Journal of Chromatography A, 1217 (2010) 2521–2532

Contents lists available at ScienceDirect

Journal of Chromatography A

journal homepage: www.elsevier.com/locate/chroma

Review

Recent developments in matrix solid-phase dispersion extraction

Anna Laura Capriotti, Chiara Cavaliere, Piero Giansanti, Riccardo Gubbiotti, Roberto Samperi, Aldo Laganà*

Dipartimento di Chimica, Sapienza Università di Roma, Box n° 34 - Roma 62, Piazzale Aldo Moro 5, 00185 Rome, Italy

ARTICLE INFO

Article history:
Available online 18 January 2010

Keywords:
Matrix solid-phase dispersion
Extraction
Sample preparation

ABSTRACT

Matrix solid-phase dispersion is a sample preparation strategy widely applied to solid, semisolid or viscous samples, including animal tissues and foods with a high lipidic content. The process consists in blending the matrix onto a solid support, allowing the matrix cell disruption and the subsequent extraction of target analytes by means of a suitable elution solvent. First introduced in 1989, MSPD employment and developments are still growing because of the feasibility and versatility of the process, as evidenced by the several reviews that have been published since nineties. Therefore, the aim of the present review is to provide a general overview and an update of the last developments of MSPD.

Contents

1. Introduction

The isolation of compounds of interest from environmental, food or biological matrices is always a key step in the development of an analytical method, and often a previous disruption of the general sample architecture is needed [1]. During the years, the classical solid-phase extraction (SPE) technique has evolved to meet the need of monitoring several classes of substances in samples of different origin, often present at trace levels. Then, matrix solid-phase dispersion (MSPD), microwave-assisted extraction (MAE), supercritical-fluid extraction (SFE) and pressurized liquid extraction (PLE) have been developed [2].

MSPD is a patented process first introduced in 1989 by Barker et al. [3], for disrupting and extracting solid samples [4]. The novelty of the technique consisted in obtaining isolation of target analytes by dispersing tissues onto a solid support, avoiding many of the difficulties encountered by employing the classical SPE approach [4], such as the need of sample homogenization and tissue debris removal prior to column application, as well as incomplete cell disruption [3]. Briefly, in the Barker's seminal work, MSPD extraction (MSPDE) was performed by blending bovine tissues with an appropriate amount of lipophilic solid-phase packing material (C18) in a glass mortar with a glass pestle, to produce a semi-dry, apparently homogeneous, easy to handle material [3]. Then, the obtained powder was packed into a common syringe barrel SPE column, from which target compounds were isolated with a suitable elution solvent. In fact, the blending of sample with an abrasive solid support allowed the mechanical disruption of the matrix structure, as confirmed by scanning electron microscopy observations [5]. The main

* Corresponding author. Tel.: +39 06 49913679; fax: +39 06 490631.
E-mail address: aldo.lagana@uniroma1.it (A. Laganà).

0021-9673/$ – see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.chroma.2010.01.030

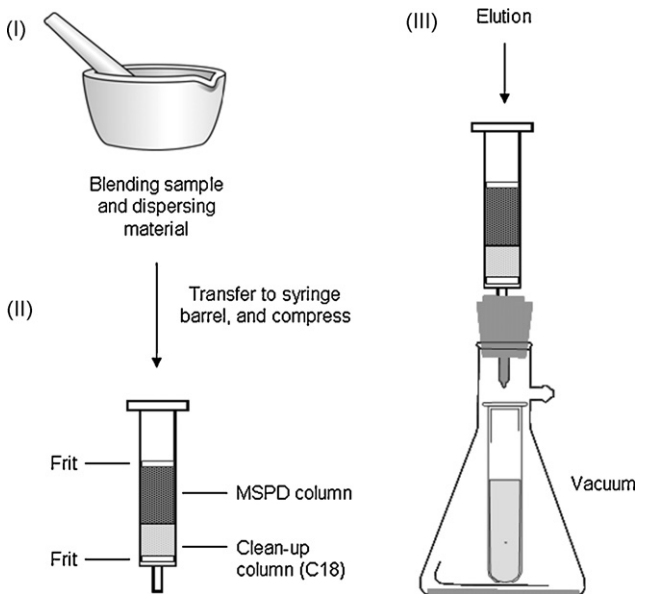

Fig. 1. Matrix solid-phase dispersion procedure. Main steps of the matrix solid-phase dispersion extraction procedure: (I) the sample is blended with the dispersant material in a mortar with a pestle; (II) the homogenized powder is transferred in a solid-phase extraction cartridge, and compressed; (III) elution with a suitable solvent or solvent mixture is performed by the aid of a vacuum pump.

steps of the process, already described deeply elsewhere [2–5], are reported in Fig. 1.

Since 1989, MSPD has been applied to the extraction of a large number of organic substances, both exogenous (drugs, pollutants, pesticides) and endogenous ones (food and bacteria components, etc.) from solid, semi-solid, and viscous matrices (animal tissues, blood, milk, bacteria, fruits, vegetables, etc.) [1–2,5,6], with some modifications. Most of MSPDE applications regard determination of xenobiotics in food [5], but this technique is particularly suitable for obtaining a complete cellular disruption of plants, bacteria and fungi, whose cell walls need more drastic conditions for lysis than animal cells [1].

The great interest for MSPD is due to the several advantages it offers, and its simplicity and flexibility have contributed to its diffusion over more classical sample preparation methods [7]. In fact, differently from classical extraction methods that require often clean-up steps, large amount of samples, sorbents and organic solvents [2] and thus are expensive and time consuming, MSPDE is rapid, less manual-intensive, and more eco-compatible. After extraction, further sample clean-up is required or not depending on target analytes and instrumentation employed for their detection [3]. Generally, after MSPDE, a liquid-chromatography (LC) or gas-chromatography (GC) separation is followed by mass-spectrometric determination (MS); less frequently, LC is coupled to UV or fluorescence detection (FLD), and GC to electron capture detection (ECD).

For all these reasons, the MSPDE protocol is considered a valid alternative to Soxhlet and MAE, as well as SFE and PLE. In fact, respect to the above mentioned techniques, MSPD requires mild extraction conditions (room temperature and atmospheric pressure) providing acceptable yield and selectivity [6]. Nevertheless, sometimes MSPD has been employed in conjunction with PLE, because the use of solvents at high temperatures and pressures can lead to increased analyte recoveries when the analytes interact strongly with the solid matrix. Moreover, MSPDE may also be improved by extracting the analytes with solvent in an ultrasonic bath before elution [2,8].

Searching in the scientific literature with the database SciFinder Scholar, in the period 1990–September 2009 the query "matrix solid-phase dispersion" gives 477 entries, 360 of which are papers or reviews written in English. Analyzing the distribution over the years of these 360 publications, it is possible to note an increasing employment of MSPD protocol in the period 2007–2009 respect to the past (see Fig. 2).

In the last ten years, several reviews focused on MSPD mechanism, strategies, advantages, applications and recent developments have been published [2,4–9]. In particular, Barker [4,5,7] described the MSPD applications for the isolation of a wide variety of analyte classes, such as drugs, pesticides, polychlorinated biphenyls, antibiotics and antibacterials, surfactants and naturally occurring compounds, in different matrices (mainly of animal origin, but also vegetables and environmental samples), pointing the attention on the performances and the advantages of MSPDE over the other extraction techniques suitable for solid or semi solid samples.

In the same period, other reviews presenting the sample preparation and extraction techniques employed in a particular analytical chemistry field, have described MSPD application for the determination of: pesticide residues in food [10–12], in fatty vegetable matrices [13], in olives and olive oil [14], and in soil [15]; veterinary drug residues in food [16–18]; and persistent organic contaminants in biota samples [19]. Therefore, the aim of this review is to provide a general overview and an update of the last developments of MSPD from 2007 to present (see Table 1).

2. General MSPD principles

Barker and et al., the first to develop and apply the MSPDE on different matrices, described in a very exhaustive manner its physical principles [1,3–5,7]. Even if MSPDE has many characteristics in common with classical SPE (i.e. the distribution of substances in the material depends on the interactions with the bound phase and solid support, with dispersed sample matrix components, and with the eluting solvents, as well as on molecular size) the mechanism governing the two processes is quite different. In fact, Barker et al. [1] observed that MSPD possesses retention properties that seem a mix of partition, adsorption and paired ion/paired chromatography. Whichever the exact mechanisms may be, MSPD selectivity strictly depends on both the nature of the sorbent materials and the elution solvent employed [2]. Most of MSPD applications employ lipophilic sorbent material such as C18-bonded silica and, less frequently, C8-bonded silica [7]. In fact Barker et al. [3] concluded that the lipophilic portion bound to a solid support helps in dispersing tissues and disrupting cell membranes, assuming the same role of the surfactants and detergents employed in classical methodologies. The hypothesis of authors was that cell membranes could be disrupted through the solubilization of phospholipid component and cholesterol into the C18 material, with undoubted advantages for extraction yield. However, in the following developments and applications, different dispersing materials, with very diverse surface nature and selectivity (underivatized silica, sand, synthetic polymers, Florisil, graphitic fibres, etc.) were tested [7], therefore a first classification of MSPD can be done on the basis of dispersing sorbent characteristics.

The solvents selected for elution are strictly connected to the nature of solid material. Normally, organic solvent mixtures are employed, but in some applications (mainly belonging to PLE procedures), hot water gave satisfactory results [9]. As in classical SPE, two strategies can be followed to obtain a clean extract: a washing step with an appropriate solvent can be carried out before target compound elution; otherwise, analytes can be eluted while interfering matrix components are retained by the sorbent [2]. A detailed discussion about the extraction strategies in MSPDE can be found in the paper by García-López et al. [6].

Table 1
Matrix solid-phase dispersion applications.

