separations

MDPI

Review

Magnetic Ionic Liquids in Sample Preparation: Recent Advances and Future Trends

Theodoros Chatzimitakos *, Phoebe Anagnostou, Ioanna Constantinou, Kalliroi Dakidi and Constantine Stalikas

Laboratory of Analytical Chemistry, Department of Chemistry, University of Ioannina, 45110 Ioannina, Greece; foebes@gmail.com (P.A.); pch01378@uoi.gr (I.C.); pch01372@uoi.gr (K.D.); cstalika@uoi.gr (C.S.)
* Correspondence: chatzimitakos@outlook.com; Tel.: +30-265-1008-725

Abstract: In the last decades, a myriad of materials has been synthesized and utilized for the development of sample preparation procedures. The use of their magnetic analogues has gained significant attention and many procedures have been developed using magnetic materials. In this context, the benefits of a new class of magnetic ionic liquids (MILs), as non-conventional solvents, have been reaped in sample preparation procedures. MILs combine the advantageous properties of ionic liquids along with the magnetic properties, creating an unsurpassed combination. Owing to their unique nature and inherent benefits, the number of published reports on sample preparation with MILs is increasing. This fact, along with the many different types of extraction procedures that are developed, suggests that this is a promising field of research. Advances in the field are achieved both by developing new MILs with better properties (showing either stronger response to external magnetic fields or tunable extractive properties) and by developing and/or combining methods, resulting in advanced ones. In this advancing field of research, a good understanding of the existing literature is needed. This review aims to provide a literature update on the current trends of MILs in different modes of sample preparation, along with the current limitations and the prospects of the field. The use of MILs in dispersive liquid–liquid microextraction, single drop microextraction, matrix solid-phase dispersion, etc., is discussed herein among others.

Keywords: magnetic ionic liquid; sample preparation; dispersive liquid–liquid microextraction; single drop microextraction; GC; HPLC

check for updates

Citation: Chatzimitakos, T.; Anagnostou, P.; Constantinou, I.; Dakidi, K.; Stalikas, C. Magnetic Ionic Liquids in Sample Preparation: Recent Advances and Future Trends. *Separations* **2021**, *8*, 153. https://doi.org/10.3390/separations8090153

Academic Editors: Attilio Naccarato and Jared L. Anderson

Received: 12 August 2021
Accepted: 7 September 2021
Published: 13 September 2021

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

The advancements in the production of new materials in liquid and solid form have significantly impacted the field of sample preparation in analytical chemistry [1]. In the past few years, a wide variety of them with exceptional properties have been utilized in the preconcentration and separation of analytes from different matrices [2,3]. The ionic liquids (ILs) are salts composed of organic cations and organic or inorganic anions [4]. They have melting points at or below 100 °C and hence, they exist as liquids in a wide temperature range. They have low melting points, negligible vapor pressures, outstanding chemical and thermal stabilities, and good affinities for both organic and inorganic analytes [4,5]. In addition, their viscosity, miscibility with organic or inorganic phases, and selectivity for several applications may be tuned based on the needs. Because of these unique physicochemical properties, they have emerged as an excellent class of alternative extraction media. Despite these advantages, poor phase separation, particularly in solvent-based extractions, remains a major challenge in analytical sample preparation [4–7].

Magnetic materials possess a prominent position in this research field as they have attracted considerable attention [3]. Recent developments have indicated that the synthesis of the single component magnetic ILs (MILs) where magnetic metals are not incorporated externally but as a part of the IL can lead to better phase separations by way of an external magnet [8]. MILs are liquids that combine the unique properties of ionic liquids with

magnetism, thus facilitating their easy retrieval during the extraction process. MILs are easy to disperse in solutions and can magnetically be separated from the other phases, negating the need for centrifugation, commonly employed in classical extraction procedures, thus, reducing the time and energy required for it. The careful tailoring of their components allows their successful application in the extraction of both hydrophilic and hydrophobic analytes from several media [3,4,8].

Much effort has been put into developing MILs based on transition metals that are less subjected to hydrolysis and possess improved magnetic properties. Therefore, MILs containing transition elements such as manganese, cobalt, gadolinium, and dysprosium have also been reported while metal-free MILs with a paramagnetic component based on organic radicals have also been synthesized [8–13].

So far, the use of MILs in sample preparation has greatly advanced, and many reports are being published with innovative concepts. Since this topic or research has great potential, our aim is to provide a literature update on the current trends of MILs in sample preparation under different conditions of operation, along with the current limitations and the prospects of the field.

2. Dispersive Liquid–Liquid Phase Microextraction

Dispersive liquid–liquid phase microextraction (DLLME) is one of the most popular solvent-based microextraction techniques. MILs have been investigated in DLLME-based approaches. Because of their favorable physicochemical properties, they can be an environmentally benign alternative to toxic organic solvents that are commonly employed. Furthermore, MILs can increase the sample throughput as they are easily harvested with the aid of a simple magnet, thereby eliminating the need for a centrifugation step.

2.1. Direct Use of MILs

2.1.1. Procedures for Organic Compounds Determination in Environmental Samples

A MIL can be used as an extraction phase for DLMME. In the study of Silva et al., such a sample preparation procedure was developed and combined with high-performance liquid chromatography with diode array detection (HPLC-DAD) for the determination of organic contaminants in river water samples [14]. The organic contaminants included pharmaceuticals (estriol, estrone, carbamazepine, diazepam, ketoprofen, ibuprofen, 17 α-ethynyl estradiol), plastic, and personal care additives (bisphenol A, triclocarban, methylparaben, ethylparaben), and pesticides (aldicarb, methyl parathion, metolachlor, and diuron). In comparison with other studies, this method does not require a centrifugation step and uses smaller volumes of solution and short time sample preparation. Although this method was published lately (compared with other procedures discussed later on), its design is rather simple.

A unique approach of MIL aqueous two-phase system (MIL-ATPs) coupled with HPLC was pursued by Yao et al. [15], for the first time. The magnetic ionic liquid was synthesized based on guanidinium cation to effectively separate chloramphenicol in a water environment. The method did not require any organic solvent and the extraction equilibrium was almost achieved when an aqueous two-phase phenomenon was applied. In these systems, different solutes can be separated from each other and separately distributed into two immiscible aqueous phases. A simple external magnetic field can be used to assist in phase separation. First, the MIL was dissolved in a cap containing only a water sample, then the anhydrous potassium phosphate was dissolved in the solution to avoid the change of ATPs temperature during salt addition. Finally, the magnetic collection was activated to separate the extraction phase and an amount of ionic liquid phase was directly injected into HPLC for quantitative analysis. Good linear range, low limit of detection and quantitation, good recovery were some of the advantages of this method. It is noteworthy that the use of different salts has a varying effect on phase separation. This information can be of interest for future studies to tune the performance of the method.

In another report of two-phase system development, three novel chiral MIL ([C_{2-4}MIM-Tempo][L-Pro])(4-Hydroxy-2,2,6,6-tetramethyl piperidine 1-oxyl free radical (4-OH-tempo)) (L-Pro:L-Pro) were used to construct an ATP system with inorganic salts (K_2HPO_4, K_2CO_3, K_3PO_4, Na_2SO_4, Na_2CO_3) for the extractive resolution of racemic phenylalanine (DL) [16]. Firstly, the MIL was added into a centrifuge tube and dissolved in water. Then, a certain amount of DL-Phe and $Cu(OAc)_2$ was added, and the mixture was shaken to form a clear solution. A volume of anhydrous dipotassium phosphate was added, so the solution turned cloudy, and the chiral MIL-ATPs was formed. Two aqueous phases formed and the enantiomer concentration of amino acid in the top phase and the bottom phase were determined by chiral HPLC-MS. This system combined the advantages of organic solvent-free, magnetic phase separation, and rapid extraction. It is worth mentioning that the MIL could be recycled at least six times with good resolution ability. This type of methods that focuses on the separation of racemic mixtures are scanty and sparse, and thus, more attention should be paid to such applications, since there is a demand for optically pure compounds.

A group of polycyclic aromatic hydrocarbons (PAHs) was extracted by three MILs and quantified with HPLC and fluorescence detection (HPLC-FD) [12]. The three MILs used were benzyltrioctylammonium bromotrichloroferrate (III) (MIL A), methoxybenzyltrioctylammonium bromotrichloroferrate (III) (MIL B), and 1,12-di(3-benzylbenzimidazolium) dodecane bis[(trifluoromethyl)sulfonyl)] imide bromotrichloroferrate (III) (MIL C). The analysis was applied to real aqueous samples, including tap water, wastewater, and a tea infusion and the analytes were benzo(a)anthracene, chrysene, benzo(a)pyrene, benzo(b)fluoranthene and benzo(k)fluoranthene. The results showed that the MIL A had the best performance for the extraction of PAHs (MIL B showed adequate extraction efficiency but was lower than that obtained with MIL A, whereas MIL C extracted the PAHs poorly). The method was able to achieve sufficient quantitation of high molecular weight PAHs, high sensitivity with low limits of detection (LODs), and sufficient reproducibility and efficiency. At the same time, a low volume of MIL and low consumption of organic solvent were required. This study corroborated the fact that MILs with different hydrophobicity have different extraction potential for the analytes, with better performance usually recorded for more hydrophobic MILs. However, the higher the hydrophobicity of a MIL the more difficult is to achieve a more homogeneous dispersion. Thus, the procedures can be improved by adding dispersive solvents or altering the pH of the solution.

In the study of Deng et al., a new hydrophobic magnetic room temperature ionic liquid {(trihexyltetradecylphosphonium tetrachloroferrate (III) ([$3C_6PC_{14}$][$FeCl_4$])} was synthesized [17]. The purpose of synthesizing this MIL was to investigate its possible use as a separation solvent for the phenolic compounds from soil samples, because of its paramagnetic characteristics as a response to an external magnet. The distribution ratios of the phenolic compounds were influenced by the pH of the aqueous phase, the nature of the ILs, and the chemical structure of the phenols themselves. Furthermore, the MIL technique showed a much higher extraction capacity than traditional nonfunctionalized RTILs. Finally, the MIL method might be efficient in real samples such as industrial, river and lake water samples, or it can be tested in recovery and recycling the MIL (probably by using centrifugation techniques or strong magnets).

Three hydrophobic MILs were synthesized and employed as extraction solvents in DLLME coupled to HPLC employing ultraviolet radiation (UV) detection [18]. The three MILs [tetrachloromanganate(II) [$MnCl_4^{2-}$]anion, aliquat tetrachloromanganate (II) ([$Aliquat^+$]$_2$[$MnCl_4^{2-}$]), methyltrioctylammonium [$MnCl_4^{2-}$]([$N_{1,8,8,8}^+$]$_2$[$MnCl_4^{2-}$]), and trihexyltetradecylphosphonium [$MnCl_4^{2-}$] ([$P_{6,6,6,14}^+$]$_2$[$MnCl_4^{2-}$])], used in the extraction of pharmaceuticals, phenolics, insecticides, and polycyclic aromatic hydrocarbons. The MIL was mixed with the disperser solvent, and then the mixture was pipetted with the sample solution, followed by shaking. The MIL containing the analytes was retrieved using a magnet rod. Finally, the MIL was dissolved in acetonitrile, and that solution was injected into an HPLC. The [$P_{6,6,6,14}^+$]$_2$[$MnCl_4^{2-}$] was the MIL that exhibited the best extraction

results for most analytes and the cleanest chromatographic background. Low LODs were obtained for all target analytes, and acceptable recoveries for water and lake samples were accomplished. In this study, an important topic was taken under consideration as most MILs based on the iron tetrachlorate anion are prone to hydrolysis. This can limit the potential of MILs for use in aqueous samples. Moreover, this anion exhibits strong UV absorbance which also limits the potential use of HPLC-UV systems for separation and analysis. Therefore, other magnetic anions, such as the manganese tetrachloride anion should be examined.

