Use of new tailored and engineered materials for matrix solid-phase dispersion

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Abstract

Matrix solid-phase dispersion (MSPD) is a nowadays widely accepted technique for the one-step extraction and purification of organic analytes in different research areas. The several innovations incorporated since its introduction 30 years ago have progressively contributed to increase its simplicity, flexibility, rapidity, robustness and straightforward nature. In recent years, progress in MSPD has continued through the incorporation of new engineered and tailored sorbents and solvents to the process, which have facilitated its miniaturization due to the enhanced sorption capacities and improved selectivity provided by these reagents. In some cases, these improved features have also stimulated the combined use of MSPD with other enhanced solvent extraction techniques, resulting in even faster, greener and less manipulative methodologies. This review paper discusses recent advances in these fields through representative application studies dealing with the analysis of organic compounds in environmental and food samples.

Keywords: Sample preparation, Extraction, Matrix solid-phase extraction, Novel sorbents; Novel solvents

1. Introduction

Sample preparation is usually recognized as the bottleneck of many modern analytical procedures. The term sample preparation is a generic name that, rigorously, groups all operations, manipulations and treatments carried out with the investigated sample with the aim of obtaining an extract representative of the initial sample and that contains the target analyte(s) in a form and concentration level suitable for accurate determination with the instrument selected for final separation-plus-detection. Therefore, this term would include from operations such as labelling, mechanical processing, homogenization, and gravimetric or volumetric operations developed with the sample received in the laboratory; to the several treatments performed to extract the target compounds from the matrix in which they are entrapped and to isolate them from any potential co-extracted interfering material. However, and despite this consideration, in this review the term sample preparation will apply exclusively for this later set of operations.

In general, the nature and the number of treatments to be incorporated to a specific sample preparation procedure are determined by several factors. These range from the physico-chemical properties of the compounds of interest, their anticipated concentration in the investigated matrix, the complexity of the latter, the sensitivity and selectivity of the instrumental technique selected for their final determination, to the final goal of the analysis (e.g., screening vs accurate quantitation) [1]. In the case of organic compounds, the actual level of development of the instrumental analytical techniques allows achieving level of sensitivity and selectivity that were difficult to imagine only a few decades ago. This is particularly true when powerful separation liquid or gas chromatographic-based techniques are used in combination with state-of-the-art mass spectrometric systems. Today, it is generally accepted that, with such instruments, the initial amount of sample can be reduced without affecting the precision and accuracy of the finally reported results. Thereby, advances achieved in the instrumental field during the last decades have promoted a significant development in the sample preparation area, where new miniaturised and sometimes simplified treatment procedures have been proposed [2-4].

Today, the miniaturisation of the analytical processes, and of the sample preparation protocols in particular, is considered a desirable feature of modern analytical methodologies, as this is also a way to approach the principles of green chemistry [5]. The miniaturisation of the sample treatments results in a low sorbent(s) and solvent(s) consumption, short analytical times and minimise wastes generation, as well as the analyst exposition to harmful reagents, including volatile organic solvents. In addition, miniaturisation is frequently considered a required step