Target compounds	Matrix	Dispersing material (amount)	Matrix/sorbent ratio	Elution solvent (v/v)	Clean-up[a]	MQL (μg kg^{-1})	Detection	Ref.
Animal tissues and food of animal origin								
Alkylphenol, bisphenol A	Milk, eggs	C18	1:1 1:2	10 mL methanol	SPE on aminopropyl	n.r.[b]	LC/ESI–MS/MS	[98]
Arsenical species	Mussel (dry)	DE[c] (1.75 g)	1:7	10 mL methanol:water (50:50)	C18	21.3–77.8	LC–ICPMS	[71]
Chloramphenicol	Fish tissues (dried)	MIPs (0.07 g)	10:7	0.5 mL methanol:acetic acid (90:10)	–	3.9	LC–UV	[82]
Cypermethrin	Bovine milk	C18 + Na_2SO_4 (1 g + 1 g)	1:4:4	10 mL acetonitrile	Florisil	80	GC–MS	[35]
Fluoroquinolones	Chicken eggs swine tissues	MIPs (0.2 g)	1:1	4 mL acetonitrile:TFA (99:1)	–	n.r.[b]	LC–FLD	[80]
Fluoroquinolones	Serum	MIPs (0.1 g)	1:1	4 mL acetonitrile:TFA (99.5:0.5)	–	30–45	LC–DAD	[81]
Fluoroquinolones, organophosphorus, *N*-methyl carbamates	Porcine tissue	C18	1:4	6 mL *n*-hexane + 8 mL acetonitrile	–	9–20	LC–DAD	[36]
Macrolides and lincomycin	Whole milk and yoghurt	Crystobalite (6 g)	1:4	5 mL acidified water at 70 °C	–	0.2–1 (milk, μg L^{-1}); 1–7 (yoghurt)	LC/ESI–MS/MS	[76]
OCPs PDBEs	Mussels and cockles (dry)	C18 (0.4 g)	1:4	1.2 mL acetonitrile	Florisil	1–23	GC–ECD	[32]
OCPs, pyrethroid pesticides, PCBs	Fatty foods	Celite (1.5 g)	1:3	5 mL DMSO	Florisil	5–10	GC–ECD	[70]
OCPs, OPPs	Liver	C18 (2 g)	1:4	10 mL ethyl acetate	Florisil	n.r.[b]	GC–MS/MS	[99]
OCPs, OPPs, PCBs	Eggs	C18 (2 g)	1:4	1.5 mL acetonitrile:*n*-hexane (85:15) + 8.5 mL ethyl acetate	Florisil	0.02–7.78	GC–MS/MS	[34]
OPPs	Bovine muscle and liver	C18 (2 g)	1:4	5 mL acetonitrile	SPE on silica	75–200 (muscle); 150–300 (liver)	LC–UV	[30]
PAHs	Mussels, tellins (dry)	C18 (0.4 g)	1:4	1.2 mL acetonitrile	Florisil (co-sorbent) + in-tube SPME	n.r.[b]	LC–FLD	[37]
PCBs	Foodstuffs	SiO_2–HSO_4 + Na_2SO_4 (0.5 g + 0.5 g)	1:2	3.5 mL *n*-hexane at 40 °C	SiO_2 + HSO_4 + SiO_2	n.r.[b]	GC–μECD	[66]
Progestogens	Egg	C18 (2 g)	1:4	8 mL methanol	SPE on GCB	0.6–5.0	LC/ESI–MS/MS	[41]
Pyrethroids	Porcine tissues	Allumina (2 g)	1:4	20 mL *n*-hexane	Diatom. earth	26–56	LC–UV	[46]
Quinolones	Bovine tissues	Crystobalite (6 g)	1:4	4 mL water at 100 °C	–	3–23	LC/ESI–MS/MS	[75]
Quinolones	Egg	Crystobalite (6 g)	1:4	6 mL acidified water at 100 °C	–	0.2–0.6	LC/ESI–MS/MS	[73]
Quinolones	Milk	Crystobalite (6 g)	1:4	6 mL water at 90 °C	–	0.3–1.5 (μg L^{-1})	LC/ESI–MS/MS	[74]
Sulfonamides	Animal tissues	C18 (2 g)	1:2	6 mL methanol at 0 °C	–	0.2–0.4 (homog. meat); 0.3–1.0 (raw meat)	LC/ESI–MS/MS	[27]
Sulfonamides	Meat	Allumina N-S (2 g)	1:4	10 mL ethanol:water (70:30)	–	8–32	LC/APCI–MS LC–DAD	[51]
Tetracyclines	Cheese	Crystobalite (5 g)	<1:4	6 mL water at 70 °C	–	1–2	LC/ESI–MS/MS	[77]
Triclosan and methyltriclosan	Fish, foodstuffs	silica (1.5 g)	1:3	10 mL dichloromethane	SiO_2–HSO_4	1–2	GC–MS/MS	[63]
Plants and plant products								
Acephate, chlorpropham, pirimicarb, bifenthrin, tetradifon, phosalone	Medicinal plant *Cordia salicifolia*	Alumina (0.5 g)	1:1	10 mL ciclohexane:dichloromethane (80:20)	C18	150–250	GC–MS	[100]
Acrylamide	Potato chips	C18 (2 g)	1:4	8 mL water	*n*-hexane (before extraction)	38.8	GC–MS	[40]
Amitrole and urazole	Apple	MFE-pack amino (0.5 g)	1:1	5 mL water	SPE on C18	n.r.[b]	CE with electrochemical detection	[69]
Buprofezin, tetradifon, vinclozolin, bifenthrin	Propolis	Silica (1 g)	1:2	20 mL dichloromethane:ethyl acetate (90:10)	Florisil	150–250	GC–MS	[101]
Carbadox, olaquindox	Feed	C18	1:2	10 mL acetonitrile:methanol (80:20)	–	70–100	LC–DAD	[102]

Table 1 (*Continued*)

Target compounds	Matrix	Dispersing material (amount)	Matrix/sorbent ratio	Elution solvent (v/v)	Clean-up[a]	MQL (μg kg^{-1})	Detection	Ref.
Fungicides	Apple, orange, banana, lettuce, grape and tomato	C18 (0.5 g)	1:1	10 mL ethyl acetate		4–100	LC/ESI–MS/MS	[103]
Glyphosate, aminomethylphosphonic acid	Tomato fruits	NH_2-silica (1 g)	1:2	30 mL water + 20 mL NaH2PO4 0.005M (pH 7)	SAX exchange silica	n.r.[b]	LC–FLD	[68]
HCH isomers	Plant matrices	Florisil + $MgSO_4$ + NaCl (0.5 g + 1 g + 0.5 g)	10:1:2:1	20 mL *n*-hexane:ethylacetate (70:30)	None or Allumina + Na_2SO_4	n.r.[b]	GC–ECD	[20,52–55]
Isoflavones	Trifolium pretense	C18 (2 g)	1:4	10 mL dichloromethane:methanol (25:75)	–	20–400 (μg L^{-1})	LC–DAD	[42]
Linuron, diuron + metabolites	Potatoes, food commodities	Florisil (0.5 g)	1:1	10 mL methanol	–	5.3–15.2	LC/UV–DAD	[49]
Maleic hydrazide, propham	Potatoes	C8 (0.5 g)	1:1	I) 3 mL 50mM phosphate buffer pH 7.4 (maleic hydrazide) II) 10 mL methanol (propham)	I) SPE on ENV+ II) none	n.r.[b]	Electrochemical detection and HPLC–UV	[33]
OPPs, triazines	Apple, pear, apricot	C8 (0.1 g)	1:1	0.7 mL ethyl acetate	–	n.r.[b]	GC–MS	[31]
Pentachloronitroben-zene + metabolites	Ginseng	Florisil (2 g)	1:2	15 mL acetone:*n*-hexane (50:50) under sonication	Allumina	0.7–3.0	GC–MS/MS	[57]
Pesticides	Apple and potato	MWCNTs (0.6 g)	10:3	15 mL acetone:*n*-hexane (50:50)	Florisil	0.3–10.1 (apple); 0.3–13.3 (potato)	GC–MS	[83]
Pesticides	Coconut pulp	C18 (1 g)	1:2	40 mL acetonitrile saturated with *n*-hexane	Florisil	150–250	GC–MS	[29]
Pesticides	Fruit juices	DE (1 g)	1:1	10 mL dichloromethane	–	0.03–3.12 (μg L^{-1})	LC/ESI–MS/MS	[72]
Pesticides	Soybean	Silica	1:2	20 mL ethyl acetate + 5 mL methanol	C8	40–80	LC–DAD	[64]
Phenolic compounds	Wine	Silica (1.5 g)	2:3	5 mL ethyl acetate	–	n.r.[b]	GC–MS	[67]
Pyrethroids	*Chironomus dilutus*	DE[c] + silica gel + PSA[d] (0.7 g + 1 g + 0.03 g)	2:7	15 mL *n*-hexane:ethyl ether (93:7)	–	0.1–5.0	GC–μECD	[62]
Pyrethroids OCPs	Cattle feed	Allumina (2 g)	1:4	5 mL ethylacetate	Florisil	n.r.[b]	GC–ECD	[47]
Aflatoxins	Hazelnuts	C18 (4 g)	1:4	25 mL methanol:water (80:20)	SPE on GCB–4	n.r.[b]	LC/ESI–MS/MS	[22]
Aflatoxins	Olive oil	C18 (1 g)	1:3	6 mL methanol:water (80:20)	–	0.04–0.12	LC/ESI–MS/MS	[21]
Ochratoxin A	Cereals	C8	5:3	20 mL methanol:HCOOH (99:1)	–	0.19	LC–FLD	[25]
Patulin	Apple, apple juice	C18 (2 g)	1:4	9 mL dichloromethane	–	10	LC–UV	[26,104]
Thricothecenes	Maize flour	C18 (2 g)	1:2	12 mL methanol:acetonitrile (50:50)	–	0.3–38	LC/ESI–MS/MS	[24]
Environmental samples								
OCPs	Sludges	Allumina + Cu (3 g + 3 g)	1:3	12 mL dichloromethane under sonication	SPE on C18	0.1–2.5	GC–MS	[44]
Organophosphate esters	Indoor dust	Florisil (0.5 g)	1:1	3 mL acetone	Allumina	40–50	GC–NPD	[48]
PAH	Sewage sludge	Allumina (3 g)	2:3	15 mL dichloromethane under sonication	C18	0.1–1.5	GC–MS	[50]
PAHs	Sewage sludge	Florisil + Na_2SO_4 (1 g + 0.5 g)	2:10:5	6 mL dichloromethane:methanol (90:10)	Florisil and silica	0.1–5	LC–FLD	[59]
PAHs	Soil	Florisil (1 g)	1:2	6 mL hexane:acetone (50:50)	Florisil + silica	0.01–060	LC–FLD	[60]
Parabens and triclosan	Indoor dust	C18 (1.25 g)	2:5	10 mL acetonitrile	Florisil	0.6–2.6	GC–MS/MS	[38]
Parabens and triclosan	Indoor dust	Florisil (3 g)	1:6	15 mL ethyl acetate at 103 °C	Florisil	1.2–3.6	GC–MS/MS	[56]
PBDEs	Sewage sludge	Allumina + Cu (3 g + 2 g)	2:3:2	12 mL dichloromethane under sonication	SPE on C18	0.15–1.8	GC–MS	[45]
Pesticides	Soil	Florisil (10 g)	1:1	50 mL acetone for 1 h	–	n.r.[b]	GC–NPD	[58]
UV filters	indoor dust	C18 (2 g)	1:4	4 mL acetonitrile	Silica)	10–40	GC–MS/MS	[39]