Another informative case is the investigation of three MILs based on the cation $[P_{6,6,6,14}]^+$, combined with tetrachloroferrate(III), ferricyanide, and dysprosium thiocyanate [19]. These MILs were evaluated as extraction solvents of three different microextraction strategies for the efficient extraction and preconcentration of four estrogens, estrone, estradiol, estriol, and ethinylestradiol, from environmental water. In the first and second one, the MIL was suspended to the aqueous solution, and stirring was performed with an external magnet using an orbital shaker and a stir bar, respectively. In the third one, MIL was first immobilized on a stir bar and then, the aqueous solution was added, with MIL remaining on the rod due to its high viscosity and strong paramagnetism. In the latter case, highest extraction recoveries of analytes were achieved with the use of $[P_{6,6,6,14}][FeCl_4]$, $[P_{6,6,6,14}]_3[Fe(CN)_6]$, and $[P_{6,6,6,14}]_5[Dy(SCN)_8]$ MILs. Of these three MILs, the $[P_{6,6,6,14}]_3[Fe(CN)_6]$ was found to be the most suitable due to its reduced cost, hydrophobicity, and easier synthesis. It is important that the design of this MIL, along with the advantages it offers, has barely been examined for its application in the analytical field. Compared with other reported techniques, due to the low consumption of solvents and the use of ionic liquids as an organic phase, it responds well to the green chemistry principles. Compared with solid–phase–based microextraction and other DLLME-based techniques, it provides similar or lower extraction times.

Along these lines, Chatzimitakos and co-workers proposed a stirring-assisted drop breakup microextraction combined with HPLC for the determination of selected phenols and acidic pharmaceuticals in aqueous matrices [20]. In this mode, an aqueous sample was added to a glass beaker and temperature and pH was adjusted. The addition of one drop of the MIL (16 ± 1 mg) accompanied by stirring, initially led to the decomposition of the droplets and the subsequent reunion into one which contained the analytes. The $N_{8,8,8,1}[FeCl_4]$ MIL was detached from the solution with a magnet and dissolved in a mixture of DDW: acetonitrile (1:3) for the injection into the HPLC-DAD system. In the authors' view, this is the first attempt to use this MIL for analytical aims through a simple, efficient, environmentally friendly, and low-cost drop-breakup microextraction for small molecules.

2.1.2. Procedures for the Determination of Organic Substances in Food Samples

The application of different MIL can also be applied in DLLME to the determination of six estrogens in samples of milk and cosmetics [21]. Six estrogens (estrone, estradiol, 17-α-hydroxyprogesterone, chloromadinone, 17-acetate, megestrol 17-acetate and medroxyprogesterone 17-acetate) were extracted by employing four MILs ($P_{6,6,6,14}^+][FeCl_4^-]$, $[P_{6,6,6,14}^+]_2[MnCl_4^{2-}]$, $[P_{6,6,6,14}^+]_2[CoCl_4^{2-}]$ and $[P_{6,6,6,14}^+]_2[NiCl_4^{2-}]$. The MIL that gave the best results including low chromatographic background, wide linear range, low detection limit, and good recovery, was the $[CoCl_4^{2-}]$-based MIL. In comparison with $[P_{6,6,6,14}^+]_2[MnCl_4^{2-}]$ and $[P_{6,6,6,14}^+]_2[CoCl_4^{2-}]$, the $[P_{6,6,6,14}^+]_2[CoCl_4^{2-}]$ shows good selectivity for six analytes, and the color of MIL based on $[MnCl_4^{2-}]$ is light yellow, which is difficult to observe and separate. In this case, also, the iron-based anion was avoided, reducing the hydrolysis of the MIL, and the color of the MIL was also taken under consideration, in order to make easier the visualization of the droplets and their magnetic harvest. The method presented fast, accurate and precise results along with accuracy, precision, effectiveness, economical, and environmentally friendly.

Wang et al. developed a MIL that can extract triazine herbicides from vegetable oils with a DLLME [22]. The 1-hexyl-3-methylimidazolium tetrachloroferrate ($[C_6mim][FeCl_4]$)

was used for extracting triazine herbicides from vegetable oils, two soybean oils, three maize oils, and two sunflower seed oils samples. Moreover, carbonyl iron powder (CIP) was applied to minimize magnetic separation time, thus can be magnetically attracted by the MIL to form a combination of CIP and MIL (CIP-MIL). Briefly, a dilution of vegetable oil sample with n-hexane was performed, then an ultrasound extraction with the MIL and the adding volume of the CIP. Next, the CIP-MIL was collected with a strong magnet and washed with n-hexane. A volume of deionized water and ethyl acetate was added to dissolve the MIL and extract the target analytes. After evaporation with a nitrogen stream, the final sample was redissolved with acetonitrile, followed by LC analysis (Figure 1). Compared with previously developed methods [23–27], the performance achieved by this method was found to be acceptable. The use of ultrasonication was an asset for this method, as it reduced the extraction time to 7 min. Thus, not only dispersion agents, but ultrasonication can also be employed for the dispersion of the MILs.

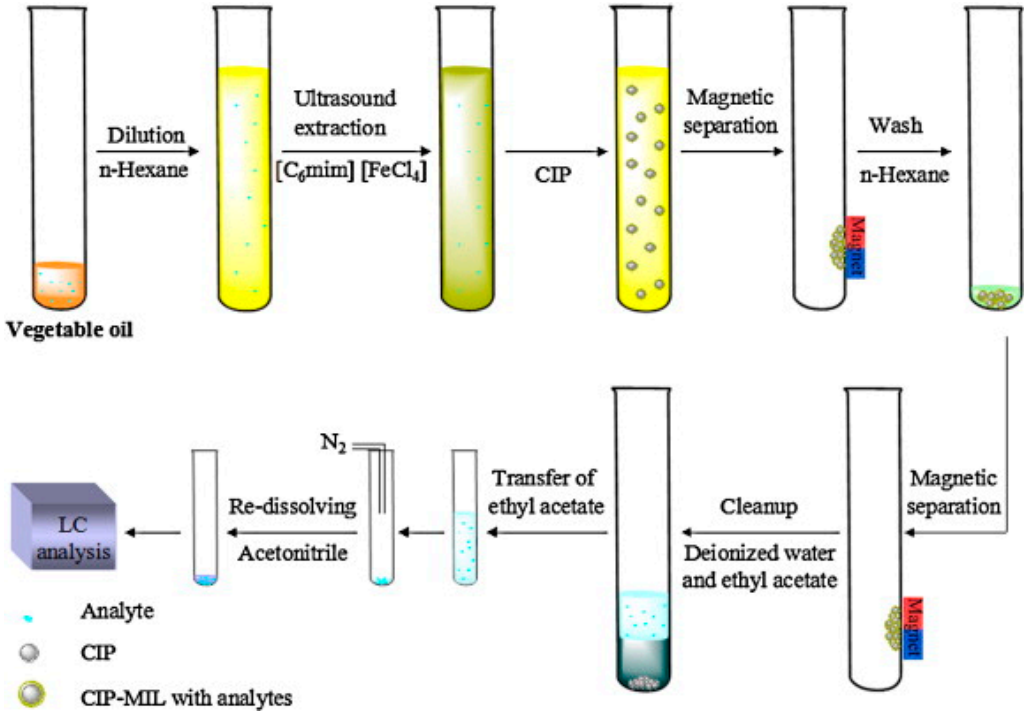


Figure 1. Schematic diagram of the DLLME extraction procedure of triazines from vegetable oils. Reproduced with permission from [22]. Copyright Elsevier, 2014.

Li et al. developed an ultrasonic-assisted extraction method (UAE) for sinomenine (SIN) microextraction from *Sinomenium acutum*, utilizing a range of MILs based on imidazolium cations and iron(III) anions [28]. S. acutum powder was added to a tube along with the MIL. The solution was ultrasonicated for the extraction of SIN and subsequently was centrifuged. The surfactant bis (2-ethylhexyl) sulfosuccinate sodium salt (AOT) was used for the reversed micellar extraction of SIN. The AOT was dissolved in isooctane and an amount of water was added into the tube. The resulting transparent AOT/isooctane reversed micellar system was added to a tube together with the aqueous MIL phase. The mixture was shaken and then placed in a separating funnel. The AOT/isooctane micellar system was separated from the aqueous phase and absolute ethanol was added to destroy the micellar system. After stirring, the mixture was transferred to a separation funnel for the reversed extraction of SIN into the ethanol phase. Compared with other methods the heat reflux extraction using MIL, ethanol-heat reflux extraction, H_2O-heat reflux extraction, Ethanol-UAE, H_2O-UAE), MIL-UAE reveals the maximum extraction yield of 10.57 mg g^{-1}, indicating the excellent extraction ability of the MIL and the rapidity of the method. Moreover, due to multi-interactions (ionic/charge-charge and hydrogen

bonding,) between SIN and the MIL, the solubility of the SIN in the solution is enhanced in the present MIL-UAE method. However, this method is still complex and contains many laborious steps, thus it needs to be further simplified in order to be used more widely.

Feng et al. reported an extraction method for polyphenols in tea leaves using magnetic ionic liquids [29]. Pulverized tea leaves were added into a conical flask along with C_3mim$FeCl_4$ MIL and the extraction was ultrasonic-assisted. The pH was adjusted to 3–3.5 and the solution was left to stand. After the removal of tea residue with filtration, NaOH was added, and the forming tea polyphenols-MIL complex was precipitated. The mixture was centrifuged and filtered. The liquid phase was diluted and analyzed with HPLC to determine its contents. The filter cake was dissolved and diluted with methanol to determine its contents. In this, a CIP was added, and the MIL was combined with the CIP. The solution was left to stand and then a magnet was used for the separation of the phases. The residual solution was diluted and analyzed with HPLC. The extraction efficiency of tea polyphenols was much higher than that achieved by the traditional solvents such as water and alcohol-water. The MIL that was used in this study has high selectivity, so it can be removed from target analytes easily. In conclusion, MILs can be a useful solvent for the extraction and determination of natural products. More attention should be paid to the iron-containing MILs, due to their increased absorbance in the UV region, which can hinder the identification and quantification of polyphenols.

A more enhanced version of MIL-DLLME came to the fore by Chatzimitakos and co-workers, who succeeded in identifying triazines (TZs) and sulfonamides (SAs) [9]. The peculiarity of this new method was the combination of a water-insoluble solid support with $[P_{6,6,6,14}{}^+][Dy(III)(hfacac)_4{}^-]$ MIL and the separation of the analytes in a one-pot, pH-modified procedure. By mixing the solid support with the MIL, difficulties related to the weighing and the uniform dispersion of the MIL were avoided. To do so, materials such as quartz silica microparticles, insoluble silica, and soluble inorganic salts were tested, with quartz silica eventually prevailing. In brief, the liquid sample was mixed with trisodium citrate and a quantity of a $[P_{6,6,6,14}{}^+][Dy(III)(hfacac)_4{}^-]$-quartz silica mixture under stirring, which led to the formation of tiny droplets. Magnetic isolation (using a neodymium cylinder magnet), and dissolution in acetonitrile solution, was followed by the HPLC analysis. A key point of the process was the pH adjustment. It was observed that by primarily adjusting the pH to 9.0 and then lowering it to 3.0, efficient extraction was achieved first of the TZs and then of the SAs. Apart from the beneficial use of the solid supporting material and the achievement of the process in one-pot, it is worth noting that both classes of analytes were simultaneously separated, with advantageous recoveries. This study is one the few that tried to address the issue of poor MIL dispersibility, a common problem for hydrophobic MILs and paved the way for the use of solid support materials, whose sole purpose is to control the dispersibility of the MIL. The solid support materials can be reused since they do not take part in the extraction process.

Mousavi and co-workers synthesized a magnetic ionic liquid that was used in the DLLME of ultra-trace amounts of parabens in wine, beer, and water samples [30]. $[N_{1,8,8,8}{}^+][FeCl_4{}^-]$, a magnetic room temperature IL, was synthesized through an easy reaction between methyltrioctylammonium chloride ($[N_{1,8,8,8}{}^+][Cl^-]$) and iron(III) chloride hexahydrate ($FeCl_3$ $6H_2O$). What stands out in the present study is the possibility of micelle formation due to the surface-active material of MIL. It was investigated, for the first time, as an important factor in phase separation, affecting the recovery of the MIL. For this purpose, 20 mL of extraction solvent ($[N_{1,8,8,8}{}^+][FeCl_4{}^-]$) was diluted in 250 mL of disperser solvent (acetone). The solution was placed into a capped glass containing the sample solution with NaCl (25%, *w*/*v*). After sonication for 1 min, a cloudy solution was formed. From this, the supernatant was removed, and the analyte-rich MIL phase was retrieved by a magnet. The analysis was further continued via HPLC-UV. According to the results, great extraction efficiencies and impressive recoveries were caused by the extensive surface contact between the $[N_{1,8,8,8}{}^+][FeCl_4{}^-]$ droplets and the sample, which forms stronger intermolecular forces (e.g., *p*-*p*, *n*-*p*) than those between water and parabens.