when setting-up (semi-)automated protocols and analytical systems [2]. It is also considered one of the most rational approaches when dealing with the analysis of size-limited samples [6]. Two different strategies are possible when approaching the miniaturisation of the sample preparation protocols. The first one is the development of novel miniaturised techniques. That was the way followed for the development of techniques based on solvent microextraction (SME) [7] and solid-phase microextraction (SPME) [8, 9], to mention a couple of representative examples of nowadays fully accepted methodologies for the treatment of aqueous samples. The second approach is the scaling down of already existing and well-established techniques. This strategy resulted in some successful and sometimes automated instruments, in particular when based on the solid-phase extraction (SPE) principles [2, 10]. However, it should be mentioned that most of these approaches have focussed on the treatment of liquid or viscous samples. Meanwhile, the development of equivalent methods for the treatment of solid matrices have been much more limited [11]. A possible explanation for this fact is that the strong retention of the analytes in these matrices made advisable the use of more powerful extraction techniques, in general involving the application of auxiliary source of energy for which the corresponding miniaturised instrument is not commercially available [6]. One of the most remarkable exceptions to this general trend is matrix solid-phase extraction (MSPD), probably because it does not involve any type of special equipment. The MSPD technique was introduced in 1989 by Baker et al. [12] for the isolation of drugs residues from complex biological tissues. During these three decades, MSPD has experienced a maybe not too fast but steady development, with a sharper rise during the last 15 years [13]. Over years, the MSPD application field has evolved from the original bio-applications described by their inventors to become a common practice in many other research areas, where it is used for the simultaneous extraction-plus-purification of widely divergent analytes [13-16]. In recent years, MSPD has been combined with other enhanced extraction techniques to reduce the extraction time, miniaturised to allow its hyphenation with the instrument selected for final analyte determination, and used in combination with new sorbents and solvents to enhance the selectivity of the process. Some of these advances have been discussed in a number of recent reviews and book chapters [11, 13, 15-17]. To avoid as much as possible overlapping with these previous texts, the present review discusses progress done in MSPD concerning the use of highly sorptive and more selective sorbents and solvents for the analysis of trace organic compounds in complex environmental and food samples, which is considered one of the most active research fields at present.

2. General principles of matrix solid phase dispersion and main analytical configurations

The basic procedure for MSPD, as initially described by Barker and his co-workers [12], is applicable to liquid, viscous, semi-solid or solid sample, and involves three main steps. The first one consists on the manual blending of the sample with a preselected dispersant sorbent or mixture of sorbents (Figure 1). This is a mechanical step typically carried out with a glass pestle in a glass or agate mortar because porous materials, such as porcelain, can lead to analyte and/or sample losses [18]. In general, the goal of this treatment is to shear and disrupt the gross sample architecture into small pieces at the time that the potential interfering matrix components are dispersed and selectively retained on the sorbent particles surface as a thin layer. (Note: Depending on the application aim, the dispersant can also be selective toward the target compounds or inert at all, as for diatomaceous earth or sea sand.) The dried homogenous powder-like mixture resulting from this process is packed and compacted in an empty syringe barrel or an SPE cartridge for subsequent selective analyte elution with an appropriate solvent. The nature of the dispersant sorbent(s) and the sample:sorbent(s) ratio, and the solvent nature and volume are critical experimental parameters with a profound influence on the selectivity and efficiency of the MSPD process. Nevertheless, other aspects, like the grinding time, the possibility of incorporating a small volume of a selected solvent to facilitate matrix disruption during the grinding step, packing of an extra sorbent under the MSPD mixture (the so-called co-sorbent), or using an external column for further purification of the MSPD eluent should also be considered [15, 17].

A variety of sorbents has been used as dispersant materials for MSPD. Inert solid supports, such as sea sand, Celite and diatomaceous earth, have demonstrated to be useful to disrupt the matrix architecture [19] and/or to prevent clogging of the MSPD column when working with small size particle mixtures [20]. However, the weak interactions set between the matrix components and these non-selective sorbents made solvent selection a critical aspect of method development, and the use of co-sorbent(s) usually mandatory to obtain ready-for-analysis extracts. Normal phase inorganic materials, such as bare (or chemically modified) silica, Florisil and Alumina and their mixtures, have also demonstrated to provide satisfactory results for the analysis of a wide variety of analytes in different matrices by MSPD (see e.g. [13, 17], and references therein). However, due to the less extensive retention of the (polar) analytes in the surface of these materials compared to reversed phase sorbents (i.e., adsorption vs dilution), in general, the optimization of the elution protocol with these sorbent is usually more demanding. Up to now, reversed phase materials, and in particular C8 and C18-silica bounded phases, have been the most profusely used sorbent for MSPD [13, 17]. These materials allow the selective