[a] If not specified differently, clean-up sorbent was present in the MSPD column (co-column).

[b] n.r. = not reported.

[c] DE = diatomaceous earth.

[d] PSA = primary/secondary amino diatomaceous earth.

MSPD has been applied to very diverse sample typologies: solid, semi-solid, viscous and liquid. The main differences consist in stronger analyte–matrix interactions and, generally, a larger number of interferences in solid samples than in liquid ones [6]. The strong analyte–matrix interactions of solid samples imply also a bigger difficulty in a correct spiking procedure with target compounds for recovery experiments (usually, equilibration times ranging from 15 min up to 2 h are required).

Besides the composition of the sample, another important critical parameter is the ratio between the sample and the dispersing material. Generally, about 0.5 g of sample are dispersed with the solid support, with ratios ranging from 1:1 to 1:4, with some exceptions [20]. Although the ratio 1:4 is the most common encountered, however it has to be optimized in function of both sample complexity and physical–chemical features of the material.

The yield of MSPD process can be increased by adding during the blending modifiers such as acids, bases, salts, chelators (e.g. EDTA), and so on, able to influence the disruption, distribution and thus the elution profile [1]. Moreover, it is important to note that the mortar and pestle used should be glass or agate, as porous materials, e.g., porcelain, have been shown to lead to analyte and sample loss [4]. Finally, the use of a second column, often obtained incorporating an adsorbent material on the bottom of the MSPD column (clean-up co-column), can allow a purification or an extra fractionation of the eluates [1,5,7] (see also Fig. 1).

3. Dispersant sorbents and extraction strategies

3.1. Reversed phase materials: C18- and C8-bonded silica

Lipophilic sorbent materials such as C18 and C8 have been widely employed in MSPD protocols, mainly for isolation of both naturally occurring and anthropogenic contaminants in food, since in many applications MSPD resulted suitable in the extraction of target analytes also in matrices with high lipid content. More recently, the employment of this sorbent typology has been extended to the determination of anthropogenic contaminants in environmental samples.

Elution strategies after matrix dispersion may vary depending on matrix nature and analyte polarity. A water washing before elution to remove salts and very polar compounds is seldom included in the procedure. Relatively clean extracts from fatty matrices can be obtained when polar solvents such as methanol, acetonitrile or warm (60–80 °C) water are used for recovery of organic compounds of medium polarity. Nevertheless, in some cases an additional step which makes use of a normal phase co-sorbent should be added to obtain a sufficiently clean extract.

When GC is employed as separation analytical technique, anhydrous Na_2SO_4 may be added to the dispersing medium for the purpose of water retention, and less polar solvents or solvent mixtures are used for desorption to improve recoveries.

In the filed of food safety, mycotoxin monitoring is an important task due to the high toxicity of these substances. Cavaliere et al. [21] extracted the four main aflatoxins (AFs) from olive oil sample by means of MSPD, utilizing a low load C18 as dispersing material, with recoveries ranging 92–107% (relative standard deviations, RSDs, below 13%); method quantification limits (MQLs) ranged between 0.04 and 0.12 $\mu g\,kg^{-1}$. No further purification step, such as lipid removal, was performed. MSPDE was preferred after evaluating classical SPE technique, and an aliquot of 320 mg of oil sample was chosen because it resulted into the maximum amount that could be dispersed with 1 g of C18. Larger aliquots of sample, as well as the employment of a high load C18 phase gave rise to a not homogeneous mixing between oil and the adsorbent material. Olive oil extract was finally analyzed by LC–MS/MS with electrospray (ESI) source (see Fig. 3), and because a signal suppression (due to matrix coeluting components) ranging between 4 and 23% was observed, the quantitation was performed by matrix matched calibration curves. The authors concluded that MSPDE appears suitable for application to other oily matrices for multiresidue mycotoxin investigation.

Generally, MSPDE performance drastically changes with the nature of sample. The same group developed a LC/ESI–MS/MS method for determination of AFs in hazelnuts [22]. Three different extraction techniques, i.e., homogenization, ultrasonic extraction, and MSPD were tested and compared in terms of recovery, matrix effect, accuracy and precision. Ultrasound extraction was the most performing sample preparation method. However, for MSPD the

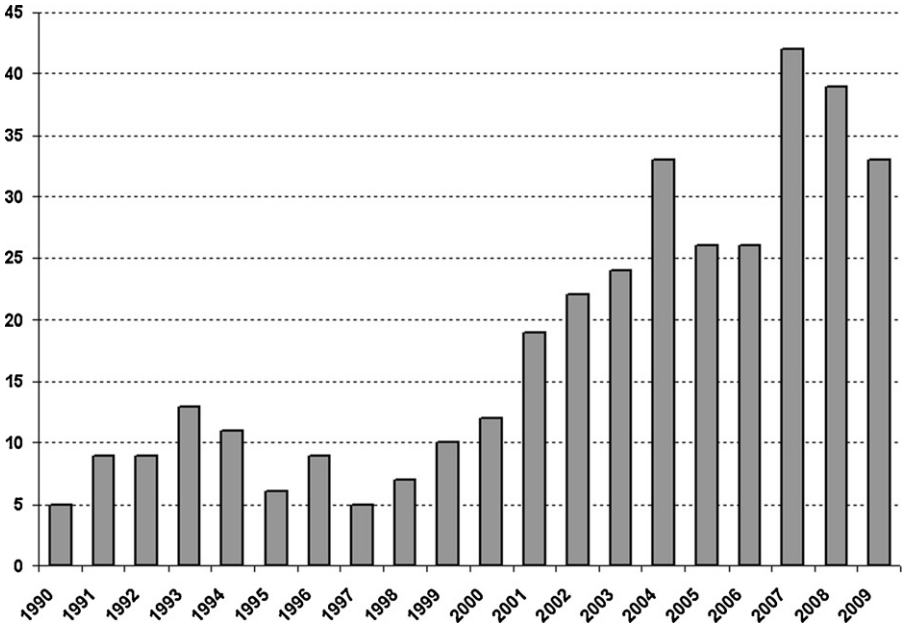

Fig. 2. Distribution of papers on matrix solid-phase dispersion. Number of scientific papers per year in the period 1990–September 2009 containing the terms "matrix solid-phase dispersion".

C18 phase proved to be better hazelnut-dispersant than other solid supports. Differently from a previous paper that utilized a sample/C18/sand ratio (1:1:0.25) [23], only using a sample/C18 1:4 ratio a homogeneous, free-flowing mixture and acceptable recoveries (70–83%, RSDs 8–28%) were obtained. An extract clean-up on Carbograph-4 (GCB) SPE column was needed. Gentili et al. [24] extracted the trichothecenes A and B from maize flour by MSPD, with recoveries ≥79% and RSDs <9%. Also in this case, an eluate fortified after extraction of a blank sample was used as reference material for calibration. In fact, for the 12 analytes, the LC/ESI–MS/MS analysis showed a matrix effect ranging from 40% to 83%; greater suppression was observed for analytes eluting with polar interfering substances. By using an internal standard specific for type-B trichothecenes (with similar polarity) it was possible to correct more efficiently, although not completely, for matrix effects for this tricothecenes subclass. However, MQLs resulted to be in compliance with maximum limits set for other food commodities.

Dispersion on C8 of cereals and their derivatives permitted the extraction and determination by LC–FLD of ochratoxin A, with recoveries ranging from 78% to 89%, RSD below 4%, and MDL 0.05 μg kg^{-1} [25].

In a comparative study between liquid–liquid extraction (LLE), MSPD and SPE for patulin extraction in apple and apple juice, although LLE method provided the highest sensitivity, MSPD resulted the most suitable, with recovery rates above 80% and RSDs <5% [26].