2.1.3. Procedures for the Determination of Organic Substances in Biological Samples

MILs can also be used as extraction phases in DLLME for the analysis of hormones (estriol, 17-β-estradiol, 17-α-ethynylestradiol, and estrone) in human urine samples [11]. Merib et al. showed that the MILs trihexyltetradecylphosphonium tetrachloromanganate (II) ($[P_{6,6,6,14}^{+}]_2[MnCl_4^{2-}]$) and aliquat tetrachloromanganate (II) ($[Aliquat^{+}]_2[MnCl_4^{2-}]$), followed by separation/detection with HPLC, could be of a biological interest too. Briefly, a mixture of a disperser solvent (methanol) and the MIL ($[P_{6,6,6,14}^{+}]_2[MnCl_4^{2-}]$) was added to urine samples, and a manual shaking step was applied to facilitate the formation of microdroplets in the solution. Right after that, the MIL was reserved with a rod magnet and the extraction phase containing the enriched analytes was desorbed in an portion of acetonitrile, before injection into the HPLC-DAD system. This extraction step was performed in a short time (90 s) without the need for a centrifugation step. In addition, chromatographic separations were conducted within 10 min allowing for high-throughput analysis and LODs, comparable to previously reported data using other microextraction techniques requiring longer extraction times. Analyzing biological samples in such an efficient and environmentally friendly way is needed in analytical chemistry.

The work of Will et al. expands the potentials of MIL with the presentation of a simultaneous determination of different compounds of human urine samples [31]. The $[P_{6,6,6,14}^{+}][Cl^{-}]$ MIL was used for the extraction of eight compounds including pesticides (carbofuran, atrazine, simazine, diuron, and metolachlor), estrogenic hormones (ethinylestradiol and estrone), and a pharmaceutical compound (diclofenac). Dispersive liquid–liquid microextraction based on the MIL was used as the sample preparation procedure (MIL-DLLME). The MIL showed good selectivity for the low-polarity compounds evaluated in the study, allowing for the simultaneous determination of different classes of compounds. A MIL-DLLME-based procedure was fully optimized, and a rapid extraction methodology was performed (11 min of extraction). In addition, this method can be easily automated, which can considerably increase the throughput features of the determination. The MIL-based approach constitutes a formidable tool to avoid chlorinated organic solvents, which have frequently been used in DLLME. Moreover, the combination of automated analyses with wide applicability is highly promising for an analytical method to be employed in routine analysis. Abdelaziz and co-workers succeeded in the determination of four antihypertensive drugs of the sartan class through a gadolinium-based MIL which was used as an extraction solvent in DLLME [32]. For this reason, three hydrophobic MILs based on the trihexyl(tetradecyl)phosphonium ($P_{6,6,6,14}$) cation containing different paramagnetic metal-halide anions ($FeCl_4^{-}$, $MnCl_4^{2-}$, and $GdCl_6^{3-}$) were synthesized according to previous reports. Although all three revealed compatibility with common reversed-phase HPLC solvents and low miscibility with aqueous samples during extraction, some complications affected the extraction efficiency. The $[P_{6,6,6,14}^{+}]_3[GdCl_6^{3-}]$ was found to be the most beneficial. It combines advantages such as higher magnetic susceptibility, better adhesion to sartans, lower toxicity, satisfactory viscosity, and it is less likely to undergo hydrolysis in aqueous samples. A comparison between the proposed method and SPE and IL-DLLME, confirms its advantageous position. $[P_{6,6,6,14}^{+}]_3[GdCl_6^{3-}]$ based DLLME provides faster and better automation. Although LOQ values were lower for the SPE methods, much lower quantitation limits should be achieved if the proposed one is coupled with highly sensitive MS/MS detection and/or applied to larger sample volumes.

In a more recent study, two room temperature MILs were synthesized to preconcentrate, determine, and separate the carbamazepine drug in urine and wastewater samples [33]. To achieve this, dispersive micro-solid phase extraction was used in conjunction with HPLC. Iron and cobalt-containing MILs $[OA]FeCl_4$ and $[OA]CoCl_3$ ((Z)-octadec-9-en-1-aminium tetrachloroferrate (III) and (Z)-octadec-9-en-1-aminium trichlorocobaltate (II)) were tested as sorbents with the satisfactory results setting the stage for future applications for the extraction of pharmaceutical trace contaminants in the water samples. For the extraction procedure, 10 mL of 300 $\mu g \cdot L^{-1}$ NaCl and 40 mL of MIL were mixed in a glass

beaker on a magnetic stirrer. Owing to the magnetic properties, the MIL adsorbent was obtained through a magnet, and analysis was continued by HPLC-DAD. The extraction was based on electrostatic interactions, between the MIL and the analyte, whereas the acetonitrile used for the desorption, exhibited stronger dipole-dipole interactions with the analyte and removed it from the MIL. Reaping such mechanisms of interaction for the extraction of the analytes can sometimes be advantageous, since hydrophobic interactions need to use more hydrophobic MILs. Thus, other type of problems may arise, whereas electrostatic interactions are weaker and are more sensitive to temperature variations.

2.1.4. Procedures for Metal Species Determination in Food Samples

Fiorentini et al. investigated a MIL-DLLME method for the determination of trace Cadmium in honey samples [34]. The honey sample was added in a tube along with ammonium diethyldithiophosphate (DDTP) and HCl. The DDTP was added to form a hydrophobic chelate with Cd(II), highly stable at pH values below three, thus the efficiency of the extraction increases. HCl was added to acidify the solution. The mixture was stirred and left to rest to ensure the formation of the Cd-DDTP complex. Subsequently, the trihexyl(tetradecyl)phosphonium, $[P_{6,6,6,14}]FeCl_4$, MIL phase and acetonitrile, as a dispersant, were added. After stirring the mixture, a magnetic bar was used to collect the MIL phase. An amount of HNO_3 was utilized to back-extract the analyte from the MIL material since the direct determination of Cd in the MIL is not attainable due to the interference of Fe in this type of solvent. Finally, the preconcentrated sample solution was injected into the graphite furnace of an electrothermal atomic absorption spectrometry (ETAAS). The LOD was 0.4 $ng \cdot L^{-1}$ Cd and extraction efficiency was 93%. This work probably constitutes the first report of $[P_{6,6,6,14}]FeCl_4$ MIL application along with the DLLME method for the determination of trace Cd in honey samples.

Another research on the MIL-DLLME technique developed also by Fiorentini et al. concerns the preconcentration and microextraction of the highly toxic Arsenic in honey samples [35]. $[P_{6,6,6,14}]FeCl_4$ MIL was utilized as extractant material and the analysis was performed using ETAAS. Before the microextraction procedure of As, aqueous solutions of 1% (w/v) honey were prepared. The pH was adjusted and then methanol was added as a dispersant material along with 2-(5-bromo-2-pyridylazo)-5-diethylamino-phen as a complexing agent. The solution was left to stand, and chloroform was added, followed by a vortex. Initially, for the determination of As, the supernatant from the above-mentioned clean-up procedure was acidified with HCl, and KI was added to reduce As(V) to As(III). After that, the mixture was left to rest to ensure the As reduction and DDTP was added followed by acetonitrile addition. The DDTP was added to form a hydrophobic chelate with As(III), highly stable under acidic conditions, thus the efficiency of the extraction increases. Acetonitrile works as a dispersant. The solution was left for a second time to rest in order to ensure the formation of the As(III)-DDTP complex. The extraction phase was added, and the sample was stirred. The MIL phase was retrieved via an external magnetic rod and an adequate amount of sample was injected into the ETAAS for trace As determination. The LOD of the analysis procedure was 12 $ng \cdot L^{-1}$ As and the extraction efficiency was 99%. The advantage of this study is the tremendous analytical recovery of 95.2–102% despite the matrix complexity along with the utilization of the $[P_{6,6,6,14}]FeCl_4$ MIL as an excellent extractant.

Fiorentini et al. have also introduced the MIL, $[P_{6,6,6,14}]FeCl_4$, for the determination of chromium in honey samples, followed by ETAAS [36]. In this work, the sample solution was acidified with HCl, and Fe(II) was added to the sample to prevent the oxidation of Cr(III). Then, $[P_{6,6,6,14}]FeCl_4$ was added and the sample was stirred for 10 min. The MIL extracts the analyte during the stirring process. The MIL phase is collected via a magnetic rod and diluted with $CHCl_3$. Thereafter, the sample was injected into the ETAAS for Cr determination. The obtained efficiency of the extraction was 98% and the LOD was 5 $ng \cdot L^{-1}$ Cr. The dominant result derived from this study is the avoidance of centrifugation

due to the facile separation of the extraction phase by an external magnetic field, using a Fe-containing MIL.

Recently, Fiorentini et al. reported the application of trihexyl(tetradecyl)phosphonium tetrachloromanganate (II), $[P_{6,6,6,14}]_2MnCl_4$, MIL along with the DLLME method for the determination of trace Pb in bee products (honey, mead, honey beer, and honey vinegar) for the first time [37]. The sample was acidified with HCl, then 1,5-diphenylcarbazide was added for the complex formation, NaCl to adjust the ionic strength and acetonitrile as a dispersant. The MIL phase was added, and the mixture was vortexed. Finally, the MIL phase was separated from the solution by a magnetic rod and an adequate amount of this containing the preconcentrated analyte was injected into the ETAAS instrument. A LOD of 3 $ng \cdot L^{-1}$ Pb and an extraction efficiency of 97% were obtained. This approach has an excellent advantage. The MIL used for the Pb detection does not contain Fe, thus the interference effects are avoided. All the above methods from the same research team, point towards the need for careful selection of the metal moiety in the anion of the MIL, since it can interfere with the detection of metal ions.

Wang et al. reported in 2016 a novel magnetic ionic liquid-based up-and-down-shaker-assisted DLLME for the speciation and determination of Selenium from five rice samples (white rice, brown rice, parboiled rice, glutinous rice, and rice flour) [38]. An aqueous solution containing Se(IV) and Se(VI) was inserted into a centrifuge tube. Further, 2,3-diaminonaphthalene, utilized as a chelating agent, was added to the tube along with diluted HCl for the pH adjustment. The MIL 1-butyl-3-methylimidazolium tetrachloroferrate, $[C_4mim][FeCl_4]$, was then injected into the solution and the tube was shaken by an up-and-down shaker. Subsequently, the Se(IV)-2,3-diaminonaphthalene complex was separated from the aqueous phase by an external magnetic field. Due to the high viscosity of the MIL phase that complicates the sample injection into the analysis instrument, an amount of HNO_3 in ethanol (1:1, v/v) was added to reduce the viscosity of the MIL. The analysis was performed using a graphite furnace atomic absorption spectrometer. After the sample preparation, the aforementioned steps were followed to determine the total Se concentration and the Se(IV) concentration. The total inorganic Se concentration was determined as well, following the same experimental course. Thus the Se(VI) concentration can be calculated by subtracting the Se(IV) concentration from the total inorganic Se concentration. This technique presents good accuracy, relative standard deviation (RSD) lower than 3%, LOD of 0.018 $\mu g \cdot L^{-1}$ and repeatability of <3.0% for Se(IV).

A novel ultrasound-assisted surfactant-enhanced emulsification microextraction combined with micro-solid phase extraction using the MIL butyl-3-methylimidazolium tetrachloroferrate ($[C_4mim][FeCl_4]$) was reported by Yao et al. for the determination of cadmium and lead in six edible vegetable oils (olive oil, soybean oil, maize oil, sunflower seed oil, and two peanut oils) [39]. For the preconcentration and detection of Cd and Pb, the sample was inserted into a tube. Non-ionic surfactant Triton X-100 was added as an emulsifier reagent along with the MIL and the mixture was ultrasonicated. Then, an amount of Fe_3O_4 nanoparticles were added and the solution was stirred. The Fe_3O_4 nanoparticles were utilized to enhance the efficiency of the MIL phase separation by absorption. The MIL-nanoparticle phase was collected after applying an external magnetic field. HNO_3 was added to the tube for ultrasonicated dissolution of the MIL. The Fe_3O_4 nanoparticles containing the target analytes were collected with a magnetic bar and injected into the GFAAS. The ultrasound procedure applied in this work accelerates the homogenous dispersed solution and the mass transfer between the analyte and the extractant. Compared with other reports in the literature, this method presents similar or lower LODs (0.002 for Cd and 0.02 for Pb), and among the advantages are simplicity, rapidity, and satisfactory sensitivity. The main advantage, however, is the avoidance of the centrifugation step that reduces the analysis time, leading to an excellent alternative technique to oil samples microextraction.