retention of matrix components with low to medium polarity, which explains their profuse use in application studies dealing with the treatment of biological samples and fatty foodstuffs. Nevertheless, they have also been used in other applications involving environmental non-fatty samples, such indoor dust [21], with satisfactory results. The strength of the interactions among the retained sample components and the sorbent surface allows the use of relatively sophisticated washing and elution protocols resulting in ready-for-analysis extracts without affecting the performance of the method [22, 23]; or, alternatively, in solventless processes [24]. Interestingly, in most already reported application studies involving these conventional inorganic sorbents for MSPD, i.e. those dealing with drugs and organic micropollutants analysis, sample:sorbent(s) ratios in the 1:1 to 1:4 range were used [15, 17]. Efforts carried out during the last years to enhance the selectivity of the MSPD process have led to the use of new and engineered sorbents with improved selectivity and loading capabilities. These new sorbents have typically allowed a further simplification and miniaturization of the MSPD methodologies, as it will be illustrated later. Meanwhile, efforts orientated to reduce the time required for analyte elution from the MSPD column or to reduce solvent volume while preserving a high analyte recovery have typically resulted in the combination of MSPD with other analytical extraction techniques able to enhance the solvent-analyte interaction. Alternatives proposed up to now with this aim have been based on (i) shaking of the MSPD mixture with the selected extraction solvent by either ultrasonication or exposure to microwaves of the slurry as packed in the extraction column (the so-called ultrasonic-assisted matrix solid-phase dispersion, UA-MSPD [25], and microwave-assisted matrix solid-phase dispersion, MA-MSPD [26]); or (ii) vortexing of the slurry in a centrifuge tube (the so-called vortex-assisted matrix solid-phase dispersion, VA-MSPD [27]). In the latter case, centrifugation is used for final separation of the solvent enriched in the target analytes from the solid support. However, this additional treatment step was avoided in a recent modification of this methodology involving graphene-based magnetic nanoparticles as MSPD dispersant material [26]. Apart from the enhanced loading capability of this material, its magnetic properties allowed an easy sorbent removal from the slurry by simple application of an external magnetic field. The technique was named magnetic-assisted matrix solid-phase dispersion (MA-MSPD). The several treatment steps involved in some of these novel MSPD-based techniques are shown in Figure 1.

Investigations on the feasibility of solvents alternative to conventional volatile organic ones that simultaneously contribute to enhance the selectivity and/or efficiency of the MSPD process have up to now been rather limited. As it will be shown in the next section, these studies have frequently involved the use of some of the previously mentioned energy or shaking enhanced MSPD-based techniques.

3. Use of novel sorbents and solvents in matrix solid-phase dispersion

As already indicated, the evaluation of novel sorbents with improved sorption capabilities or specific recognition capabilities, and of tailored solvents are recognized trends in MSPD at present [13, 15-17]. The enhanced loading capacity and/or selectivity provided by these newly designed or engineered materials result in an improved enrichment capability for the MSPD technique, which yields an enhanced sensitivity. The same consideration applies for the use of more selective extraction solvents. The improvement in the sensitivity of the MSPD process ultimately allows its miniaturization, reducing the amounts of reagents used and waste generation. In other words, the MSPD process becomes greener than in conventional applications. Selected representative examples of these trends are summarized in Table 1.

Novel Sorbents. Molecularly-imprinted materials (MIPs) are synthetic porous materials with selective binding cavities for the specific recognition of a particular analyte or class of chemically related analytes. Due to these special features, MIPs have been used in different formats for the selective extraction and preconcentration of specific compounds from a variety of matrices [48]. In particular, the synthesis of novel hydrophilic MIPs facilitated their use as MSPD dispersant, in most cases in combination with a more abrasive sorbent, e.g. sand [20], to ensure proper matrix disaggregation. Apart from the improved selectivity inherent to these materials, the hydrophilicity of their surface facilitated the incorporation of washing steps into the elution protocol, which further contributed to eliminate potential matrix interferences before analyte elution [28]. In fact, these treatments typically resulted in relatively concentrated and clean extracts allowing the unambiguous determined of the investigated compounds even with non-selective detectors. In a representative recent study, Arabi et al. [29] proposed a new strategy for the sol-gel synthesis of silica imprinted nanoparticles in a single step using propanamide as dummy template. The new sorbent was used for the selective extraction and preconcentration of acrylamide from foodstuffs (i.e., bread and biscuits) with minimum sample (100 mg), sorbent (150 mg of the acrylamide-MIP and 126 mg of sand) and solvents consumption (1 mL of hexane for fat removal and 2.5 mL of 1:1, v/v, acetonitrile:methanol for analyte extraction). The enhanced selectivity provided by the MIP, combined with the defatting step, resulted in very clean extracts and low limits of detection (LODs) of $16 \mu\text{g kg}^{-1}$ using an LC-UV instrument for final determination.