Regarding to drug residue analysis, an interesting MSPD protocol was followed by Sergi et al. [27]: sulfonamides (SAs) were extracted in raw meat and meat-based baby food by dispersing the sample with C18 and eluting with methanol maintained at 0 °C in order to reduce its eluotropic power. This expedient permitted to obtain quantitative recovery and high selectivity, as the co-elution of fat or proteic substances from the matrix was minimized.

Determination of pesticide residues and environmental contaminants in food has been treated by several authors. For the determination of phosmet and its metabolites in olives and olive oil, Cunha et al. [28] proposed a MSPD protocol using C18 and anhydrous $MgSO_4$ as sorbent, a combination more efficient than polar sorbents such as silica, alumina, Florisil or aminopropyl. No further clean-up was required prior to GC–MS analysis.

Silva et al. [29] described a simple and effective extraction method based on MSPD to determine dimethoate, malathion, lufenuron, carbofuran, 3-hydroxycarbofuran, thiabendazole, difenoconazole and trichlorfon in coconut pulp by GC–MS. Different procedure parameters, i.e., type of sorbent (C18, alumina, silica-gel and Florisil), sorbent amount and eluent were evaluated. The best results were obtained using C18 as dispersant sorbent, and Florisil as clean-up sorbent, while a mixture acetonitrile–*n*-hexane was used as eluting solvent. Average recoveries ranged from 70% to 99%, with RSDs below 15%, except for lufenuron and difenoconazole, for which recoveries were less than 50%. Method detection limits (MDLs) for coconut pulp ranged from 20 to 170 μg kg^{-1}.

Quantitative extraction of five organophosphorus pesticides (OPPs) from bovine tissue samples was achieved by dispersing the sample on C18 sorbent combined with a silica gel clean-up and acetonitrile elution [30]. Recoveries were higher than 94% for all the analytes but chlorfenvinphos in liver (55%). The use of acetonitrile as eluent produced better recoveries and less coloured extracts than the methanolic eluents, indicating also a lower level of co-extracted interferents. In addition, a washing step with acetonitrile–water (25:75, v/v) could eliminate an important fraction of interferences without breakthrough of parathion–methyl, the most polar pesticide analyzed.

An ultrasonic-assisted MSPD method employing C8 as sorbent was developed for extracting and cleaning-up 15 OPPs and 9 triazines in fruits [31], in order to increase process efficiency. The method performances were compared with those of a conventional MSPDE and with those of a heat-assisted MSPDE. The employment of a sonoreactor allowed to reduce to 1–3 min the sonication time, and consequently to avoid the possible analyte degradation associated with increased temperatures occurring in longer sonication times. The low MDLs of the ultrasound-assisted MSPD method ensured proper determination of maximum allowed residue levels for all, except for dimethoate and disulfuton. All the evaluated samples, i.e., apples, pear and apricot, showed a low or no matrix effect.

Segovia-Martínez and co-workers [32] developed a miniaturized method based on MSPD for the determination of organochlorine pesticides (OCPs) and polybrominated diphenylethers (PBDEs) in biota samples by GC–ECD. After comparison between Florisil–acidic silica and C18 as dispersant for samples, the combination of C18–Florisil (fat retainer) was preferred. The miniaturized procedure reduced the amount of sample, dispersant and solvent volume by approximately 10 times, and its MQLs ranged from 1 to 23 μg kg^{-1} (expressed as wet mass).

The application of the MSPD process as sample treatment in connection with the electrochemical detection was studied for the first

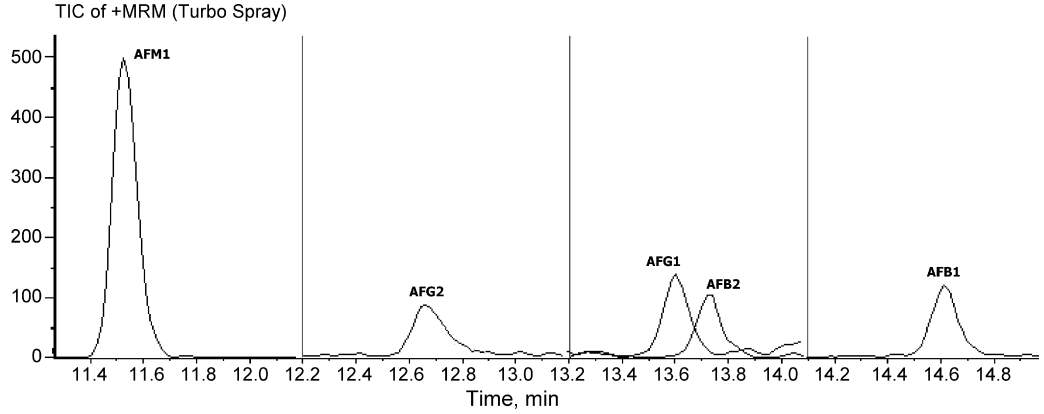

Fig. 3. Liquid chromatography tandem mass spectrometry total ion current of an oil extract. The figure shows the liquid chromatography tandem mass spectrometry total ion current (TIC) in multiple reaction monitoring (MRM) acquisition mode obtained by injecting 50 μL of an aflatoxin-free olive oil sample of 320 mg fortified with 0.1 μg kg^{-1} of aflatoxins B_1 (AFB_1), B_2 (AFB_2), G_1 (AFG_1), and G_2 (AFG_2). Aflatoxin M_1 (AFM_1, the hepatic metabolite of AFB_1) was used as internal standard and 0.2 ng were added to the extract. Target analytes were extracted by matrix solid-phase dispersion and no further purification step was applied.
Reprinted from [21], with permission from Elsevier.

time by Sánchez Arribas et al. [33]: two herbicides were extracted from potatoes by blending them with C8 bonded phase. Selective analyte extraction was then achieved by successive treatment of the blended sample with phosphate buffer and methanol.

Multiresidue method for the simultaneous analysis of 57 pesticides and polychlorinated biphenyls (PCBs) in hen eggs was developed and validated [34]. C18 was the dispersant sorbent, and Florisil the co-sorbent for clean-up purpose. Recoveries were in the range of 70–110%.

For isolating cypermethrin residue in cows' milk, Macedo et al. [35] employed C18 and anhydrous sodium sulfate, in order to trap fats and water, respectively, while Florisil was the co-sorbent.

A rapid method for detecting five types of fluoroquinolones (FQs), OPPs and *N*-methyl carbamates in porcine tissue simultaneously with the use of MSPD followed by LC–DAD was proposed by Wang et al. [36]. After having optimized the matrix/C18 sorbent ratio, recoveries were 60–108%, strictly depending on spiked level, and MDLs in porcine tissue ranged from 9 to 22 $\mu g\,kg^{-1}$.

Polycyclic aromatic hydrocarbons (PAHs) from bivalve samples were extracted by miniaturized MSPD process [37]; additional clean-up and analyte enrichment were accomplished by in-tube solid-phase microextraction (SPME) prior to LC–FLD. The overall recoveries ranged from 10% to 28% for the studied compounds, but MSPD recoveries ranged between 52 and 100% (RSDs $\leq$9%). The small sample amount (0.1 g) was eluted by 1.2 mL acetonitrile, and in this condition the most apolar PAHs were not totally desorbed from the MSPD cartridges. However, the employment of larger volumes of acetonitrile did not increase significantly analyte responses of the late eluting compounds, and diluted unnecessarily the sample extracts. MDLs were $\leq$0.6 $\mu g\,kg^{-1}$ (dry weight). The proposed procedure was very simple and rapid, and the consumption of organic solvents and extractive phases was drastically reduced.

Four parabens and triclosan in indoor dust were extracted from the sample and isolated from interfering species using MSPDE [38]. After evaluation of several factors on extraction yield and selectivity, under final working conditions, 0.5 g samples were mixed with the same amount of anhydrous sodium sulfate and dispersed on 1.25 g C18. Florisil was used as co-sorbent. After removing less polar species using dichloromethane, analytes were recovered using acetonitrile and quantified by GC–MS/MS.

Negreira and et al. [39] determined six UV filters in dust from indoor environments by MSPDE using C18 and GC–MS/MS analysis. Recoveries for samples spiked at two different concentrations ranged between 77% and 99%. None of the compounds could be eluted with *n*-hexane, while dichloromethane failed in extracting two analytes containing a phenolic group in the structure, probably leading to a stronger interaction with the dust matrix and/or with the normal-phase co-sorbent than the rest of analytes.

Potato chips sample dispersed in C18 required a previous clean-up with *n*-hexane to eliminate fat (representing about 40% of this food), after that acrylamide was eluted with water [40]. Hot water was not used as eluent to avoid the co-extraction of undesired components from the matrix.

Unconjugated progestogens were extracted from eggs by MSPD with C18 [41] using methanol as eluent; because of the egg high protein content, a washing step with water containing 10% (v/v) methanol was necessary for partial protein removal. After elution, the complexity of the matrix required a further clean-up by SPE on GCB. Recoveries of the target compounds varied from 84% to 111% and RSDs ranged from 10% to 24%. MDLs of 0.2–2.0 $\mu g\,kg^{-1}$ were suitable for real sample analysis, in which 9.9–40.0 $\mu g\,kg^{-1}$ of progesterone in eggs were detected.

C18 was used as MSPD sorbent also for the determination of isoflavones in *Trifolium pratense* [42], and of fenthion and its metabolites in olives and olive oils [43]. Other applications are reported in Table 1.

3.2. Normal phase inorganic materials: alumina and Florisil

The mechanism occurring by blending the sample with the inorganic normal phase supporting materials, i.e., Florisil and alumina, is not the same proposed for silica bonded phase sorbents. These materials do not dissolve the sample matrix but only adsorb the organic molecules, however, the basic principles, such as abrasion and sample architecture disruption, are common [7]. The main differences consist in an incomplete cellular disruption [5] and in the reduced chemical interactions between matrix components and surface of the dispersing material [7].