A very interesting study was reported by Wang et al. in 2018 for the determination of arsenite and arsenate in five types of leafy vegetable samples (leaf lettuce, bok choy, spinach, celery, and coriander) applying a novel effervescence tablet-assisted magnetic

ionic liquids-based microextraction (ETA-MILs-ME) [40]. For the ETA-MILs-ME procedure, the sample was added into a tube along with ammonium molybdate, and ascorbic acid and the mixture was acidified (Figure 2). An effervescent tablet was added to the solution and bubbles rose rapidly from the bottom of the tube. During this step, the MIL 1-butyl-3-methylimidazolium tetrachloroferrate ([C_4mim][$FeCl_4$]) dispersed homogeneously in the aqueous phase and the formed As(V)-ammonium molybdate complex was extracted by the MIL. The MIL phase was separated from the aqueous solution with a magnetic rod. Finally, it was diluted with ethanol and injected into the GFAAS. For the total As the sample was weighed into a PTFE reactor. HNO_3 and H_2O_2 were added, and the mixture was digested. Then, As(III) was oxidized to As(V) and the fore-mentioned ETA-MILs-ME procedure was followed for the total As calculation. For the detection of As(V), the sample was weighed into a tube and nitric acid was added to extract inorganic arsenic. The solution was sonicated and centrifuged to obtain the extract. The supernatant was filtered with a cellulose acetate membrane and the ETA-MILs-ME methodology was performed. For the calculation of the total inorganic As the formerly obtained supernatant was filtered and an amount of $KMnO_4$ solution was added to oxidize As(III) to As(V) with the aid of sonication. The sample was subjected to the ETA-MILs-ME procedure for the total inorganic measurement. As(III) was calculated by subtracting the As(V) from the total inorganic As concentration. This work presents a simple, rapid, and efficient method with a LOD of 0.007 $\mu g \cdot L^{-1}$ and 97.9–105.8% recovery for As(V) in a variety of leafy vegetable samples. The use of effervescence is another way to address the issue of poor MIL dispersibility, similar to the use of solid support materials, as mentioned above. As this is one of the main restrictions of (hydrophobic) MILs usage, more alternative options like the ones mentioned above, should be examined.

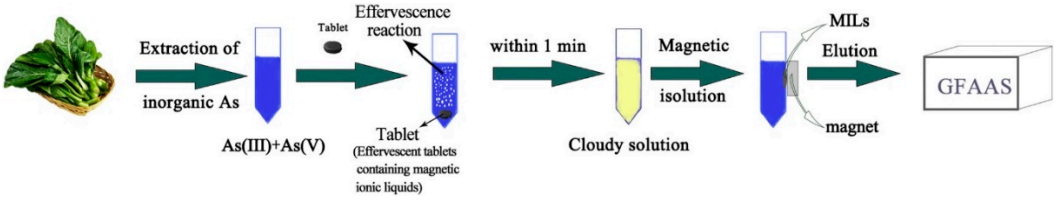


Figure 2. The scheme of the proposed ETA-MILs-ME. Reproduced with permission from [40]. Copyright Elsevier, 2018.

2.1.5. Procedures for Metal Species Determination in Environmental Samples

In 2016, Wang et al. proposed a novel magnetic ionic liquid-based air-assisted liquid–liquid microextraction (MIL-AALLME) for the trace Arsenite and Arsenate species determination in five environmental water (river, pond, tap water), sediment, and soil samples [41]. This technique combines MIL and air-assisted liquid–liquid microextraction. The 1-butyl-3-methylimidazolium tetrachloroferrate ([C_4mim][$FeCl_4$]) MIL was used as the extractant phase. For the detection of the total inorganic As in water samples, $Na_2S_2O_3$ and KI were added to the sample to reduce arsenate to arsenite. The solution was left to rest to ensure the reduction. In the mixture containing ammonium pyrrolidine dithiocarbamate as a chelating reagent, diluted nitric acid/ammonia was added for the pH adjustment. Subsequently, the MIL was inserted into the tube and the solution was rapidly withdrawn and rapidly injected into the tube for 10 times via a syringe to accelerate the MIL dispersion in the sample. The MIL phase containing the As(III)-ammonium pyrrolidine dithiocarbamate complex was collected by an external magnet rod and HNO_3 in ethanol (1:1, v/v) was added to reduce the viscosity, thus the aliquot sample could be injected into the graphite furnace atomic absorption spectrometry (GFAAS) instrument. The total inorganic As concentration and the As(III) concentration were determined following the above-mentioned steps. As(V) concentration is calculated by subtracting the As(III) concentration from the total inorganic As concentration. For the detection of the total As in solid and sediment samples As(V) was reduced to As(III) and then the MIL-AALLME process was performed. An amount of the solid and sediment samples was weighed and transferred to a polytetrafluoroethylene

(PTFE) reactor. HNO_3 in ethanol (1:1, v/v), H_2O_2 and HF were injected into the PTFE reactor and the samples were digested by a microwave digestion system. The PTFE reactor was cooled and then KI and $Na_2S_2O_3$ were added to the residual solution for the reduction of As(V) to As(III) with microwave assistance. Finally, the MIL-AALLME process was performed for the calculation of the total As concentration. For the determination of As(V) and As(III), the samples were weighed and added into a tube along with the extraction solution (phosphoric acid and ascorbic acid). The mixture was sonicated and centrifuged for obtaining the extracted As(V) and As(III). In order to obtain As(III) concentration, an aliquot of the filtered supernatant was diluted and subjected to the MIL-AALLME procedure. KI and $Na_2S_2O_3$ solutions were added to another aliquot of filtered supernatant for the reduction of As(V) and As(III) with microwave assistant. The total inorganic arsenic concentration was evaluated by the MIL-AALLME procedure. The As(V) concentration was calculated by subtracting the As(III) concentration from the total inorganic arsenic. Compared with different approaches reported in the literature for trace inorganic As species determination in natural samples, this method has low sample consumption and short extraction time, it shows an acceptable LOD (0.029 $\mu g\ mL^{-1}$) in the range of and the linear dynamic range is acceptable (0.04–10.0 $\mu g{\cdot}L^{-1}$)compared with other reported techniques.

In a recently reported work, Oviedo et al. developed a MIL-DLLME method to determine inorganic Antimony species in natural water samples (tap, dam, mineral, wetland, underground, rain, and river water) [42]. For the determination of Sb(III) the sample was mixed with HCl and DDTP solution as a chelating reagent. The solution was left to stand to ensure the formation of the Sb(III)-DDTP complex. Then, NaCl was added to adjust the ionic strength and the acetonitrile in order to disperse the extraction phase. The MIL hexyl(tetradecyl)phosphonium tetrachloroferrate ($[P_{6,6,6,14}]FeCl_4$) was used as an extractant material. The sample was vortexed, and the extraction phase was separated from the aqueous phase with a magnetic rod and subsequently was diluted with chloroform. An aliquot sample was injected into the graphite furnace of ETAAS. For the total inorganic Sb determination, KI was inserted in the sample and then the solution was acidified with HCl. The mixture was left to stand and the above-mentioned MIL-DLLME technique was performed to calculate the total inorganic Sb. The Sb(V) concentration was calculated by subtracting the Sb(III) concentration from the total inorganic Sb concentration. This method constitutes the first application of the MIL for extraction and preconcentration of Sb in natural water samples. The extraction efficiency for Sb(III) was 98.0% and for Sb(Vwas 92.6%, LOD for Sb(III) was 0.02 $\mu g{\cdot}L^{-1}$ and the linear range was 0.08–20 $\mu g{\cdot}L^{-1}$.

Aguirre et al. have proposed an analytical MIL-DLLME approach for the detection of cadmium in three fuel samples (engine oil, gasoline, and diesel) [43]. For the microextraction and detection of Cd, sample was mixed with an amount of the MIL bis(1-ethyl-3-methylimidazolium) tetrathiocyanatocobaltate (II), $[Emim]_2[Co(SCN)_4]$, and the tube was vortexed (Figure 3). The MIL phase was collected with the aid of a magnetic rod and an aliquot was transferred into a HNO_3 solution for the back-extraction of the target analyte to the aqueous phase. This is the first study that demonstrates MIL-DLLME and back-extraction procedures in combination with the ETAAS instrument for Cd determination in engine oil, gasoline, and diesel fuels. The obtained LOD value (0.084 $\mu g{\cdot}kg^{-1}$) reveals that the MIL-DLLME technique can enhance the sensitivity of the ETAAS analysis. The extraction of Cd from the difficult-to-handle fuel samples via a compatible aqueous phase is an advantage that makes this approach a promising method for facile and sensitive determination of Cd in comparable types of samples. As can be seen so far, most of the methods developed for metal species determination are more complex, compared with those developed for organic compounds. This is an issue that needs further attention, since future methods for metal species should be simpler, so that they can be used in routine analysis.

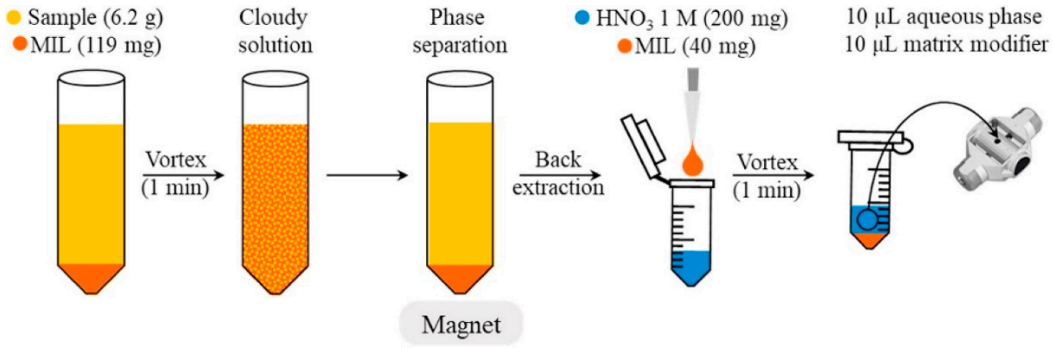


Figure 3. Scheme of the analytical procedure for Cd quantification. Reproduced with permission from [43]. Copyright Elsevier, 2020.

2.2. In-Situ Formation of MILs

The in-situ DLLME approach is an adjustment of the classical DLLME method that uses ILs as extraction solvents [44]. A limited number of reports have exploited this alternative formation of MILs in micro-extraction approaches, which until now include the determination of harmful analytes in water and food samples, and most recently the extraction of DNA [45]. In these cases, the magnetism of MILs enables magnetic isolation of the extraction solvent with a strong magnet, thus replacing the centrifugation and filtration steps [44]. For this application, mixing of a hydrophilic IL with a metathesis reagent is required, leading to an anion exchange and generation of a hydrophobic IL. Through this reaction, multiple hydrophobic IL micro-droplets are formed that are able to interact with the analytes [46]. Most of the time, the MILs designed contain paramagnetic anions. However, some restrictions in their use in DLLME have been observed, such as hydrolysis in water at room temperature and incompatibility with HPLC [44].