Several studies have taken advantage of the improved loading capabilities of carbon nanotubes (CNTs) to scale-down the MSPD process. Nevertheless, researchers not always agreed regarding the practicability of these materials for MSPD. Thereby, Vosough et al. [35] compared the performance of two nano-materials, MWCNT-silica and nano-silica-C18, for the extraction of sulfadiazine, sulfamerazine and sulfamethoxazole from a complex matrix, municipal sewage sludge, and found the former sorbent superior to the latter. When using MWCNT as dispersant, 30 mg of sorbent sufficed for the efficient dispersion of 200 mg of the dried sample, and 5 mL of acetonitrile for the quantitative recovery of the target analytes from the MSPD mixture, which was packed on top of 200 mg of SiO₂ (recoveries in the 91-95% range; RSD below 10%). Meanwhile, the use of nano-silica-C18 as dispersant resulted in slightly larger sorbent and solvent consumptions (300 mg of sorbent and 7 mL of acethyl acetate). More importantly, a larger number of interferences were observed during the LC-DAD determination of the investigated analytes when using this nano-sorbent. Cai et al. [36] also found MWCNT superior to conventional sorbents, i.e. C18 and diatomaceous earth, for the extraction with on-line purification on Florisil of 11 food packaging ink photoinitiators in tea powder and milk powder. While 0.2 g of MWCNT sufficed for dispersion of 4 g of the corresponding investigated sample, 1 g was required in the case of the conventional sorbents. Furthermore, while acceptable recoveries were obtained with the MWCNTs (77-121 %), a wider dispersion was observed in the case of C18 (57-116%) and diatomaceous earth (54-114%). However, Shen et al. [34] drawn the opposite conclusion when comparing the performance of MWCNTs, C18, neutral silica and hydrophilic-lipophilic balance (HLB) materials for the extraction of sulfonamides from fish tissues. In this study, the authors mention that the use of MWCNTs as dispersant resulted, instead on the expected homogenous mixture, on a black film that affected negatively the extraction of sulfonamides from this fatty sample. In fact, the recoveries obtained with this sorbent were systematically (and significantly) lower than those found with the other assayed materials. HLB was finally selected for the study. The enhanced sorption capacity provided by this sorbent, combined with the use of a highly selective and sensitive technique for final determination, LC-MS/MS, allowed the accurate determination of a large majority of the 14 investigated sulfonamides in fish muscle, even although only 10 mg of sample were used. With such a small amount of sample, 20 mg of HLB sufficed for homogenous sample dispersion. The resulting mixture was then packed in a pipette tip. This configuration allowed sample treatment to be completed in 6 min with only 200 µL of a mixture of methanol:H₂O:ammonia (50:49:1, v/v/v). The performance of the optimized method was found to be slightly superior to that of the conventional method, i.e. in cartridge MSPD, (recoveries of 71-91% vs 66-87%, respectively,

with RSD below 12% in both cases). Matrix effect was minimum and essentially similar in both cases.

Several studies have reported that, for some applications, chemically modified MWCNTs provided better results than the non-modified materials. That was the case of chitosan-grafted MWCNTs for the analysis of acrylamide in potato chips and toast foods. In this case, the modified MWCNTs provided more efficient adsorption of acrylamide than the unmodified material (recoveries, 85-95; RSD, 4%) [37].