These materials have as main field of application the extraction of environmental pollutants, although in the recent literature application to plant and animal tissues are much more present than in the past. Probably, the mechanical disruption of the cells sufficiently permits the organic compound migration to the sorbent surface. Selection of eluents to be used for recovery of analytes with retention of matrix compounds is function of analyte polarity and reversed phase materials are sometimes used as co-sorbent.

The polar surface of alumina was exploited in a MSPD-based method for determining 16 OCPs [44] and 14 PBDEs [45] in municipal wastewater treatment facility sludge, with the aim of minimizing solvent usage. Lyophilized sludge samples were blended with deactivated Al_2O_3 and activated copper powder in a glass mortar; thereafter, the blended sample was transferred to the column, and extracted twice with dichloromethane assisted by sonication. Extract purification was carried out on C18 SPE column; finally, detection was achieved by GC–MS. A comparison with Florisil as dispersant material was done, but alumina provided cleaner extracts [44]. To improve the recovery for some OCPs, alumina had to be deactivated with deionized water before use, while larger amount of adsorbent did not increase extraction yield. In addition, copper powder was added in the MSPD step to remove the chromatographic interferences of sulphur [44–45]. A purification step of the extract on C18 was required to decrease the high organic matter content of the sludge, and recoveries around 80–110% were obtained for all the target analytes.

The pyrethroids cypermethrin and deltamethrin were isolated from different porcine tissues (liver, muscle, heart and kidney) by means of neutral alumina-based MSPD [46]. With HPLC–UV detection, MQL were 26–56 $\mu g\,kg^{-1}$ for the two analytes.

The simultaneous extraction of 36 common pesticides and breakdown products (mostly pyrethroids and OCPs) in cattle feed was carried out by MSPD [47]. The procedure was optimized using a multivariate statistical approach to investigate the effect of three variables: nature of dispersing phase (C18, alumina and Florisil); nature of clean-up adsorbent (alumina and Florisil); and volume of eluting solvent (ethyl-acetate). In conclusion, 0.5 g of feed sample blended with 2 g of alumina as dispersing phase and 200 mg of anhydrous Na_2SO4, clean-up with a co-column of 2 g of Florisil and elution with 5 mL of ethyl acetate represented the best compromise for all the analytes. The final analyses were carried out by GC–ECD, and the MQLs complied with the regulated maximum residue levels in animal feed and in main crops used in the preparation of cattle feeding materials.

For the isolation of several organophosphate esters (mainly employed as flame retardants and plasticizers) from indoor dust samples [48], 0.5 g of dust were dispersed with equal amounts of anhydrous sodium sulfate and Florisil, and loaded onto a cartridge containing 0.5 g of alumina. Washings with hexane permitted to remove the non-polar interferences, while analytes were eluted with acetone.

Boti et al. [49] employed a 3-level fractional factorial design for the thorough evaluation of the MSPDE process and the subsequent evaluation of main factor influence on the yield of the simultaneous extraction of the target analytes, i.e., linuron, diuron, and their

common metabolites, in food commodities. The criteria were to find the experimental conditions allowing the highest average recovery, and displaying at the same time the lowest standard deviation for all analytes. A 0.5 g of potatoes blended with an equal amount of Florisil, gave MQLs varying between 5.3 and 15.2 $\mu g\,kg^{-1}$. Analogue MQL values were found for the same analytes in carrots, apples, orange juice, and cereal/wheat flour, even if with lower recovery yields.

Determination of 27 PAHs in wastewater treatment sludge from urban, industrial, or rural zones was achieved by sonication-assisted MSPD (employing alumina), followed by C18 SPE purification, and GC–MS analysis [50]. Dichloromethane was selected as extracting solvent because it gave cleaner extracts than other solvents, probably due to a reduced lipid co-extraction. After optimization, the method was also validated using a certified reference sludge, obtaining recoveries ranging between 85 and 108%.

In multiresidue analysis of six SAs in meat of different origin, sample preparation was attained by normal-phase MSPD (2 g alumina N-S); elution was carried out with ethanol [51]. The LC–MS with atmospheric pressure chemical ionization and photodiode array determination showed recoveries higher than 90% with RSDs below 6%. In all the processes, no toxic solvents were used at all.

The presence of combined residues of hexachlorocyclohexane (HCH) isomers was determined in various plant matrices (i.e., vegetables, fruits, leaves, grains and roots) by GC–ECD after MSPDE [20,52–55]. Florisil (0.5 g) was used for blending the sample (5 g) in an uncommon ratio, in presence of anhydrous $MgSO_4$ and NaCl. Selective elution from MSPD column in presence of alumina was attained with a mixture of *n*-hexane–ethyl acetate solvent 70:30 (v/v); if necessary, additional alumina for co-column sample clean up was used, obtaining higher reproducibility. Mean recoveries were found in the range of 91–98%. In preliminary MSPD tests, Florisil gave better results than GCB, C18, C8, C2, silica, and alumina. The use of Florisil for microdispersion of plant matrices produced higher recoveries than those obtained with non-polar solid phases. Moreover, Florisil produced the cleanest chromatographic profiles probably due to preferential adsorption of polar sample components, interfering with compounds, such as pigments and chlorophylls on the Florisil surface. The observed matrix effect had 6% mean value.

A PLE-based method was proposed for the determination of four alkyl parabens and triclosan in indoor dust [56]. Florisil was used as both dispersant and clean-up co-sorbent; non-polar species were removed with *n*-hexane under mild conditions (40 °C, 3.4 MPa), while analyte were eluted with ethyl acetate at 103 °C and 13.8 MPa. Recovery ranged from 76% to 98%, however MQLs of this PLE process were lower than those achieved by a similar and conventional MSPD method [38].

Pentachloronitrobenzene and its two metabolites pentachloroaniline and pentachlorothioanisole residues were determined in ginseng [57]. Extraction and clean-up were carried out in a single step: Florisil was used as dispersant sorbent, instead alumina constituted the clean-up co-column. Elution of target compounds was attained by a mixture acetone-*n*-hexane assisted by sonication. GC–MS/MS analysis was finally performed.

Modified MSPD was developed for quantitative analysis of five pesticides in soil by Shen et al. [58]. Florisil was used as dispersant; the sample mixture, placed into an extraction thimble of a glass apparatus, was eluted continuously for 1 h with 50 mL acetone. Modified MSPD gave recoveries ranging from 93% to 100% with RSDs lower than 10%; MDLs ranged from 0.2 to 2.0 $\mu g\,kg^{-1}$. On the other hand, with this expedient analysis time was longer than in classical MSPD.

Pena et al. [59] developed a MSPD-based strategy for PAH extraction in wastewater sludge. Both reversed phase (C18) and normal phase sorbents (Florisil, SiO_2, neutral Al_2O_3), as well as polymeric materials (Oasis HLB, Oasis MAX) and an inert support (sand) were tested to assess sorbent effect on MSPD yield and selectivity. Extraction yields for different compounds obtained by MSPD were 76–104% employing the dispersant showing the best performances, i.e., Florisil. The same group slightly modified the method for PAH determination in soil [60]. The extraction yields for the different compounds obtained by MSPD were compared with the yields obtained by MAE. The addiction of saturated methanolic potassium hydroxide solution before blending the sample with the sorbent increased recovery yield. In fact, preliminary assays showed that this treatment was important in terms of minimising extract residues and maximising recoveries of PAHs. For most of the analytes, recoveries decreased in the absence of alkaline treatment, while increased as the amount of alkali increased, until a constant value was reached.

A multiresidue method for determining 13 emerging and priority pollutants in lettuce (pesticides, pharmaceuticals, personal care products, PAHs, and phenolic estrogens) exploited the combination MSPD-pressurized fluid extraction (PFE) followed by GC–MS/MS [61]. A sequential optimization strategy based on solvent optimization first, followed by experimental design, was performed in order to maximize target analyte extraction with the aid of response surface methodology. The sample was dispersed in Florisil with a ratio 1:2, then extracted in PFE conditions with solvent mixtures acetone–hexane and ethyl acetate–hexane.

Other papers employing Florisil as sorbent in MSPDE are reported in Table 1.

3.3. Normal phase materials: underivatized silica and silica-based polar chemically bonded phases

Much less retentive dispersing materials than alumina and Florisil such as silica and amino bonded silica have found many applications in determination of pesticides residues in food of different origin. The mechanism occurring by blending the sample with a low retentive solid support is probably the same as for more retentive normal-phase material and also similar should be the strategies for selective and quantitative analyte recovery.

For detecting eight pyrethroid insecticides in the aquatic invertebrate *Chironomus dilutus* [62], a mixture of silica gel, diatomaceous earth (DE) and primary/secondary amino solid absorbents were selected as the dispersion matrix, while 7% ethyl ether in hexane was used as elution solvent. MDLs for the target pyrethroids ranged from 0.46 to 4.4 $\mu g\,kg^{-1}$, and recoveries ranged between 44 and 124% at different spiked levels.

Triclosan and methyltriclosan were simultaneously extracted and purified in fish and foodstuff samples [63]. Lipid-free extract and quantitative recoveries were obtained by using neutral silica in MSPD process and acidic silica as co-sorbent. In fact, under these conditions, analytes were recovered with dichloromethane whereas lipids were oxidized and retained in the layer of acidic silica.

Maldaner et al. [64] proposed a method for the determination of six pesticides (imazethapyr, imazaquin, metsulfuron–Me, carboxin, chlorimuron–Et, and tebuconazole) in soybeans using MSPD with silica and a clean-up step with C8 co-column. The additional clean-up step before HPLC–DAD determination was proposed because the extracts obtained contained relatively large quantities of co-extracted fat and proteins. In these experimental conditions, recoveries were 60–120% and MQLs satisfied maximum residue limits of main regulatory agencies.

