas in either positive or negative mode, GC-MS/MS under positive chemical ionization using isobutene as reagent gas and gas chromatography-flame ionization detector (GC-FID) have also been used for identification and quantification of PAEs in food samples (Moret et al. 2012).

LC such as HPLC using C18-columns running either in isocratic or gradient elution have also been widely used for the determination of PAEs in food samples due to its ability in analysing thermally-unstable and non-volatile organic chemicals (Moret et al. 2012; Yang et al. 2015). The recoveries (R), relative standard deviations (RSD), limit of detections (LOD) and limit of quantifications (LOQ) may vary when using different extraction and instrumental analysis which are summarized in Table 4 with the analytes stated only focusing on the most common PAEs. However, even though the analysis depends on the pre-treatment step, instrumental conditions and the sample matrix in which they are obtained, several studies had concluded that GC methods are able to obtain better LODs than HPLC methods (Moret et al. 2012; Bošnir et al. 2007; Ostrovský et al. 2011; Kozyrod and Ziaziaris 1989; Petersen 1991; Prokůpková et al. 2002).

Comparison of Sample Preparation Methods

Based on the literature review, the advantages and drawbacks of various sample preparation/extraction methods of PAEs analysis in food/beverages and food packaging materials are presented in Table 5. In the authors' opinion, QuEChERS is an interesting method as its simplicity in sample preparation and extraction with the use of low quantities of organic solvent, low cost, as well as requiring only a short amount of time has gained particular interest from researchers. This method is highly efficient in detecting target compound where it has successfully extracted 23 PAEs from food samples when paired with HPLC-MS/MS. A recent study performed by Dong et al. (2017) using the QuEChERS-GC/MS method was able to analyse 14 PAEs from wheat samples; with satisfactory recoveries between 84.8–120.3% and RSD of 0.6–

Table 5 Advantages and drawbacks of each sample preparation/extraction method used

Sample preparation/extraction methods	Extractants/adsorbents	Advantages	Drawbacks
Liquid-liquid extraction (LLE)	➢ Organic solvents	➢ Non-fatty liquid samples: no clean-up procedure ➢ Low cost ➢ Reduced extraction time	➢ Oils and fatty extracts: clean-up using different SPE phase such as silica or Florisil ➢ Fatty solid foods: some proposed additional step • The addition of aluminium oxide and sodium chloride solution to decrease interference from proteins, fats and other components • The addition of sodium chloride/sodium sulphate to eliminate water • Clean-up with gel permeation chromatography (GPC) and gas-purge microsyringe extraction (GP-MSE)
Dispersive liquid-liquid microextraction (DLLME)	➢ Commonly chloro-containing organic extractants, or ➢ Ionic liquids as green extractants	➢ Better efficiency, simplicity and rapidity than LLE ➢ Only few microliters organic solvent is required ➢ Fast ➢ Inexpensive ➢ Only involve simple equipment ➢ Low cost	➢ Possible environmental pollution due to the chloro-containing organic solvents but only microliters are used ➢ Ionic liquids are • Unstable • Tendency to decompose when in contact with some metallic catalysts • The synthesis of ionic liquids requires few toxic solvents • Complex purification process • High cost • Limited wide application ➢ Samples are not well separated: may require further centrifugation ➢ Disperser solvent peaks may overlap with analyte peaks
Ultrasound-assisted dispersive liquid-liquid microextraction (UA-DLLME)		➢ Reduce the volume of solvent used ➢ Simple, inexpensive and more reliable than DLLME	
Ultrasound-vortex-assisted dispersive liquid-liquid microextraction (USVADLLME)		➢ Reduce the volume of solvent used ➢ Improve extraction efficiency ➢ Able to analyse matrices with large alcohol content ➢ Able to detect trace and ultra-trace levels	
Magnetic stirring-assisted dispersive liquid-liquid microextraction (MSA-DLLME)	➢ Low-density extraction solvent (dodecane)	➢ Simple, fast and efficient ➢ No disperser solvent which increase extraction recovery	➢ Use of dodecane result in poor response of DMP
Air-assisted liquid-liquid microextraction (AALLME)	➢ 1,1,2,2-Tetrachloroethane	➢ Higher efficiency ➢ Clear blank chromatogram	➢ Possible environmental pollution due to the chloro-containing organic solvents but only microliters are used
Low density solvent-based vortex-assisted surfactant-enhanced-emulsification liquid-liquid microextraction (LDS-VSLLME)	➢ Toluene (extraction solvent) ➢ Cetyltrimethyl ammonium bromide (surfactant)	➢ Reduced amount of organic dispersive solvent compared to conventional DLLME ➢ High extraction efficiency due to the surfactant and vortex agitation ➢ Fast, efficient, simple, cost-effective	➢ Extraction efficiency decreased with increasing salt content in water samples
Solid-phase extraction (SPE)	➢ C18 ➢ C8 ➢ Polystyrene ➢ XAD-2 adsorbents ➢ Multiwall carbon nanotubes (MWCNTs) ➢ XAD-2 adsorbents	➢ Reduce the use of solvents ➢ Improving extraction efficiency ➢ Yield more purified extracts	➢ Often requires extensive sample handling and treatment of sample prior to analysis ➢ High blank values ➢ Requires clean-up using Florisil ➢ Clogging of cartridges