In principle, the very large surface area, flexibility, chemical stability, and π -electron rich structure made of graphene a good candidate as sorption material. These positive features were exploited by Liu et al. [38] in a pioneer study that demonstrated that this sorbent led, in general, to superior recoveries than conventional materials (i.e., C18-silica, Florisil) and MWCNTs for the extraction of polybrominated diphenyl ethers (PBDEs) and their hydroxylated (OH-PBDEs) and methoxylated (MeO-PBDEs) analogues from different environmental matrices. However, other authors have reported practical difficulties for the direct use of this material. Among the most relevant, it can be mentioned frits clogging, difficulty to collect the MSPD mixture from the mortar due to the tiny graphene sheets, unsuitability of the sorbent to disrupt the sample architecture, and the possibility of irreversible aggregation through van der Waals interaction. Immobilization of graphene onto an appropriate silica-based sorbent [39] or transformation to three-dimensional graphene aerogel [40] have been strategies adopted to avoid these problems while maintaining the main advantageous features of the graphene sheets.

An alternative approach that allows circumventing some of the practical problems associated to the use of these tiny carbon-based sorbents is their modification to act as magnetic nanosorbents. This approach was successfully assayed by Fotouhi et al. [26] in a recent study dealing with the determination of parabens in breast milk. The poly(indole-thiophene) coated magnetic graphene oxide (MGO@PIT) used as MSPD sorbent was obtained by co-polymerization of thiophene and indole on the surface of the previously synthesized $\text{Fe}_3\text{O}_4/\text{GO}$. The presence of the co-polymer coating on the surface of the magnetic GO was confirmed by Fourier Transform Infrared, while scanning electron microscopy (SEM) was used to evaluate the size and surface morphology of the synthesized particles (Figure 2). Particle sizes in the 23.2-54.6 nm were confirmed. The optimized methodology consisted on the dispersion of 200 μL of breast milk on 50 mg of MGO@PIT and 550 mg of Na_2SO_4 . The resulting dried mixture was transferred into a breaker containing 5 mL of distilled water and mechanically stirred for 5 min. Then, the sorbent was separated from the suspension with a strong magnet. Parabens preconcentrated in the sorbent surface were extracted by vortexing the mixture for 2 min with 1 mL of methanol. The eluate was separated from this new suspension by sorbent removal with a magnet and, then,

transferred to a vial containing 9 mL of ultrapure water for dispersive liquid-liquid extraction of the analytes with 90 μ L of 1-octanol. After centrifugation at 4000 rpm for 5 min, the thin layer of 1-octanol containing the target micropollutants was analysed by LC-UV or LC-MS/MS. Despite its highly manipulative nature, the optimized VA-MSPD-based methodology showed a satisfactory performance, with LODs of 0.5 ng mL⁻¹ by LC-MS/MS, recoveries above 87% and repeatabilities better than 10% for real samples.

The potential benefice derived from the incorporation of tailored ionic liquids (ILs) to the MSPD process has also been evaluated in a number of application studies. ILs have been directly added to the MSPD mixture [43, 44], but also immobilized on the surface of the sorbed that acted as solid support [45]. The latter approach was used for the selective extraction of caffeic acid, ferulic acid, morin, luteolin, quercetin, apigenin, chrysin, and kaempferide from 50 mg of propolis using 200 mg of a silica material containing 10% of [C6MIM]Cl as MSPD sorbent. After a washing step with hexane (20 mL), the target analytes were selectively eluted with methanol (15 mL) and analysed by LC-UV after solvent exchange and concentration. Compared with other conventional (exhaustive) extraction methods, such as UAE and Soxhlet extraction, the MSPD procedure yielded lower but still acceptable recoveries (66-92%) due to its satisfactory repeatability (RSDs, 9-11%). In addition, the solvent and time consumption was notably reduced. Finally, it is worth mentioning that a few recent studies have also reported on the potential of some, up to now, unusual sorbent for MSPD. Assayed sorbents include the combination PSA/GCB, typically used to remove vegetable pigments in the QueChers method and successfully evaluated for MSPD with a similar goal in a study dealing with the determination of mycotoxins in vegetable commodities [30]; the use of β -Cyclodextrin and PSA for the isolation of ibuprofen enantiomers [31]; or chitosan for the analysis of pharmaceutical in fish tissues [49]. Despite the somehow disappointing results, this latter study emphasized the use of eco-friendly sorbents as an alternative way to further green the MSPD methodologies.