MSPD process can be used also for purifying the sample after solvent extraction. A novel approach for determination of 2-mercaptobenzimidazole and other thyreostatic residues in animal tissues by GC–MS was presented [65]. The analytes were extracted from animal tissues by acetonitrile, and then purified by a MSPD

procedure after the extraction residues had been dissolved in water. Different kinds of solid supports with various polarities for the MSPD procedure were investigated, and it was found that silica gel was the mot suitable for the purpose. The average recoveries of the thyreostatic drugs in animal tissues ranged from 71% to 97% with the RSDs below 10%.

Ramos and et al. [66] applied a laboratory-made miniaturised device for PLE to the selective extraction of PCBs from solid fatty foodstuffs: a small amount of sample was dispersed with Na_2SO_4 and acidic silica, with the latter efficiently contributing to fat removal (in-cell purification). Although by combining PLE and MSPD increased extraction yield was not relevant respect to a conventional Soxhlet or MSPD method carried out under atmospheric conditions; however the miniaturization allowed reduced solvent and sample consumption. MDLs were below 0.3 $\mu g\,kg^{-1}$, with recoveries in the range 83–133%.

Minuti and Pellegrino [67] developed a protocol for simultaneous extraction of 23 phenolic compounds from wine prior to GC–MS detection. The optimized MSPD procedure required just a small volume of wine (1 mL), dispersed on silica gel, and a small volume of eluting solvent; analysis time was only 15 min.

García de Llasera et al. for isolating glyphosate and its major metabolite aminomethylphosphonic acid (AMPA) from tomato fruit, dispersed the sample in NH_2-silica [68]. The two fractions obtained by employing two different elution solvents, i.e., water for AMPA and NaH_2PO_4 buffer for glyphosate, were cleaned up by ion exchange chromatography, and determined by LC–FLD. Mean recoveries were 87% for glyphosate (MDL 50 $\mu g\,kg^{-1}$) and 78% for AMPA (MDL 30 $\mu g\,kg^{-1}$). NH_2-silica was selected due to its high affinity provided for polar compounds, then, it was necessary to make a previous matrix modification to disrupt the apparently very strong interaction of glyphosate with the blended sorbent phase by adding small volumes of nitric acid.

Silica modified with amino groups (MFE®-pack amino) was used for dispersing apple samples, and purified water as the elution solvent, in order to extract the two polar pesticides amitrole and urazole [69]. Clean-up on C18 was required for eliminating efficiently interfering substances before capillary electrophoresis with amperometric detection analysis.

3.4. Non-retentive supporting materials: sand and diatomaceous earth

The use of inert materials for MSPD leads to cost-effective methods at expense of selectivity which is just regulated by the molecule solubility. A considerable portion of works employing inert material as dispersant make use of warm–hot water as selective solvent [9,15].

A single-step extraction and purification method was developed for the separation of 26 OCPs, 3 pyrethroid pesticides and 6 PCBs from fatty foods of either animal or vegetable origin (portions of meat adipose tissues, meat products, milk and milk products, cheese, eggs, etc.) [70]. The method included homogenization of isolated fat and DE (celite). Separation was achieved using a mini Pasteur pipet where a MSPDE was carried out with only 5 mL of DMSO as an eluting solvent. A Pasteur pipet was joined to a pre-packed slurry filled Florisil column, where a LLE and adsorption chromatography successively took place. Recoveries for PCBs were from 81% to 86% and for OCPs 68–94% but one, which gave lower, and more variable recoveries. Excellent recoveries were obtained for pyrethroid pesticides, mostly more than 80%. The method was applied to 509 fatty samples for monitoring these compounds.

MSPD has been applied for extracting arsenical species from seafood products [71], followed by HPLC–ICPMS analysis. All the variables affecting MSPD were evaluated, and after a comparison between DE, sea sand, C18, and Florisil, DE was selected as solid supports and C18 as co-sorbent, in order to reduce the amount of polar substance in the analytical column.

Analysis of pesticides belonging to different classes was performed by LC–MS/MS after MSPDE using DE as dispersant and dichloromethane as eluent [72]. Significant matrix effects observed for most of the pesticides tested were eliminated using matrix-matched calibration. Recoveries were in the range 71–118%, with RSDs 5–15%. It was determined that pH had a decisive influence on the carbendazim recovery, while its influence was not so prominent for other tested pesticides. The highest recoveries for carbendazim were obtained with pH-value adjusted to 6, and a slight increase in recoveries of other pesticides was observed too.

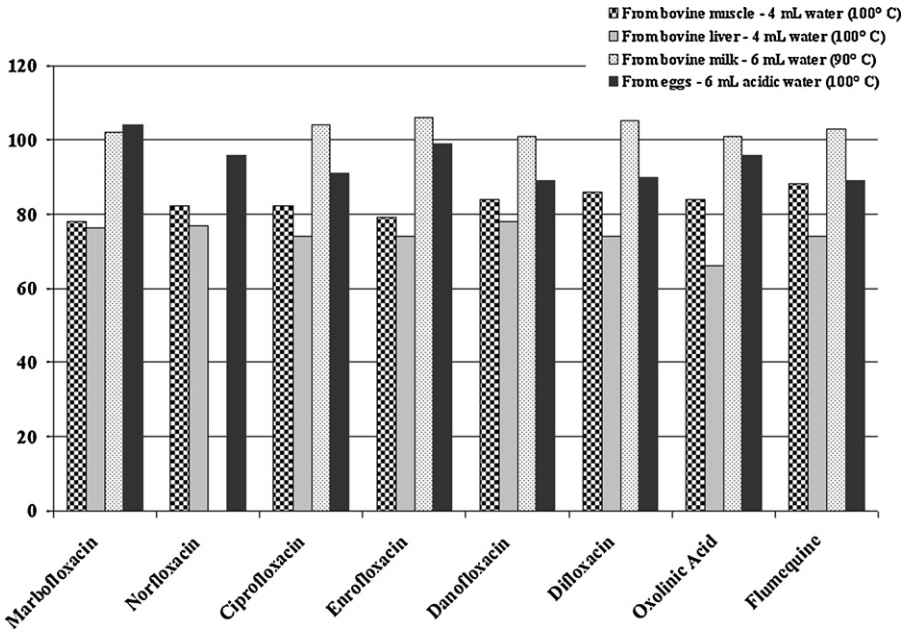

Fig. 4. Recoveries of quinolones from different matrices. Recoveries of quinolones antimicrobials by applying matrix solid-phase dispersion extraction with hot water in four different matrices: bovine muscle and liver tissues [75], bovine milk [74] and whole eggs [73].

As mentioned above, MSPD yield can be improved using a PLE instrument to achieve faster, but still selective, extraction at elevated temperature and/or pressure [2]. On this basis, Bogialli et al. published several works in which MSPD was performed with a non retentive material such as sand (crystobalite) [9,73–76]. After dispersion of the sample on crystobalite, the attained dried material was packed in a stainless-steel extraction cell; hot water was employed as extractant at 1 mL min^{-1} flow rate by means of a HPLC pump in controlled pressure and temperature conditions. Analyte determination was finally done by LC/ESI–MS/MS.

The procedure was successfully applied, with slight modifications, to residue determination of macrolides and lincomycin in whole milk and yoghurt [76]; of tetracycline in cheese [77]; of quinolone antibacterials in whole eggs [73], in bovine milk [74], and in bovine muscle, kidney and liver tissues [54]. As can be seen in Fig. 4, the recovery yield of the procedure depends on the nature of the sample.

The recoveries of quinolones from egg [73] increased drastically by adding to water formic acid and increasing extractant temperature. In fact, when a non-retentive dispersing material is employed in MSPD, selectivity strongly depends on extractant characteristics. As water is heated at high temperatures, its surface tension, viscosity and polarity progressively decrease. Heated water, thus, becomes an efficient medium for extracting from a given matrix even those organics that are scarcely soluble in water at ambient temperature. The risk inherent to the use of hot water as extractant is that it could decompose those compounds that are thermolabile and/or prone to hydrolytic attack [74].

In conclusion, the main advantages of this extraction procedure are the use of a non-toxic solvent, i.e., H_2O, whose selectivity in target analyte extraction can be obtained by suitably controlling its temperature. Furthermore, only limited manipulation of the extract is required, and relatively large volumes of the final extract can be injected into a reversed phase LC column. A SPE clean-up step could be eventually added for detectors less selective than mass spectrometer.

A similar method based on MSPD with sand and PLE with hot water was proposed by Blasco et al. for tetraciclynes determination in various animal tissues [78]. However, differently from previous works [75,79], a clean-up on OASIS HLB SPE cartridge was carried out before LC/ESI–MS/MS analysis.

3.5. Highly selective supporting materials: molecular imprinted polymers

Recently, a very interesting a promising application of MSPD has been carried out by Yan et al. [80]: they employed molecularly imprinted polymers (MIPs) as dispersant sorbent for the extraction some FQs from chicken eggs and swine tissues. Molecular imprinting has now established itself as a way to produce polymeric materials programmed to recognise a given target or target class with high affinity and selectivity [MIPs]; in fact, these synthetic materials mime the action of antibodies and enzymes [80]. The water-compatible ofloxacin imprinted polymers were prepared and characterized. Then, a small aliquot of samples (0.2 g) was blended with them and employed for the MSPD procedure. The recoveries of the five analytes were better than those obtained by using conventional sorbent materials such as C18, silica, Florisil, and sand. In particular sand, a non-retentive dispersant, gave the worst recoveries. Moreover, due to the selective extraction, in the chromatograms of both chicken eggs and swine tissues no interferences from the biological matrix were observed; MDLs varied between 0.05 and 0.09 μg kg^{-1}.