To overcome the problems associated with these types of MILs, Anderson and co-workers reported a new generation containing paramagnetic cations [44]. The in-situ MIL-DLLME was compared with the conventional MIL-DLLME for the verification of the successful extraction of polar and non-polar pollutants in aqueous samples. In combination with HPLC the determination of UV filters, polycyclic aromatic hydrocarbons (PAHs), alkylphenols, a plasticizer, and a preservative was achieved. Therefore, five different MILs consisting of cations containing Ni(II) centers coordinated with four ligands of N-alkylimidazole and chloride anions with different alkyl substituents (R), were synthesized and tested as extraction solvents in in-situ DLLME. These can go through a metathesis reaction with the bis[(trifluoromethyl)sulfonyl]imide ($[NTf_2^-]$) anion. Among them, $[Ni(C_4IM)_4^{2+}]_2[Cl^-]$ and $[Ni(BeIM)_4^{2+}]_2[Cl^-]$ showed the highest extraction efficiencies. A mixture of the aqueous MIL solution in the chlorinated $[Cl^-]$ form and the extraction solvent, was added to a glass vial containing an aqueous solution of the analytes. A certain amount of ion-exchange reagent was added to achieve the formation of MIL:$[Li^+][NTf_2^-]$ in a ratio of 1:1, 1:2, or 1:3. Assisted by vortex, the metathesis reaction was accelerated and thus the configuration of the magnetic drops containing the analytes. These were magnetically isolated and diluted in acetonitrile solution to reduce viscosity. To illustrate the superiority of the designed method, a comparison was made with MIL-DLLME. It was found that the extraction efficiencies for the in-situ MIL-DLLME, were higher and ranged from 46.8–88.6% and 65.4–97.0% for the $[Ni(C_4IM)_4^{2+}]_2[Cl^-]$ and the $[Ni(BeIM)_4^{2+}]_2[Cl^-]$ MILs, respectively.

In view of this new category of MILs, four novel organic ones were synthesized by Yao and Du [47]. Through a similar approach, an in-situ MIL-DLLME coupled with HPLC was established to simultaneously separate, preconcentrate, and determine trace amounts of sulfonamides in milk samples for the first time. Along the same lines with the previous report, the MIL was dissolved in a vial containing the milk sample with the analytes. Then, the addition of the ion-exchange reagent resulted in the immediate formation of a light red turbid solution. The hydrophobic MIL drops were directly isolated

via a neodymium magnetic bar (30 s) and immersed into methanol for subsequent HPLC analysis. A comparison between this developed method and others that have been reported has shed light on its multiple benefits. Through its application, the extraction time is reduced, as steps such as centrifugation and agitation are avoided. In addition, a small amount of an inorganic salt is generated and no organic toxic solvents are required. Taking everything into account, this is the first time to realize all these advantages in an analytical method.

In a recently published work, a unique analytical method, known as in-situ parallel-dispersive droplet extraction evolved for the first time [45]. Combined with HPLC-DAD, micropollutants in aqueous environmental samples were successfully detected. To begin with, for the formation of the hydrophobic MIL, a cation precursor (CP), and an anion exchange reagent (AER) were required. Three different hydrophilic MILs (CPs) $[Ni(C_4IM)_4{}^{2+}]_2[Cl^-]$, $[Ni(BeIM)_4{}^{2+}]_2[Cl^-]$, $[Co(C_4IM)_4{}^{2+}]_2[Cl^-]$ were evaluated, with the latter prevailing. $[Li^+][NTf_2{}^-]$ was used as AER. One of the main advantages of the method is its automation. This is achieved using a 96-well plate system on which NdFeB were adjusted, thus increasing the throughput of the process. By adding 1.25 mL of sample and 100 μL of an aqueous solution of $[Co(C_4IM)_4{}^{2+}]_2[Cl^-]$ at a concentration of 40 $g{\cdot}L^{-1}$ to the plates vials, a hydrophilic compound was formed. After 5 min of vigorous agitation, the addition of 40 μL of an aqueous solution of $LiNTf_2$ converts it to a hydrophobic, maintaining agitation for 75 min. Eventually, the MIL microdroplets attached to the rod magnets were diluted in ACN and the solution was injected in the HPLC-DAD. The advantages of this method are not limited to its automation. Compared with others used for the determination of analytes in water samples, less extraction time is required (0.78 min) and a low amount of toxic organic solvents and sample is consumed (MILs are synthesized in aqueous media, 20 μL of ACN and 1.25 mL of sample are needed). In addition, due to the increase of the surface area of the MIL, higher extraction efficiency is achieved. On the other hand, it is worth noting that LODs were slightly higher than those mentioned by other studies, and concerns associated with the solubility of MIL in aqueous samples were noticed.

The same concept was introduced for the in-situ DLLME of DNA samples. To give an illustration of that, the research carried out by Bowers and co-workers proved the successful extraction of long and short double-stranded DNA through the formation of hydrophobic MILs droplets [46]. As previously described, the aqueous solution of the MIL in the chloride form was mixed with the DNA sample and the dispersive solvent (dimethylformamide). Then, with the addition of the ion exchange reagent ($[Li^+][NTf_2{}^-]$), the hydrophobic MIL droplets settled at the bottom of the vial. An aliquot of the upper aqueous phase was used for further analysis. In this study, up to ten different MILs consisting of N-substituted imidazole ligands (with butyl-, benzyl-, or octyl-groups as substituents) coordinated to different metal centers (Ni^{2+}, Mn^{2+}, or Co^{2+}) as cations, and chloride anions were synthesized. Co-based MILs provided the highest EFs (>85%) while Ni-based MILs showed the greatest selectivity in extracting the different sized duplex DNA fragments. It is worth noting that the subsequent analysis was performed by both HPLC-DAD and fluorescence spectroscopy with the latter technique to be more suitable for the faster detection of DNA. This is due to various chromatographic complexities such, as high solvent consumption and frequent column cleaning. Despite this, the preparation method was compared both with other IL- and MIL-based extraction methods and the conventional MIL-DLLME. The results showed the superiority of the method, based on its simplicity and highest extraction efficiencies. It is noteworthy that it is an affordable alternative for the extraction of DNA instead of commercially available DNA extraction kits.

Apart from the in-situ DLLME, an in-situ derivatization combined with MIL-based fast DLLME has been reported for the determination of biogenic amines (Bas) in food samples [48]. Once more, the experimental course is based on a similar philosophy as before. In a vial containing 5 mL of the sample (at set pH), the derivatizing agent, dansyl-chloride, (DNS-Cl) was added and the mix was left in the incubator for 15 min at 60 °C. The

derivatization process was then completed, and the DNS-Cl was removed. An amount of MIL and methanol was added and the mixture was agitated via vortex. Next, the analytes were removed using a neodymium magnet, and redissolved in acetonitrile. The resulting solution was filtered and subjected to the HPLC system. This stage of derivatization is necessary, as BAs are not easily detected by HPLC-UV due to the lack of chromophore groups in their structure. It is worth mentioning that although cobalt(II)-based MILs have not been extensively studied yet, the authors synthesized the MIL trihexyltetradecylphosphonium tetra-chlorocobalt (II) $[P_{6,6,6,14}{}^{+}]_2[CoCl_4{}^{2-}]$ as it completely dissolves in the mobile phase, exhibits low absorbance eliminating background and allowing sensitive analysis of the analyte. This method seems to be a suitable and fast way, with high sensitivity for the determination of amines in real samples such as wine and fish. In fact, by comparing it to other methods such as SPE and UPLC/Q-TOFMS, it has been shown to provide lower LOD values and improved analytical performance as it can pre-concentrate and extract at the same time. From the above-mentioned applications, it can be seen that the method of in-situ formation of MILs addresses properly some issues that exist with DLLME procedures. Therefore, such procedures are more promising and worth further research to advance this topic.

2.3. Single Drop Microextraction Procedures

Single-drop microextraction is a straightforward, environmentally friendly technique that has been used, mainly, for the extraction and subsequent determination of low-molecular-weight compounds after coupling to various chromatographic techniques. The extraction is performed using a few microliters of an organic solvent either immersed into an aqueous sample or exposed to the headspace of the matrix with the aid of a micro syringe. MILs can provide a viable alternative to organic solvents in this technique because of their low volatility and high viscosity/hydrophobicity, overcoming the problem of droplet instability.

A new method named: weighing paper-assisted magnetic ionic liquid headspace single-drop microextraction, using microwave distillation followed by gas chromatography–mass spectrometry (WP-MIL-HS-SDME), was developed to determine a total of 39 volatile compounds in 16 lavender samples from three different harvest years with principal component analysis [49]. An amount (9 μL) of the magnetic ionic liquid 1-octyl-3-methylimidazolium tetrachloroferrate ($[C_8mimFeCl_4$) could stably be divided on the weighing paper for long time extraction. The lavender samples were placed into a headspace vial. The $[C_8mim]FeCl_4$ was distributed into the weighing paper, which was adhered to the sealing cap containing PTFE-silicone septum, suspended in the headspace of the lavender sample. The bottle was sealed, and headspace extraction was achieved by microwave irradiation. After that, the weighing paper, with the analyte, was transferred directly into a polyethylene (PE) tube containing a back-extractant (cyclohexane). Next, the PE tube was vortexed, centrifuged, and then was forced to magnetic separation. Finally, a sample of back-extractant was injected into the GC-MS instrument for analysis. The increase of the extractant volume resulted in a significant increase in the extraction efficiency of the WP-MIL-HS-SDME than MIL-HS-SDME method, while the disadvantages of traditional HS-SDME, such as the microdroplet in the needlepoint being easy to drop and high operational requirements got through. Although this method is a rather unique approach, it is complex enough and many steps are needed for the extraction. These two drawbacks override the benefits.

The team of Jiwoo et al. investigated with HS-SDME and a DLLME methods, two tetrachloromanganate ($[MnCl_4{}^{2-}]$)-based MIL as extraction solvents for the determination of twelve aromatic compounds, including four polyaromatic hydrocarbons from lake water samples [50]. The optimized HS-SDME method was compared to the DLLME method employing the same two MILs as extraction compounds. The method of DLLME with the two MIL($([P_{6,6,6,14}{}^{+}]_2[MnCl_4{}^{2-}]$) and $([Aliquat^{+}]_2[MnCl_4{}^{2-}]$) showed much faster extraction and higher enrichment for analytes with low vapor pressure. On the other hand,

HS-SDME showed advantages in extracting analytes possessing relatively high vapor pressure. Both methods provided low LODs and high precision for the target analytes as well as acceptable relative recoveries from the samples, suggesting that the examined MILs can be exercised in microextraction techniques. The disadvantage of the HS-SDME method compared with DLLME was that in DLLME the total sampling time required was less than 5 min, which demonstrates its potential as a high throughput sampling technique. However, the HS-SDME method can easily be employed in cases of complex matrices. Generally, the use of $[MnCl_4^{2-}]$-based MILs provides advantages, such as convenient ways of extractions, low UV absorbance which permits the direct coupling to HPLC for chromatographic analysis, and high extraction selectivity.

A novel technique was presented in the manuscript of Trujillo-Rodríguez et al., which was developed by using a vacuum headspace single-drop microextraction method based on the use of magnetic ionic liquids (vacuum MILHS-SDME) (Figure 4) [51]. This method provided a successful approach for the determination of a group of short-chain free fatty acids (FFAs) (from C_3 to n-C_7), responsible for the aroma of milk and other dairy products. The use of MIL ($[P_{6,6,6,14}^+][Mn(hfacac)^{3-}]$) demonstrated advantages at decreased pressure conditions, with analytes reaching equilibrium faster than regular atmospheric pressure MIL-HS-SDME showed an improvement in the extraction efficiency for all analytes, at any extraction time. Furthermore, the method does not require derivatization of the free fatty acids to their methyl ester analogues and combined with vacuum headspace single-drop microextraction, analytes are determined in an automated approach using GC-MS without any interferences from the MIL solvent.

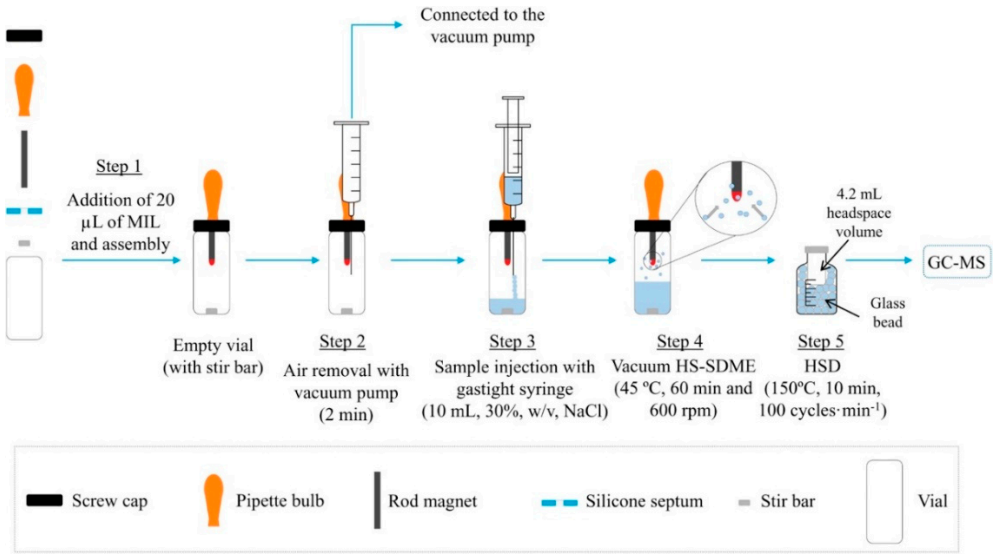


Figure 4. Schematic of the vacuum MIL-HS-SDME procedure under optimum conditions. Reproduced with permission from [51]. Copyright Elsevier, 2017.