Novel Solvents. Up to now, only a limited number of studies have evaluated the feasibility of tailored (i.e., ILs) [27, 46] and/or green solvents (i.e., non-ionic surfactants) [47] as alternative to the volatile organic solvents commonly used as extractants in MSPD. By now, these novel solvents have been applied to the selective isolation and retrieval of relatively abundant bioactive compounds from plants, a field in which they have provided satisfactory results. Xu et al. [46] used 0.4 mL of 250 mM [BMIM]BF₄ for the conventional MSPD extraction of bioactive flavonoid glycosides from 50 mg of dried lime fruit dispersed on 150 mg of Florisil. The collected extract was centrifuged at 13,000 rpm for 5 min and the supernatant directly analysed by UPLC-UV. The authors suggested that the OH- groups of the flavonoid glycosides could facilitated their

initial linkage to the Florisil surface through hydrogen bond. Then, the fluorine atom in the [BMIM]BF₄ would promote a stronger hydrogen bond of the solvent with the target compounds, enabling their elution as a concentrated extract with minimum volume consumption. The recoveries, were in the 90-97 % range (spiking level, 60 mg/g) and the LODs were 4-5 µg/g. Although the authors did not refer elution problems during method development, in principle, the high density of most ILs and surfactants could make advisable to use one of the novel energy-assisted MSPD configurations for these types of applications. This later analytical strategy was adopted by Du and co-workers in their pioneer study reporting on the use of surfactants as MSPD extraction solvents for the isolation of phenols from a herb, i.e. *Fosythiae Fructus*. [47]. In this study, the authors compared the performance of several sorbents as MSPD dispersants (C18, AZO, SiO₂, Alumina-A, Alumina-B, Alumina.N and Florisil PR) and different surfactants (Triton X-114, Triton X-100 and Genapol X-080 and their mixtures) as eluents (Figure 3). The best results were obtained when 20 mg of the Florisil were used to blend 20 mg of the herb powder in an agate mortar for 3 min. The MSPD mixture was then transferred into a 10 mL centrifuge polypropylene tube for vortexing (3 min) with 2 mL of the non-ionic surfactant Triton X-114 (10%, v/v). The optimized VA-MSPD with a non-ionic surfactant methodology was found to provide reproducible (RSDs, 1-5%) and higher recoveries (95-104%) of the test compounds than conventional MSPD or ultrasound assisted extraction, a finding that, according to the authors, derived from the higher simplicity of the technique.

4. Conclusions

MSPD is considered a well-established, simple, flexible and rather straightforward technique that has already demonstrated its performance in many analytical application areas. When properly designed, optimized MSPD methods yield ready-for-analysis extracts in a single step so reducing sample manipulation and speeding up the analytical process. Recent advances in this field include the use of new engineered and highly selective sorbents, which have further contributed to green the MSPD process by promoting further miniaturization of the process while maintaining the required standards of quality. The emerging evaluation of tailored (i.e., ILs) and green solvents (e.g., non-ionic surfactants) as eluents alternative to conventional volatile organic solvents is another interesting trend also contributing to improve the selectivity and greenness of the MSPD process. Interestingly, some of these new approaches require further combination of MSPD with certain enhanced extraction techniques, thereby stimulating the development of

new analytical methodologies, but also inspiring novel application studies that demonstrate that MSPD is still an attractive and active research field.

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Table 1. Selected application studies involving the use of new sorbents and solvents in MSPD.