Even in a complex biological matrix such as serum, the same MIPs developed in the previous work, used as dispersant were able to isolate six FQs eliminating simultaneously the sample interferences [81]. The average recoveries of the FQs at different spiked levels ranged from 72% to 114% with RSD below 7%.

MIPs for MSPD application were used also for determination of chloramphenicol (CAP) in three different fish tissues [82]. The CAP-imprinted polymers gave analyte recoveries in the range ca. 90–101%, with better performance than C18 and attapulgite.

3.6. An emerging supporting material: multiwalled carbon nanotubes

Multiwalled carbon nanotubes (MWCNTs) are a kind of carbon-based nanomaterial. In theory, MWCNTs can have excellent adsorption ability owing to their extremely large surface area and structural characteristics; it is believed that the reasons for MWCNT adsorption may be primarily due to their dramatically hydrophobic surface and unique structure with internal tube cavity [83]. In literature there are some reports describing the employment of MWCNTs as sorbent in SPE for extraction of pesticides and herbicides from water [84–90], then Fang et al. [83] decided to test their efficiency in MSPDE applications. MWCNTs were used as dispersant for extracting 31 pesticides from agriculture samples by MSPD prior to GC–MS determination. The extracts obtained by using MWCNTs were cleaner than those obtained by using C18 and diatomite as dispersant materials, with recoveries above 71% for both apple and potato samples. MDLs ranged from 0.1 to 3.1 μg kg^{-1} for apple, and from 0.1 to 4.0 μg kg^{-1} for potato.

4. Limitations of MSPD process

Although MSPD strategy presents many advantages, however it is not always reported as more efficient than other techniques. Bajer et al. [91] extracted isoflavonoids in various plants comparing performances of MSPD, SFE, pressurized fluid extraction, extraction in an ultrasonic bath, and extraction by means of an ultrasonic homogenizer, Soxhlet extraction, and SPE. For MSPD, the sample was blended with the sorbent HLB Oasis (preferred to C18) in the ratio 1:2. However, other techniques, such as Soxhlet extraction, ultrasonic extraction and SFE, gave best performances depending on the particular selected analytes.

Liquid–solid extraction by a high-speed homogenizer and subsequent clean-up by gel permeation chromatography showed better yields in extracting organochlorine OCPs and OPPs from animal liver than MSPD with C18 [92].

For analyzing fipronil in pollen, Jiménez et al. [93] tested the extraction with organic solvents, SPE and MSPD with Florisil as a dispersing agent. Even if with MSPD the recoveries obtained in GC–MS were the highest of all the extraction procedures, however the amount of co-extracted compounds and the irregularity of the baseline were notable in GC–ECD.

Bianchi et al. [94] studied the capabilities of SPE and MSPD in some hormones determination by GC–MS in a complex matrix like porcine follicular fluids, proving the highest effectiveness of the SPE technique.

Artemisinin (an antimalarial compound) was isolated from the medicinal plant *Artemisia annua* L. by MSPD on Florisil, and directly analyzed by HPLC [95]. Results from the MSPD method did not significantly differ from those of Soxhlet and ultrasonic wave extraction. MSPD method for phenolic compound and organic acid extraction from white grapes [96] was compared with a conventional analytical method previously developed that combines solid liquid (SL) extraction and SPE to separate the two groups of compounds. Although the results were qualitative similar for both techniques, the SL–SPE gave more quantitative recovery than MSPD.

It is important to keep in mind that dealing with analysis of complex matrices, especially foods, a combination of different techniques is often required to achieve the required performances in terms of accuracy and sensitivity [97].

5. Conclusions

The main advantages of MSPD extraction are that it requires only small amounts of sample and solvents, is rapid, inexpensive, and can be carried out under mild extraction conditions (room temperature and atmospheric pressure) providing acceptable yield and selectivity. Moreover, the flexibility and versatility of MSPD allows the application of the process to a wide variety of analytes and biological and environmental matrices. In fact, MSPDE has showed is feasibility not only for solid or semi-solid samples, but also for the viscous ones (milk, blood, etc.). For these reasons, the employment of MSPD, first introduced in 1989, has still grown in the last years.

Even if MSPD process has some limitations and can not be completely automatized, because it requires the blending in a mortar with a pestle by an operator, however since 1989 the literature has been showing a great interest in this extraction technique. Furthermore, during the last years an increased employment of MSPD has been observed, and at the same time novel dispersing materials, both highly selective as MIPs and less specific as MWCNTs have been introduced. Then, besides all the well-known advantages, in our opinion this technique presents potential improvements, mainly based on the development of more specific sorbents for blending the samples, and process miniaturization.