In another study, a microextraction technique using a MIL was coupled with voltammetric determination of ascorbic acid (AA) in samples of vitamin C effervescent compounds and orange juice [52]. The MIL $([Aliquat^+]_2[MnCl_4^{2-}]$ was used as the extracting solvent and was exposed directly on the surface of the working electrode. The MIL had a double purpose: as a cleanup (no interfering species) and as an electrode modifier (with TiO_2 nanoparticles). With this method, no dilution step was needed and in comparison to other voltammetry techniques, lower LOD, as well as increased sensitivity was achieved because a preconcentration step was performed before the electrochemical measurement. For the first time, the assets of the ionic characteristics of the IL as well as of the Mn^{2+} ion for the modification of the electrode and enhancement of the electron transfer of AA were taken advantage of.

Fernández et al. used 1-ethyl-3- methylimidazolium tetraisothiocyanatocobaltate(II) ($[Emim]_2[Co(NCS)_4]$) as a MIL to extract nine chlorobenzenes (i.e., 1,2-dichlorobenzene,1,3-dichlorobenzene, 1,4-dichlorobenzene, 1,2,3-trichlorobenzene, 1,2,4-trichlorobenzene, 1,3,5-trichlorobenzene, 1,2,3,4-tetrachlorobenzene, 1,2,4,5-tetrachlorobenzene, and pentachlorobe nzene) for analyses from water samples (tap water, pond water, and wastewater) [53]. In this study, with the method of magnetic headspace single-drop microextraction, the MIL was located on one end of a small neodymium magnet, and the extracts were determined by GC-MS. This approach showed lower LOD values than in the IL-based HS-SDME method with shorter extraction times and lower IL supply.

2.4. Matrix Solid-Phase Dispersion Procedures

For the most part, solvent-based extraction methods are the leading for the extraction of analytes from fatty solid samples. However, lately, matrix solid-phase dispersion (MSPD) has become an upward trend, mainly due to the low consumption of organic solvents. Likewise, DLLME, has attracted much attention considering its relatively high extraction efficiency. Wang and co-workers combined these two methods with a MIL followed by UFLC-UV to determine six triazine herbicides in oilseeds (Figure 5) [54]. Two types of MIL $[C_4mim][FeCl_4]$ and $[C_6mim][FeCl_4]$ were tested to observe the influence of the structure. Admittedly, the polarity of $[C_4mim][FeCl_4]$ with the target analytes, which was slightly different compared to $[C_6mim][FeCl_4]$, offered higher recoveries. Moreover, this addition was found to be highly advantageous, since the MSPD-MIL-DLLME method achieved better precision and lower LODs compared with results by QuEChERS coupled with UFLC. The MIL succeeds in replacing the centrifugation step in QuEChERS with magnetic separation and thus simplifies the method. Another key fact to mention is that LODs and LOQs obtained by the developed method are similar to or lower than those reported in methods for the determination of target analytes in solid, fatty matrices. Although the combination of the two techniques is innovative, the fact that both are employed increases the overall time of analysis.

In a more recent work, MIL $[P_{6,6,6,1,4}{}^+][Co(II)(hfacac)_3{}^-]$ was directly used for the first time in a matrix solid-phase extraction procedure [55]. Developed by Chatzimitakos and co-workers, this method provided a valuable approach for the determination of multi-class pesticides residues in raw vegetables. Taking advantage of its magnetic properties, MIL was readily harvested after the extraction step by simply using a magnet. In addition, its hydrophobic and viscous nature made separation and retrieval feasible and assisted in mixing with the matrix. Described in more detail, chopped vegetables were pulverized and one drop of MIL was added to the sample, forming tiny droplets. Then, a saturated sodium chloride solution was added resulting in coalescing and creation of larger droplets which were separated more easily from the bulk phase. The homogenized mixture was ultrasonicated. Due to the dark red color of the chosen MIL, discrimination and harvesting from the solution were easily done. Droplets coupled with target analytes were transferred via magnet to 1 mL of acetonitrile in order to be dissolved (Figure 6). After the evaporation with a gentle nitrogen stream, the sample was ready to be injected into the HPLC-DAD system for further separation and detection of pesticides. In order to find the most efficient conditions, authors examined the effect of vegetable matrix and dispersion material as well as the selection of the most suitable MIL. For this purpose, MIL that differs in the metal and the number of anionic ligands were tested with the results showing that neither plays a decisive role in the extraction, on the contrary, the extraction is based, mainly, on the cation. Continuing in this line, the selection was based on the visual discrimination from the rest of the system, with dark red $[P_{6,6,6,1,4}{}^+][Co(II)(hfacac)_3{}^-]$ preferred. As regards the vegetable matrix, low recoveries occurred with matrices of low water content. The best combination was found to be vegetables with "soft" texture and a high water-content matrix (e.g., potatoes). Lastly, silica, quartz silica, sodium chloride, and sodium sulfate were tried as dispersion materials in the developed method. Based on the results, solid dispersing materials, as well as the addition of both salts were found to be ineffective. However, when

only one salt was added, the reproducibility of the procedure was improved (without the salt solution, RSD of five measurements was 9.5% and with the salt solution was 6.0%). Such direct procedures are highly welcome, since they can be carried out by analysts with less expertise and they have reduced cost, compared with other procedures.

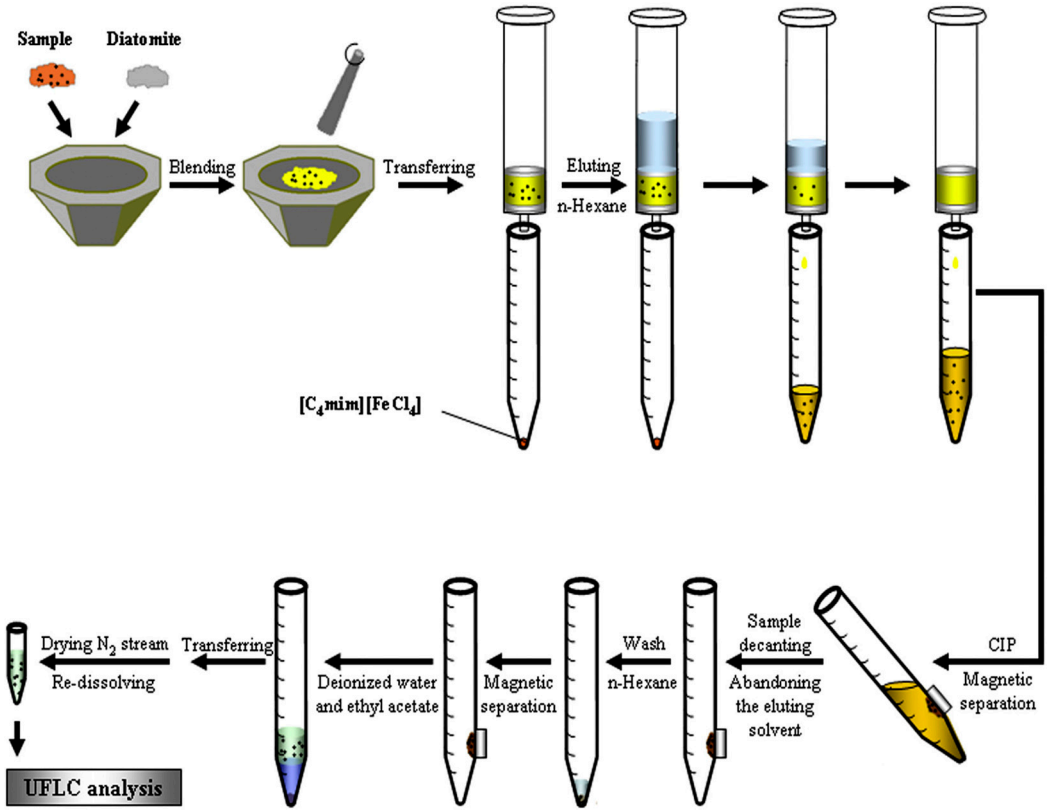


Figure 5. Schematic diagram for the MSPD-DLLME extraction procedure. Reproduced with permission from [54]. Copyright Elsevier, 2015.

2.5. Stir-Bar Dispersive Procedures

A novel hybrid microextraction method called stir bar dispersive liquid microextraction (SBDLME) opens new insights into the microextraction field, due to the facile retrieval of the target analytes [56]. This approach combines the advantages of stir bar sorptive extraction and DLLME. The first report of this approach was by Peng et al., 2012. His team developed a SBDLME method for the determination of three fungicide residues in real water samples (tap water, rainwater, and lake water), utilizing the MILs 1-butyl-3-methylimidazolium hexafluorophosphate ([C_4mim][PF_6]), and 1-hexyl-3-methylimidazolium hexafluorophosphate ([C_6mim][PF_6]) as extractant. The ionic liquid and magnetic stir bar were held within a sealed PCR tube pierced with many micro-holes on the wall. The ionic liquid magnetic bar was then placed in the aqueous solution for extraction. Meanwhile, the magnetic stirrer was switched on and the ionic liquid magnetic bar dispersed freely in the sample. When the magnetic stirrer was switched off the MIL was retrieved on the rod magnet. The obtained ionic liquid extract was too viscous to be injected directly into the HPLC system, thus it was firstly diluted with acetonitrile. LODs were varying from 1.4 to 3.4 $\mu g \cdot L^{-1}$, RSD values ranged from 2.9 to 6.0%, and recoveries of carbamate pesticides at spiking levels of 5 and 50 $\mu g \cdot L^{-1}$ were in the range of 85-98.0%, 80-98% respectively, leading to a simple, practical and efficient method for the determination of trace level of carbamates in environmental samples.

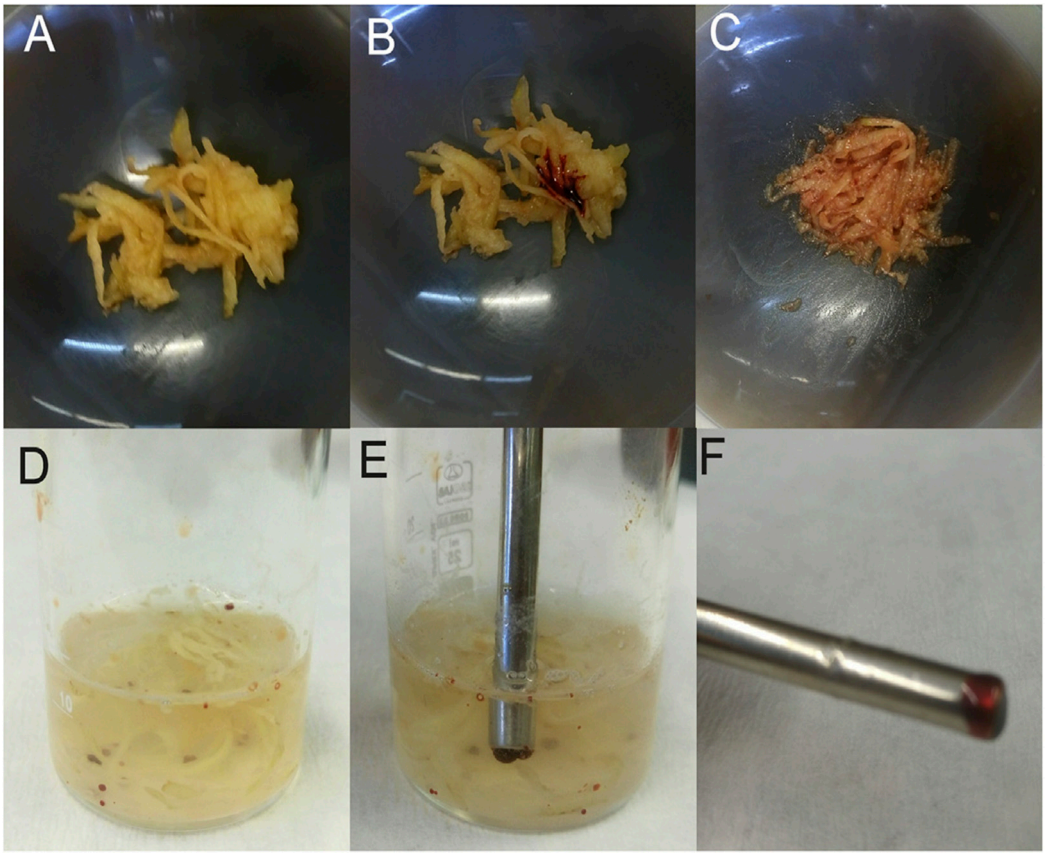


Figure 6. Representative pictures of the various steps of the developed procedure: (**A**) chopped potato in a mortar, (**B**) chopped potato with a drop of MIL before mixing, (**C**) chopped potato and MIL after mixing, (**D**) mixture of potato and MIL in saturated sodium chloride solution after ultrasonication, (**E**) harvesting the MIL droplets with a magnetic rod and (**F**) the collected MIL droplets on the magnetic rod. Reproduced with permission from [55]. Copyright Elsevier, 2018.