Matrix (amount)	Analyte	Dispersant	Extraction solvent	Recovery (RSD ¹ , %)	Instrumental determination	Ref.
Novel sorbents						
Goat milk (0.2 mL)	Steroids	MIP ² (48 mg) + Na ₂ SO ₄ (126 mg) + sea sand (126 mg)	ACN ³ (1 mL)	81-110 (1-12)	MECK ⁴ -DAD ⁵	[20]
Fruits (apple, pear, orange) (2000 mg)	OPPs ⁶	MIP (500 mg)	<i>n</i> -C ₆ ⁷ (30 mL) + MeOH ⁸ :acetic acid (95:5) (5 mL)	81-105 (1-5)	GC ⁹ -FPD ¹⁰	[28]
Biscuits, bread (100 mg)	Acrylamide	MIP-SiO-NP ¹¹ (150 mg) + sea sand (126 mg)	<i>n</i> -C ₆ (1 mL) + ACN:MeOH (1:1) (2.5 mL)	86-100 (1-7)	LC ¹² –UV ¹³	[29]
Vegetables (100 mg)	Microcystins	PSA ¹⁴ (70 mg)+ GBC ¹⁵ (30 mg)	MeOH (100 mL)	72-97 (1-9)	LC-MS/MS ¹⁶	[30]
Breast milk (500 mg)	Ibuprofen enantiomers	β-CD (21 mg) + PSA (260 mg) + DE ¹⁷ (300 mg) + Na ₂ SO ₄ (300 mg)	MeOH (2 mL)	71-86 (4-6)	Chiral LC-UV	[31]
Loquat leaf (24 mg)	Isomeric triterpenoid acids	MCC ¹⁸ (24 mg)	EtOH ¹⁹ (0.2 mL × 3)	90-108 (6-8)	UHPLC-Q-TOF/MS ²⁰	[32]
<i>Schisandrae Chinensis</i> fructus (25 mg)	Lignans	Mesoporous molecular sieve, TS-1 (50 mg)	MeOH (0.5 mL)	99-102 (2-3)	MEKC-UV	[33]
Fish tissue (10 mg)	Sulfonamides	HLB ²¹ (20 mg)	MeOH:H ₂ O:ammonia (50:49:1) (0.2 mL)	71-91 (<10)	LC-MS/MS	[34]
Municipal sewage sludge (200 mg)	Antibiotics	MWCNT ²² (30 mg) + SiO ₂ (200 mg)	ACN (5 mL)	91-95 (3-10)	LC-DAD	[35]

Tea powder, milk powder (4000 mg)	Food packaging ink photoinitiators	MWCNTs (200 mg)	Acetone: <i>n</i> -C ₆ (1:1) (15 mL)	71-121 (0.1-4)		[36]
Potato chip, toast (1000 mg)	Acrylamide	Chitosan-MWCNTs (2000 mg)	<i>n</i> -C ₆ (2 mL) + MeOH: H ₂ O:acetic acid (90:10:2, 4 mL)	85-94 (4)	LC-UV	[37]
Soils, tree bark, fish (100 mg)	PBDEs ²³ , MeO-BDEs ²⁴ , OH-BDEs ²⁵	Chemically converted graphene (10 mg)	<i>n</i> -C ₆ :DCM ²⁶ (1:1; 0.5 mL) + acetone (1 mL)	29-116 (3-20)		[38]
Leaves of <i>Murraya panaculata</i> (L.) Jack (25 mg)	Poly-methoxylated flavonoids	GO ²⁷ encapsulated silica (50 mg)	MeOH (5 mL)	93-102 (2-5)	UHPLC-UV	[39]
Soil (-)	Chlorophenols	Graphene aerogel (10 mg)	Acetone (1 mL)	86-111 (4-10)	LC-UV	[40]
Breast milk (0.2 mL)	Parabens	MGO@PIT ²⁷ (50 mg) + Na ₂ SO ₄ (550 mg)	MeOH (1 mL)	87-112 (2-10)	LC-MS/MS	[26]
Soil (100 mg)	PAHs	PTS-MgO ²⁹ (100 mg)	<i>n</i> -C ₆ (4 mL) + DCM (4 mL)	72-113 (1-7)	LC-FLD	[41]
Wastewater (100 mL)	PCBs	MBC ³¹ (30 mg)	Acetone (0.3 mL)	97-111 (3-7)	GC-ECD ³²	[42]
Condiments (500 mg)	Synthetic dyes	[C ₆ MIM][BF ₄] ³³ (120 mg) + DE (1500 mg)	H ₂ O (6 mL)	91-113 (1-9)	LV-UV	[43]
Vegetables (1000 mg)	Pesticides	[P ₆₆₆₁₄ ⁺][Co(II)(hfacac) ₃ ⁻] ³⁴ (15 mg)	Saturated NaCl sol (10 mL)	92-105 (5-7)	LC-DAD	[44]
Raw propolis (50 mg)	Phenolic acids and flavonoids	[C ₆ MIM]Cl ¹² -silica (200 mg)	<i>n</i> -C ₆ (20 mL) + MeOH (15 mL)	66-92 (9-11)	LC-UV	[45]
Novel solvents						
Lime fruit (50 mg)	Bioactive flavonoid glycosides	Florisil (150 mg)	[BMIM]BF ₄ ¹³ (250 mM, 0.4 mL)	90-97 (1-3)	UPLC-UV	[46]