References

[1] S.A. Barker, A.R. Long, M.E. Hines II, J. Chromatogr. 629 (1993) 23.
[2] E.M. Kristenson, L. Ramos, U.A.Th. Brinkman, Trends Anal. Chem. 25 (2006) 96.
[3] S.A. Barker, A.R. Long, C.R. Short, J. Chromatogr. 475 (1989) 353.
[4] S.A. Barker, J. Chromatogr. A 885 (2000) 115.
[5] S.A. Barker, J. Chromatogr. A 880 (2000) 63.
[6] M. García-López, P. Canosa, I. Rodríguez, Anal. Bioanal. Chem. 391 (2008) 963.
[7] S.A. Barker, J. Biochem. Biophys. Methods 70 (2007) 151.
[8] J. Moreda-Piñeiro, E. Alonso-Rodríguez, P. López-Mahía, S. Muniategui-Lorenzo, D. Prada-Rodríguez, V. Romarís-Hortas, M. Míguez-Framil, A. Moreda-Piñeiro, P. Bermejo-Barrera, Trends Anal. Chem. 28 (2009) 110.
[9] S. Bogialli, A. Di Corcia, J. Biochem. Biophys. Methods 70 (2007) 163.
[10] Y. Picó, M. Fernández, M.J. Ruiz, G. Font, J. Biochem. Biophys. Methods 70 (2007) 117.
[11] A. Hercegová, M. Dömötörová, E. Matisová, J. Chromatogr. A 1153 (2007) 54.
[12] F.E. Ahmed, Trends Anal. Chem. 20 (2001) 649.
[13] B. Gilbert-López, J.F. García-Reyes, A. Molina-Díaz, Talanta 79 (2009) 109.
[14] J.F. García-Reyes, C. Ferrer, M.J. Gómez-Ramos, A. Molina-Díaz, A.R. Fernández-Alba, Trends Anal. Chem. 26 (2007) 239.
[15] V. Andreu, Y. Pico, Trends Anal. Chem. 23 (2004) 772.
[16] B. Kinsella, J. O'Mahony, E. Malone, M. Maloney, H. Cantwell, A. Furey, M. Danaher, J. Chromatogr. A 1216 (2009) 7977.
[17] M.D. Marazuela, S. Bogialli, Anal. Chim. Acta 645 (2009) 5.
[18] T.A. McGlinchey, P.A. Rafter, F. Regan, G.P. McMahon, Anal. Chim. Acta 624 (2008) 1.
[19] N. Fidalgo-Used, E. Blanco-González, A. Sanz-Medel, Anal. Chim. Acta 590 (2007) 1.
[20] P.C. Abhilash, S. Jamil, N. Singh, J. Chromatogr. A 1176 (2007) 43.
[21] C. Cavaliere, P. Foglia, C. Guarino, M. Nazzari, R. Samperi, A. Laganà, Anal. Chim. Acta 596 (2007) 141.
[22] A. Bacaloni, C. Cavaliere, F. Cucci, P. Foglia, R. Samperi, A. Laganà, J. Chromatogr. A 1179 (2008) 182.
[23] J. Blesa, J.M. Soriano, J.C. Moltó, R. Marín, J. Mañes, J. Chromatogr. A 1011 (2003) 49.
[24] A. Gentili, F. Caretti, G. D'Ascenzo, L. Mainero Rocca, S. Marchese, S. Materazzi, D. Perret, Chromatographia 66 (2007) 669.
[25] C. Juan, J.C. Moltó, C.M. Lino, J. Mañes, Food Chem. 107 (2008) 525.
[26] R.N. Wu, F.L. Han, J. Shang, H. Hu, L. Han, Eur. Food Res. Technol. 228 (2009) 1009.
[27] M. Sergi, A. Gentili, D. Perret, S. Marchese, S. Materazzi, R. Curini, Chromatographia 65 (2007) 757.
[28] S.C. Cunha, J.O. Fernandes, M.B.P.P. Oliveira, Talanta 73 (2007) 514.
[29] M.G. Dantas Silva, A. Aquino, H. Silveira Dórea, S. Navickiene, Talanta 76 (2008) 680.
[30] M.P. García de Llasera, M.L. Reyes-Reyes, Food Chem. 114 (2009) 1510.
[31] J.J. Ramos, R. Rial-Otero, L. Ramos, J.L. Capelo, J. Chromatogr. A 1212 (2008) 145.
[32] Y. Moliner-Martinez, P. Campíns-Falcóa, C. Molins-Legua, L. Segovia-Martínez, A. Seco-Torrecillas, J. Chromatogr. A 1216 (2009) 6741.
[33] A. Sánchez Arribas, E. Bermejo, M. Chicharro, A. Zapardiel, Talanta 71 (2007) 430.
[34] P. Plaza Bolaños, A. Garrido Frenich, J.L. Martínez Vidal, J. Chromatogr. A 1167 (2007) 9.
[35] A.N. Macedo, A.R.A. Nogueira, S.H. Govoni Brondi, Chromatographia 69 (2009) 571.
[36] S. Wang, H. Mu, Y. Bai, Y. Zhang, H. Liu, J. Chromatogr. B 877 (2009) 2961.
[37] P. Campíns-Falcó, J. Verdú-Andrés, A. Sevillano-Cabeza, C. Molins-Legua, R. Herráez-Hernández, J. Chromatogr. A 1211 (2008) 131.
[38] P. Canosa, I. Rodríguez, E. Rubí, R. Cela, Anal. Chem. 79 (2007) 1675.
[39] N. Negreira, I. Rodríguez, E. Rubí, R. Cela, J. Chromatogr. A 1216 (2009) 5895.
[40] J.O. Fernandes, C. Soares, J. Chromatogr. A 1175 (2007) 1.
[41] Y. Yang, B. Shao, J. Zhang, Y. Wu, J. Ying, J. Chromatogr. B 870 (2008) 241.
[42] T. Visnevschi-Necrasov, S.C. Cunha, E. Nunes, M.B.P.P. Oliveira, J. Chromatogr. A 1216 (2009) 3720.
[43] S.C. Cunha, J.O. Fernandes, M.B.P.P. Oliveira, Food Addit. Contam. 24 (2007) 156.
[44] C. Sánchez-Brunete, E. Miguel, J.L. Tadeo, Talanta 74 (2008) 1211.
[45] C. Sánchez-Brunete, E. Miguel, J.L. Tadeo, J. Sep. Sci. 32 (2009) 109.
[46] J. Cheng, M. Liu, Y. Yu, X. Wang, H. Zhang, L. Ding, H. Jin, Meat. Sci. 82 (2009) 407.
[47] M. Fernandez-Alvarez, M. Llompart, J.P. Lamas, M. Lores, C. Garcia-Jares, R. Cela, T. Dagnac, J. Chromatogr. A 1216 (2009) 2832.
[48] M. García, I. Rodríguez, R. Cela, Anal. Chim. Acta 590 (2007) 17.
[49] V.I. Boti, V.A. Sakkas, T.A. Albanis, J. Chromatogr. A 1216 (2009) 1296.
[50] C. Sánchez-Brunete, E. Miguel, J.L. Tadeo, J. Chromatogr. A 1148 (2007) 219.
[51] K. Kishida, Food Control 18 (2007) 301.
[52] P.C. Abhilash, V. Singh, N. Singh, Food Chem. 113 (2009) 267.
[53] P.C. Abhilash, N. Singh, Environ. Sci. Pollut. Res. 16 (2009) 727.
[54] P.C. Abhilash, S. Jamil, V. Singh, A. Singh, N. Singh, S.C. Srivastava, Chemosphere 72 (2008) 79.
[55] P.C. Abhilash, N. Singh, Bull. Environ. Contam. Toxicol. 81 (2008) 604.
[56] P. Canosa, D. Pérez-Palacios, A. Garrido-López, M.T. Tena, I. Rodríguez, E. Rubí, R. Cela, J. Chromatogr. A 1161 (2007) 105.
[57] J. Li, F. Dong, X. Liu, Y. Zheng, J. Yao, C. Zhang, Chromatographia 69 (2009) 1113.
[58] X. Shen, Q. Su, X. Zhu, Y. Gao, Ann. Chim. Rome 97 (2007) 647.
[59] M.T. Pena, M.C. Casais, M.C. Mejuto, R. Cela, Anal. Chim. Acta 626 (2008) 155.
[60] M.T. Pena, M.C. Casais, M.C. Mejuto, R. Cela, J. Chromatogr. A 1165 (2007) 32.
[61] D. Calderón-Preciado, C. Jiménez-Cartagena, G. Peñuela, J.M. Bayona, Anal. Bioanal. Chem. 394 (2009) 1319.
[62] Y. Ding, J. You, M.J. Lydy, Bull. Environ. Contam. Toxicol. 83 (2009) 388.
[63] P. Canosa, I. Rodríguez, E. Rubí, M. Ramil, R. Cela, J. Chromatogr. A 1188 (2008) 132.
[64] L. Maldaner, C.C. Santana, I.C.S.F. Jardim, J. Liquid Chromatogr. Relat. Technol. 31 (2008) 972.
[65] Y. Liu, Q.H. Zou, M.X. Xie, J. Han, Rapid Commun. Mass Spectrom. 21 (2007) 1504.
[66] J.J. Ramos, C. Dietz, M.J. Gonzïalez, L. Ramos, J. Chromatogr. A 1152 (2007) 254.
[67] L. Minuti, R. Pellegrino, J. Chromatogr. A 1185 (2008) 23.
[68] M.P. García de Llasera, L. Gómez-Almaraz, L.E. Vera-Avila, A. Peña-Alvarez, J. Chromatogr. A 1093 (2005) 139.
[69] M. Moreno, E. Bermelo, A. Sánchez, M. Chicharro, A. Zapardiel, Anal. Bioanal. Chem. 391 (2008) 867.
[70] Kodba, Zdenka Cencic, Voncina, Darinka Brodnjak, Chromatographia 66 (2007) 619.
[71] A. Moreda-Piñeiro, E. Peña-Vázquez, P. Hermelo-Herbello, P. Bermejo-Barrera, J. Moreda-Piñeiro, E. Alonso-Rodríguez, S. Muniategui-Lorenzo, P. López-Mahía, D. Prada-Rodríguez, Anal. Chem. 80 (2008) 9272.
[72] M. Radišić, S. Grujić, T. Vasiljević, M. Lauševic, Food Chem. 113 (2009) 712.
[73] S. Bogialli, G. D'Ascenzo, A. Di Corcia, A. Laganà, G. Tramontana, J. Chromatogr. A 1216 (2009) 794.
[74] S. Bogialli, G. D'Ascenzo, A. Di Corcia, A. Laganà, S. Nicolardi, Food Chem. 108 (2008) 354.
[75] S. Bogialli, G. D'Ascenzo, A. Di Corcia, G. Innocenti, A. Laganà, T. Pacchiarotta, Rapid Commun. Mass Spectrom. 21 (2007) 2833.
[76] S. Bogialli, A. Di Corcia, A. Lagana, V. Mastrantoni, M. Sergi, Rapid Commun. Mass Spectrom. 21 (2007) 237.
[77] S. Bogialli, C. Coradazzi, A. Di Corcia, A. Laganà, J. AOAC Int. 90 (2007) 864.
[78] C. Blasco, A. Di Corcia, Y. Picó, Food Chem. 116 (2009) 1005.
[79] S. Bogialli, R. Curini, A. Di Corcia, A. Laganà, G. Rizzuti, J. Agric. Food Chem. 54 (2006) 1564.
[80] H. Yan, F. Qiao, K.H. Row, Anal. Chem. 79 (2007) 8242.
[81] H. Sun, F. Qiao, G. Liu, S. Liang, Anal. Chim. Acta 625 (2008) 154.
[82] L. Guo, M. Guan, C. Zhao, H. Zhang, Anal. Bioanal. Chem. 392 (2008) 1431.
[83] G. Fang, G. Min, J. He, C. Zhang, K. Qian, S. Wang, J. Agric. Food Chem. 57 (2009) 3040.
[84] A.H. El-Sheikh, J.A. Sweileh, Y.S. Al-Degs, A.A. Insisi, N. Al-Rabady, Talanta 74 (2008) 1675.
[85] Q. Zhou, J. Xiao, Y. Ding, Anal. Chim. Acta 602 (2007) 223.
[86] S. Wang, P. Zhao, G. Min, G. Fang, J. Chromatogr. A 1165 (2007) 166.

[87] A.H. El-Sheikh, A.A. Insisi, J.A. Sweileh, J. Chromatogr. A 1164 (2007) 25.
[88] Q. Zhou, Y. Ding, J. Xiao, Anal. Bioanal. Chem. 385 (2006) 1520.
[89] Q. Zhou, W. Wang, J. Xiao, Anal. Chim. Acta 559 (2006) 200.
[90] Q. Zhou, J. Xiao, W. Wang, G. Liu, Q. Shi, J. Wang, Talanta 68 (2006) 1309.
[91] T. Bajer, M. Adam, L. Galla, K. Ventura, J. Sep. Sci. 30 (2007) 122.
[92] A.G. Frenich, P. Bolanos Plaza, J.L. Vidal Martinez, J. Chromatogr. A 1153 (2007) 194.
[93] J.J. Jiménez, J.L. Bernal, M.J. del Nozal, M.T. Martín, R. Mayo, J. Chromatogr. A 1146 (2007) 8.
[94] F. Bianchi, M. Careri, A. Mangia, M. Musci, S.E. Santini, G. Basini, J. Pharmaceut. Biomed. 44 (2007) 711.
[95] H. Liu, Q. Li, S. Li, Y. Zou, A. Gu, J. Chromatogr. Sci. 46 (2008) 122.
[96] M.S. Dopico-García, P. Valentão, A. Jagodziñska, J. Klepczyñska, L. Guerra, P.B. Andrade, R.M. Seabra, Talanta 74 (2007) 20.
[97] K. Ridgway, S.P.D. Lalljie, R.M. Smith, J. Chromatogr. A 1153 (2007) 36.
[98] B. Shao, H. Han, X. Tu, L. Huang, J. Chromatogr. B 850 (2007) 412.
[99] A. Garrido Frenich, P. Plaza Bolaños, J.L. Martínez Vidal, J. Chromatogr. A 1153 (2007) 194.
[100] P.H. Viana de Carvalho, V. de Menezes Prata, P.B. Alves, S. Navickiene, J. AOAC Int. 92 (2009) 1184.
[101] T.F. Santana dos Santos, A. Aquino, H. Silveira Dórea, S. Navickiene, Anal. Bioanal. Chem. 390 (2008) 1425.
[102] G. Kesiūnaite, E. Naujalis, A. Padarauskas, J. Chromatogr. A 1209 (2008) 83.
[103] S. Wang, Y. Xu, C. Pan, S. Jiang, F. Liu, Anal. Bioanal. Chem. 387 (2007) 673.
[104] R.N. Wu, Y.L. Dang, L. Niu, H. Hu, J. Food Compos. Anal. 21 (2008) 582.