Juan et al. proposed a SBDLME procedure for the determination of (ultra)trace amounts of 10 PAHs in three natural water samples (river, tap, and rainwater) [57]. Regarding this, they utilized the $[P_{6,6,6,14}{}^{+}][Ni(II)(hfacac)_3{}^{-}]$ MIL as an extraction material that magnetically coats a neodymium magnetic stir bar. When the stirring rate is low, the MIL remains on the stir bar. At a high stirring rate, the MIL is dispersed in the solution and achieves the extraction of the analytes. As long as the stirring rate decreases, once again the MIL attaches to the magnetic bar. The MIL-coated stir bar is subsequently thermally desorbed into a GC system coupled to a MS detector. The determination of trace amounts of PAHs in water samples at the low $ng \cdot L^{-1}$ level indicates the sensitivity of the SBDLME method in addition to the simplicity and efficiency of this approach. Moreover, compared to previous methods for the determination of PAHs, this method requires little sample manipulation, reduces the analysis time and it does not require solvent evaporation and external magnetic field.

In another study employed from the aforementioned research group, eight lipophilic organic UV filters from environmental water samples (river, sea, and swimming pool water samples) were determined by the above method using the $[P_{6,6,6,14}{}^{+}][Co(II)(hfacac)_3{}^{-}]$ and $[P_{6,6,6,14}][Ni(II)(hfacac)_3{}^{-}]$ MILs [58]. This work contributes to the development of expedient and sensitive methods for the determination of trace compounds in aqueous media and enables the use of tailor-made solvents (i.e., MILs).

In another interesting study, Trujillo-Rodríguez et al. attempted to develop an in-situ stir bar dispersive liquid–liquid microextraction technique for the first time [10]. Using three different MILs containing Ni^{2+} or Co^{2+} metal centers coordinated with N-

butylimidazole or N-octylimidazole ligands as extraction solvents ($[Ni(C_4IM)_4^{2+}]2[Cl^-]$, $[Ni(C_8IM)_4^{2+}]2[Cl^-]$ and $[Co(C_8IM)_4^{2+}]2[Cl^-]$ MILs), they determined seven organic pollutants on tap and mineral water. The microextraction method was combined with headspace gas chromatography mass spectrometry. The procedure of microextraction consists of the addition of the sample solution and the NdFeB stir bar into the extraction vial, followed by the insertion of MIL and dispersive solvent to the vial under stirring. The ion-exchange reagent ($[Li^+][NTf_2^-]$) was then added to achieve a 1:2 MIL:$[Li^+][NTf_2^-]$ molar ratio and the stirring rate was increased. During stirring, the MIL (in the $[NTf_2^-]$-form generated from the metathesis reaction) was dispersed within the extraction vial. When the stirring was stopped, the hydrophobic MIL immediately settled to the bottom of the vial and was collected onto the rod magnet. Finally, the MIL-coated stir bar was transferred to a HS vial. LODs down to 10 $\mu g \cdot L^{-1}$, adequate reproducibility, and relative recoveries between 72.5% and 102% were obtained. This method containing an in-situ metathesis reaction during the microextraction procedure revealed that long alkyl chains substituents in the ligand can increase the thermal stability of the MILs, indicated the important role of ligand in the MIL to the optimum extraction conditions required for the method.

2.6. Other Procedures

Definite proof of the beneficial combination of nanomaterials with magnetic ionic liquids is the research carried out by Zhu and co-workers [59]. Two endocrine-disrupting chemicals, bisphenol A and 4-nonylphenol were determined in vegetable oils by DLLME followed by HPLC-MS/MS. Although MILs can facilitate separation, in the present work, the magnetism of the ionic liquid was found to be insufficient. This limitation was resolved by the addition of Fe_3O_4 nanoparticles. Briefly, a diluted sample of vegetable oil (0.5 g in 10 mL of n-hexane) was mixed with the diluted sample of MIL (80 µL in 400 µL acetone) with the aid of stirring in vortex. This was followed by the addition of Fe_3O_4 nanoparticles (20 mg) and centrifugation to remove the supernatant n-hexane layer. The magnetic ionic layer that interests us, was extracted through *p*-xylene (2 × 300 µL), which was isolated by using a magnet. The sample was prepared for further analysis by HPLC-MS/MS, after evaporation under nitrogen atmosphere, filtration through a membrane (0.22 µm), and dissolution in methanol (0.5 mL). After testing various MILs ($[C_4mim][FeCl_4]$, $[C_8mim][FeCl_4]$) they concluded that $[C_6mim][FeCl_4]$ was the most suitable, providing a higher EF for BPA and 4-NP. The proposed method could find application in other analyses of different pollutants in vegetable oil.

Hongmei et al. prepared a novel magnetic ionic liquid-gold nanoparticles/porous silicon (MIL/Au NPs/PSi) active substrate through the immersion method for the detection of Arsenic in pure water samples with three easy steps [60]. First, the preparation of PSi, second the reduction of Au-NPs on PSi with the assistance of microwave, and last one the deposition of MIL layer on the composite. To prove its high-sensitive detection of Arsenite, a set of arsenic solutions of different concentrations was prepared, and then the MIL/Au NPs/PSi substrate was immersed in 1.5 mL of each one for 1h. Afterward, it was left to dry at room temperature and the surface-enhanced Raman spectroscopy (SERS) spectrum was obtained. In the same way, the procedure was repeated with the Au NPs/PSi and PIL/Au NPs/PSi substrates, respectively. To do so, the magnetic ionic liquid 1-methyl-3-hexyl imidazole ferric tetrachloride ($[C_6mim]FeCl_4$) and the poly ionic liquid poly (1-hexyl-3-vinyl imidazolium tetrafluoroborate ($[Hmim]BF_4$) were used for the separate modifications of the Au NPs/PSi SERS substrate. Under the same Raman test conditions, the functionalized substrates (MIL-Au NPs/PSi and PIL-Au NPs/PSi) were found to have a stronger SERS response than Au NPs/PSi SERS on their own. This occurs due to the EM (electromagnetic mechanism) and CM (chemical mechanism) enhancement that is caused by Au NPs, and the IL enriched analytes. Furthermore, much stronger signal intensity was achieved with the addition of MIL, via a specific binding between NPs and arsenite. As reported, this is the first time that this direct modification took place, and it is characterized as a simple and cost-effective method to load a MIL film on Au NPs/PSi

and improve the stability and sensitivity of the detection (the detection limit is as low as 0.5 ppb, and the RSD only 1.6%). Considering the convenience of designing and grafting functional groups in MIL, it is expected to have a successful use for the qualitative and quantitative detection of trace components in complex systems and gain practical value in environmental or biological sample detection.

In another study, the magnetic 1-allyl-3-octylimidazolium tetrachloroferrate ionic liquid was synthesized and combined with a molecularly imprinted polymer for the extraction of phenolic acids in apple samples [61]. Tashakkori et al. developed a magnetic sorbent for SPE instead of using the method itself, to minimize the extraction time. The MIP was prepared by suspension polymerization using the MIL as a functional monomer and chlorogenic acid as a template molecule. The selection of the resulting magnetic imprinted polymer as a sorbent provided not only a wide linear range (1-1000 $\mu g \cdot L^{-1}$ for chlorogenic acid) with a small amount of it (2 mg) but also lower LOD values (0.31$\mu g \cdot L^{-1}$ for chlorogenic acid) compared with other SPE methods. Analytical parameters, such as the type and volume of elution solution, pH of sample solution, sorbent amount, extraction, and the desorption time were optimized, before the analysis by HPLC. This environmentally friendly way achieves separation and pre-concentration of phenolic acids, with high reproducibility and reliability. A summary of all the sample preparation procedures discussed herein along with their analytical figures of merit is presented in Table 1.

Table 1. Summary of developed analytical procedures based on MILs; LOD: limit of detection.

Ionic Liquid	Extraction Technique	Matrix	Target Analytes	LOD ($\mu g \cdot kg^{-1}$ or $\mu g \cdot L^{-1}$)	Recoveries (%)	Analytical Instrumental System	Reference
$[P_{6,6,6,14}{}^{+}][Dy(III)(hfacac)^{4-}]$	MIL-DLLME	water samples	sulfonamides and triazines	0.011–0.029 and 0.013–0.030	90–101 and 89–98	HPLC-DAD	[9]
$[Ni(C_8IM)_4{}^{2+}]_2[NTf_2{}^{-}]$	SBSDME	tap and mineral water	organic pollutants	<10	72.5–102	HS-GC-MS	[10]
trihexyltetradecylphosphonium tetrachloromanganate (II) ($[P_{6,6,6,14}{}^{+}]_2[MnCl_4{}^{2-}]$)	DLLME	human urine	estriol, 17-β-estradiol, 17-α-ethynylestradiol, and estrone	2	67.5–115.6	HPLC	[11]
benzyltrioctylammonium bromotrichloroferrate (III)	magnet-based microextraction	aqueous sample	benzo(a)anthracene (BaA), chrysene (Chy), benzo(a)pyrene (BaPy), benzo(b)fluoranthene (BbF) and benzo(k)fluoranthene (BkF)	0.005–0.02	91.5–119	HPLC-FID	[12]
$[P_{6,6,6,14}{}^{+}]_2[MnCl_4{}^{2-}]$	DLLME	river water	estrone, estradiol, 17-α-hydroxyprogesterone, chloromadinone 17-acetate, megestrol 17-acetate and medroxyprogesterone 17-acetate	1.5–15.1	56-123	HPLC-DAD	[14]
$[P_{6,6,6,14}{}^{+}]_2[CoCl_4{}^{2-}]$	DLLME	milk and cosmetics	estrone, estradiol, 17-α-hydroxyprogesterone, chloromadinone 17-acetate, megestrol 17-acetate and medroxyprogesterone 17-acetate	5–15	98.5–109.3 and 96.3–111.4	HPLC	[21]
[TMG][TEMPO OSO_3]	MILATPs	environmental waters	chloramphenicol	0.14	94.6–99.72	HPLC	[15]
[C_4MIM-Tempo][L-Pro]	aqueous two-phase (ATPs) system	-	phenylalanine (D-L)	-	-	HPLC	[16]
trihexyltetradecylphosphonium $[MnCl_4{}^{2-}]$ ($[P_{6,6,6,14}{}^{+}]_2[MnCl_4{}^{2-}]$)]	DLLME	tap water, wastewater, and a tea infusion	pharmaceutical drugs, phenolics, insecticides, and polycyclicaromatic hydrocarbons	0.25–1.00	53.8–114.7 (spiking 5 $\mu g \cdot L^{-1}$ for phenanthrene) 106.7–150 (spiking 37.5 $\mu g \cdot L^{-1}$ for phenanthrene)	HPLC, UV	[18]
1-hexyl-3-methylimidazolium tetrachlo-roferrate ($[C_6mim][FeCl_4]$)	liquid–liquid microextraction technique (DLLME)	vegetable oils, two soybean oils, three maize oils and two sunflower seed oils	triazine herbicides	1.31–1.49	81.8–114.2	HPLC	[22]