<i>Fructus Corni</i> (20 mg)	5-HMF ³⁶ and iridoid glycosides	SiO ₂ (40 mg)	[DoMIM]HSO ₄ ³⁷ (6 mL)	95-103 (3-5)	UHPLC-UV	[27]
<i>Forsythiae</i> fructus (20 mg)	Bioactive phenolic compounds	Florisil (20 mg)	Triton X-114 (10%, v/v)	95-104 (1-5)	UHPLC-UV	[47]

¹ Relative standard deviation; ² Molecularly-imprinted materials; ³ Acetonitrile; ⁴ Micellar electrokinetic chromatography; ⁵ Diodo array detector; ⁶ Organophosphorous pesticides; ⁷ *n*-Hexane; ⁸ Methanol; ⁹ Gas chromatography; ¹⁰ Flame photometric detector; ¹¹ Nano-particles; ¹² Liquid chromatography; ¹³ Ultraviolet detector; ¹⁴ Primary secondary amine; ¹⁵ Glassy black carbon; ¹⁶ Tandem mass spectrometry; ¹⁷ Diatomaceous earth; ¹⁸ Microcrystalline cellulose; ¹⁹ Ethanol; ²⁰ Tandem quadrupole-time-of-flight mass spectrometry; ²¹ HLB: hydrophilic-lipophilic balance; ²² Multiwalled carbon nanotubes; ²³ PBDEs: Polybrominated diphenyl ethers; ²⁴ MeO-BDEs: Methoxy-brominated diphenyl ethers; ²⁵ OH-BDEs: Hydroxy-brominated diphenyl ethers; ²⁶ Dichloromethane; ²⁷ Graphene oxide; ²⁸ Poly(indole-thiophene) coated magnetic graphene oxide; ²⁹ Phenyltrichlorosilane-functionalized magnesium oxide microspheres; ³⁰ Fluorescence detector; ³¹ Magnetic bamboo charcoal; ³² Electron capture detector; ³³ 1-Hexyl-3-methylimidazolium tetrafluoroborate; ³⁴ Trihexyl(tetradecyl)phosphonium cobalt(II) hexafluoroacetylacetonate; ³⁵ 1-Hexyl-3-methylimidazolium chloride; ³⁶ 5-Hydroxymethylfurfural; ³⁷ 1-n-Dodecyl-3-methylimidazolium sulfate.

Figure 1. Schematic diagram of the basic MSPD extraction procedure and of several recent modifications of the technique [16].

Figure 2. SEM images of (A) GO, (B) magnetic GO, MGO, and (C and D) MGO@PIT [26].

Figure 3. Influence of the type and concentration of the extraction solvent on the MSPD efficiency for six selected bioactive compounds. (a-f) 2.5-15.0% Triton X-100; (g-k) 5.0-15.0% Triton X-114; (l-q) 2.5-15.0% Genapol X-080 (increments are 2.5% in all cases); (r) 0.5% Genapol X-080 + 05% Triton X-100; (s) 0.5% Triton X-114 + Triton X-100 + Genapol X-080 (2.5%); (v) Triton X-114 + Triton X-100 + Genapol X-080 (5.0%); (w) 70 % Methanol; and (x) Methanol [47].