Table 5 (continued)

Sample preparation/extraction methods	Extractants/adsorbents	Advantages	Drawbacks
Molecularly imprinted polymer-solid-phase extraction (MISPE)	➢ Polymer	➢ Higher selectivity, sensitivity and reliability than SPE	➢ Usually require a polymer synthesis step
Magnetic dummy molecularly imprinted dispersive solid-phase extraction (MAG-MIM-dSPE)	➢ Magnetic nanosorbents such as: • Multi-walled carbon nanotubes (MWCNTs) • Single-walled carbon nanotubes (SWCNTs) • Graphene • Phthalates • Polypyrrole-coated Fe_3O_4 magnetic microsphere • Polythiophene-coated Fe_3O_4 supermagnetic nanosorbent	➢ Simple ➢ Low cost ➢ Environmentally friendly ➢ Able to eliminate co-existent interferents ➢ Polypyrrole-coated Fe_3O_4 has large surface area, thus • Convenient • Fast separation ability • Prevent aggregation of microspheres • Improve dispersibility ➢ Polythiophene-coated Fe_3O_4 • Shorter extraction time as no time consuming column passing, filtration or centrifugation • Low consumption of organic solvent • Higher adsorption capacity due to higher surface area-to-volume ratio thus more efficient extraction	➢ Magnetic sorbents should be modified • To increase monodispersity ➢ New coatings should be developed • To protect magnetic cores • To enhance dispersity in sample solutions • To obtain multifunctional magnetic sorbents
Solid-phase microextraction (SPME)	➢ PDMS/DVB (polydimethylsiloxane/-divinylbenzene) fibre	➢ In comparison to SPE, SPME is • Simple and efficient • Low cost • Solvent-free • Does not require any prior sample preparation • Able to reduce the risk of secondary contamination • High sensitivity	➢ Limited life-time with the use of fibre due to the fragility and degradation ➢ Batch- to-batch variation, artefact formation and low repeatability ➢ Low capacity
Headspace SPME (HS-SPME)		➢ No sample manipulation is required and hence minimizing cross contamination from glassware, solvents and samples	➢ Fibres have tendency to break and are relatively expensive
Direct immersion SPME (DI-SPME)		➢ Simple, reduce the volume of solvents used, better linearity, repeatability and sensitivity	
Stir bar sorptive extraction (SBSE)	➢ PDMS	➢ Higher sample capacity, recovery and sensitivity improvement by a factor of 100–1000 in comparison with SPME ➢ Better sensitivity than LLE and SPE ➢ Low detection limits at the sub-ng/L level ➢ No clean-up required for liquid samples	➢ Limited to PDMS sufficiently enriched substances ➢ Batch- to-batch variation, artefact formation and low repeatability
Soxhlet extraction	➢ Organic sovents	➢ Simple, minimum sample handling ➢ Sample-fresh solvent ➢ No filtration procedure ➢ Good reproducibility and efficiency ➢ Minimal steps required prior to extraction	➢ Time consuming ➢ Requires large amount of solvent and sample ➢ Contamination and may cause loss of some analytes in the pre-concentration steps
Ultrasonic extraction (UE)	➢ Organic solvents		

Table 5 (continued)

Sample preparation/extraction methods	Extractants/adsorbents	Advantages	Drawbacks
		➢ Simple, minimum sample handling	➢ May requires additional steps prior to extraction such as migration test in which the food simulants are then extracted with SPE ➢ Or additional step where exchanging the sample extracts was done with CH_2Cl_2 followed by purification with GPC or GP-MSE
Supercritical fluid extraction (SFE)	➢ CO_2 ➢ Ethanol ➢ Methanol	➢ Easy, requires minimum handling and time ➢ Requires only small amount of organic solvent ➢ Safe and environmentally friendly ➢ Additional migration tests could be avoided as SFE technique provides a good way to evaluate the potential chemical migration to food, thus assuming 100% migration ➢ No pre-treatment is required	➢ High cost as it requires high pressure ➢ The optimization of SFE procedure may need to be carried out depending on experimental design
Acelerated solvent extraction (ASE)	➢ Organic solvents	➢ Fast extraction ➢ Low amount of solvents used ➢ Better analyte recovery	➢ High cost with the use of high temperature and pressure ➢ Use of deuterated corresponding phthalates which are costly ➢ Migration test is required and performed over a period of 2 months
Direct analysis in real time (DART)	➢ (Ionizes gases, liquids, solids)	➢ Direct and rapid analysis ➢ No sample pre-treatment is required ➢ Analysis under ambient conditions ➢ Reduced cross contamination	➢ High cost ➢ High LOD
Membrane filtration-enrichment SPE	➢ Nylon membrane	➢ More rapid, sensitive and selective than conventional SPE	➢ Selection of membranes may be difficult if multiple analytes are analysed simultaneously ➢ Large amount of solvent is used
QuEChERs (quick, easy, cheap, effective rugged and safe)	➢ Organic solvents	➢ Fast, simple and inexpensive ➢ Low solvent usage and waste ➢ Minimum handling ➢ Only requires few devices to carry out this procedure; small work space, mobile lab	➢ May require primary secondary amine to remove possible co-extracted matrix ingredients that can be mistaken as analyte and eluted at the same time
Hollow fibre-liquid phase microextraction (HF-LPME)	➢ Organic solvents	➢ Higher efficiency than SPME	➢ Manipulation of hollow fibre may introduce contamination

9.0% for intra-day and inter-day precision, respectively, whereas the LOD ranged from 0.1–2.5 μg/kg.

On the other hand, 3 different extraction methods as performed by Fierens et al. in 2012 has analysed as many as 400 food samples of various matrices. High-fat and low-fat food were extracted with acetone/*n*-hexane mixture followed by centrifugation and a clean-up by gel permeation chromatography, while a liquid-liquid extraction with dichloromethane was used for aqueous-based beverages and in the case of food packaging materials, ultrasonic extraction with *n*-hexane was carried out. This study has successfully analysed 8 PAEs with LOD levels in the range of 0.003–0.3 ppb, recoveries between 82 and 104% and RSD of below 14%.

In 2012, Guo et al. also did a study on analysing 9 PAEs from 78 various food samples which were sorted into 3 different matrices for extraction such as liquid samples, solid food sample and cooking oil. Although this study has only performed extraction simply by liquid extraction and a liquid-liquid partition clean-up in the case of solid food samples and cooking oil, it was able to achieve detection limit down to 1 ppt level.

Conclusion

The widespread use of products containing PAEs has caused growing concerns on their effects on human health; this has prompted researches in the development of sample preparation and analytical methods for the determination of PAEs in the last two decades. This review shows that there has been an increase in the number of PAEs being analysed in increasing types of food matrices especially in the last 5 years. Methods of sample preparation have progressed towards the use of green extractants as well as minimizing the use of organic solvent that could lead to environmental pollution. GC and HPLC with various detectors such as MS, FID and ECD are still widely used as the preferred instruments for the PAEs analysis with the levels of LOD improved to as low as 1 ppt level.

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Conflict of Interest Nur Zatil Izzah Haji Harunarashid declares that she has no conflict of interest. Lee Hoon Lim declares that she has no conflict of interest. Mohammad Hilni Harunsani declares that he has no conflict of interest.

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