Table 1. *Cont.*

Ionic Liquid	Extraction Technique	Matrix	Target Analytes	LOD ($\mu g \cdot kg^{-1}$ or $\mu g \cdot L^{-1}$)	Recoveries (%)	Analytical Instrumental System	Reference
$[P_{6,6,6,14}^{+}][Cl^{-}]$	Dispersive liquid-liquid microextraction	human urine	carbofuran, atrazine, simazine, diuron, metalochlor, ethinylestradiol, estrone, diclofenac		75–130	HPLC	[31]
1-ethoxyl-3-methyl-imidazoliumtetrachloroferrate $[C_2OHmim]FeCl_4$	UAE	sinomenium acutum	sinomenine (SIN)	-	81.3	HPLC	[28]
$C_3MIMFeCl_4$		tea leaves	polyphenols	-	99.8	HPLC-UV-Vis	[29]
$[P_{6,6,6,14}^{+}]_3[GdCl_6^{3-}]$	MIL-DLLME	river and tap water	four antihypertensive drugs	-	82.5–101.48	HPLC-UV	[32]
$[P_{6,6,6,14}]_3[Fe(CN)_6]$	IL-on SBME	environmental water	four estrogens	0.2–0.5	88.5–99.6 and 88.4–99.9	HPLC-UV	[19]
methyltrioctylammonium tetrachloroferrate ($N_{8,8,8,1}[FeCl_4]$)	SADBME	aqueous matrices	phenols and acidic pharmaceuticals	1.05–33.0	89–94	HPLC-DAD	[20]
methyltrioctylammonium tetrachloroferrate ($[N_{1,8,8,8}^{+}][FeCl_4]$)	MIL-DLLME	water, beer and beverage samples	parabens	300–500	95–103	HPLC-UV	[30]
[OA]FeCl	D-μSPE	human urine and wastewater samples	carbamazepine drug	0.51	85.5–98	HPLC-DAD	[33]
trihexyl(tetradecyl)phosphonium tetrachloroferrate(III) ($[P_{6,6,6,14}]FeCl_4$)	MIL-DLLME	honey	Cd	0.0004	95.5–102	ETAAS	[34]
trihexyl(tetradecyl)phosphonium tetrachloroferrate (III) ($[P_{6,6,6,14}]FeCl_4$)	DLLME	honey	As	0.012	95.2–102	ETAAS	[35]
exyl(tetradecyl)phosphonium ($[P_{6,6,6,14}]FeCl_4$)	DLLME	honey	Cr	0.005	94.0–101	ETAAS	[36]
trihexyl(tetradecyl)phosphonium tetrachloromanganate (II) ($[P_{6,6,6,14}]_2MnCl_4$)	DLLME	honey, mead, honey vinegar and honey beer	Pb	0.003	94.8–101	ETAAS	[37]
1-butyl-3-methylimidazolium tetrachloroferrate $[C_4mim][FeCl_4]$	MIL-UDSA-DLLME	rice	Se	18	94.9–104.8	GFAAS	[38]
1-butyl-3-methylimidazolium tetrachloroferrate ($[C_4mim][FeCl_4]$)	AALLME	environmental water, sediment and soil samples	As	29	93.0–108.5	GFAAS	[41]

Table 1. *Cont.*

Ionic Liquid	Extraction Technique	Matrix	Target Analytes	LOD ($\mu g \cdot kg^{-1}$ or $\mu g \cdot L^{-1}$)	Recoveries (%)	Analytical Instrumental System	Reference
trihexyl(tetradecyl)phosphonium tetrachloroferrate ($[P_{6,6,6,14}]FeCl_4$)	DLLME	n tap, dam, mineral, wetland, underground, rain and river water samples	Sb	0.02	94.0–100	ETAAS	[42]
bis(1-ethyl-3-methylimidazolium) tetrathiocyanatocobaltate (II) $[Emim]_2[Co(SCN)_4]$	DLLME	engine oil, gasoline and diesel	Cd	0.084	95–110	ETAAS	[43]
butyl-3-methylimidazolium tetra-chloroferrate ($[C_4mim][FeCl_4]$)	UASEME	vegetable oil	Cd, Pb	0.002, 0.02	95.0–105.8	GFAAS	[39]
1-butyl-3-methylimidazolium tetrachloroferrate ($[C_4mim][FeCl_4]$	ETA-MILs-ME	vegetable samples	As	7	97.9–105.8	GFAAS	[40]
$([Ni(C_4IM)_4{}^{2+}]_2[Cl^-]$ and $[Ni(BeIM)_4{}^{2+}]_2[Cl^-]$	in situ MIL-DLLME	aqueous samples	polar and non-polar pollutants	0.13–5.2 and 0.012–1.6	67.7–120 and 86.5–96.6	HPLC-DAD	[44]
$[Co(C_4IM)^{+2}{}_4]_2[NTf_2]$	in situ Pa-DDE/MIL	aqueous environmental samples	organic micropollutants	7.5	53.9–129.1	HPLC-DAD	[45]
$[P_{6,6,6,14}{}^+][Ni(II)(hfacac)^{3-}]$	in situ MIL-DLLME	-	long and short double-stranded DNA	-	-	fluorescence emission spectroscopy	[46]
$[C_4MIM\text{-}TEMPO]Cl$	in-situ MIL-DLLME	milk samples	sulfonamides	0.534–0.891	95–105	HPLC-UV	[47]
$[P_{6,6,6,14}{}^+]_2[CoCl_4{}^{2-}]$	in situ derivatization-MIL-DLLME	wine and fish samples	six biogenic amines	1.3–3.9 and 1.2–3.8	93.2–103.1 and 94.5–102.3	LC-UV	[48]
1-octyl-3-methylimidazolium tetrachloroferrate ($[C_8MIM]FeCl_4$)	weighing paper-assisted magnetic ionic liquid headspace single-drop microextraction (WP-MIL-HS-SDME)	16 lavender samples	39 volatile compounds	-	-	GC-MS	[49]
$([P6,6,6,14^+]_2[MnCl_4{}^{2-}])$ and $([Aliquat^+]_2[MnCl_4{}^{2-}])$	HS-SDME, DLLME	lake water samples	twelve aromatic compounds and four polyaromatic hydrocarbons	0.04–1.0 and 0.05–1.0	70.2–109.6 and 68.7–104.5	HPLC	[50]
$[P_{6,6,6,14}{}^+][Mn(hfacac)^{3-}]$	vacuum MIL-HS-SDME	milk samples	free fatty acids (FFAs)	14.5–70.3	79.5–111	GC-MS	[51]
aliquat tetrachloromanganate (II) $[Aliquat^+]_2[MnCl_4{}^{2-}]$	single-drop microextraction	aqueous samples	ascorbic acid	0.042–48.7	101.0–104.1	voltammetric determination	[52]

Table 1. *Cont.*

Ionic Liquid	Extraction Technique	Matrix	Target Analytes	LOD ($\mu g \cdot kg^{-1}$ or $\mu g \cdot L^{-1}$)	Recoveries (%)	Analytical Instrumental System	Reference
1-ethyl-3- methylimidazolium tetraisothiocyanatocobaltate(II) ($[Emim]_2[Co(NCS)_4]$)	magnetic headspace single-drop microextraction (Mag-HS-SDME)	water samples	1,2-dichlorobenzene,1,3-dichlorobenzene, 1,4-dichlorobenzene, 1,2,3-trichlorobenzene, 1,2,4-trichlorobenzene, 1,3,5-trichlorobenzene,1,2,3,4-tetrachlorobenzene, 1,2,4,5-tetrachlorobenzene, and pentachlorobenzene	0.003–0.152	82–114	GC-MS	[53]
1-butyl-3-methylimidazolium tetrachloroferrate ($[C_4$ MIM$][FeCl_4]$)	MSPD-MIL-DLLME	oilseeds	triazine herbicides	1.20–2.72	82.9–113.7	UFLC-UV	[54]
$[P_{6,6,6,14}{}^+][Co(II)(hfacac)^{3-}]$	MSPD	raw vegetables	ten pesticides	-	65–85	HPLC-DAD	[55]
$[C_6MIM][PF_6]$	ILMB-ME	water samples	carbamate pesticides	1.4–3.4	85–98.0 (spiking 5 $\mu g \cdot L^{-1}$), 80–98 (spiking 50 $\mu g \cdot L^{-1}$)	HPLC-DAD	[56]
$[P_{6,6,6,14}{}^+][Ni(II)(hfacac)^{3-}]$	SBDLME	natural water samples	polycyclic aromatic hydrocarbons (PAHs)	0.0005–0.0087	84–115	GC-MS	[57]
$[P_{6,6,6,14}{}^+][Ni(hfacac)^{3-}]$	SBDLME	environmental water samples	lipophilic organic UV filters	0.0099–0.027	87–113 (river water), 91–117 (sea-water), 89–115 (swimming pool water)	TD-GC-MS	[58]
1-hexyl-3-methylimidazolium tetrachloroferrate ($[C_6MIM][FeCl_4]$)	DLLME	vegetable oil	bisphenol A and 4-nonylphenol	0.1 and 0.06	70.4–112.3	HPLC-MS/MS	[59]
1-methyl-3-hexyl imidazole ferric tetrachloride ($[C_6MIM]FeCl_4$)	immersion method	water samples	arsenic	0.500	-	-	[60]
1-allyl-3-octylimidazolium tetrachloroferrate	SPE	apple samples	phenolic acids	0.31–1.72	81–100	HPLC-DAD	[61]
trihexyltetradecylphosphonium tetrachloroferrate (III) ($[3C_6PC_{14}][FeCl_4]$)	magnetic room temperature ionic liquid	soil samples	phenol (Ph), 4-nitrophenol (4-NP), 2-chlorophenol (2-CP), 4-chlorophenol (4-CP), 2,4-dichlorophenol (2,4-DCP), 3,5-dichlorophenol (3,5-DCP), pentachlorophenol (penta-CP), and 2-benzyl-4-chlorophenol (2-Bn-4-CP)	-	-	UV-Vis-NIR spectrometer, HPLC	[17]

3. Conclusions and Future Perspectives

The development of novel sample preparation procedures is a never-ending field of research, as the need for more accurate and easier analytical methods increases. To this end, much effort has been put into employing MILs in sample preparation and great advancements have been made up to now. The results presented in this review article corroborate the significance of designing various kinds of magnetic ILs in order to be successfully applied to sample preparation. The MILs not only exhibit high extraction capacity activities and moderate selectivity, but also showed facile recovery and recyclability. These features render them suitable choices for designing environmentally benign sample preparation procedures in (bio)chemical analysis. However, efforts should be made towards heightening the magnetic susceptibility so that a more efficient retrieval of the MIL is allowed for more complex matrixes, under a lower magnetic field. Moreover, properties of the MILs such as the hydrophobicity and the viscosity should be more easily tuned, to broaden their applicability. Tuning the hydrophobicity of the MILs will assist in the extraction of different analytes. On the other hand, the high viscosity of the MILs generally causes many problems regarding the use of exact amounts of MILs and their handling and generation of droplets during dispersion. This can be addressed either by using supporting materials or by in-situ formation of MILs. However, these solutions are difficult to be employed in complex matrixes. Finally, the direct injection of MILs in HPLC systems, currently has many limitations, such as high back pressure, immiscibility with the mobile phase and absorbance in the UV region. Thus, the synthesis of new MILs with other organic groups that can alter the physicochemical characteristics of the MILs can address the problems, thus, avoiding time consuming steps, such as back extraction. Despite the current limitations, this topic of research is developing rapidly, and many advancements are expected to occur in the near future.

Author Contributions: Conceptualization, T.C. and C.S.; writing—original draft preparation, T.C., P.A., I.C. and K.D.; writing—review and editing, T.C. and C.S. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Reyes-Garcés, N.; Gionfriddo, E.; Gómez-Ríos, G.A.; Alam, N.; Boyacı, E.; Bojko, B.; Singh, V.; Grandy, J.; Pawliszyn, J. Advances in solid phase microextraction and perspective on future directions. *Anal. Chem.* **2018**, *90*, 302–360. [CrossRef]
2. Zhang, B.-T.; Zheng, X.; Li, H.-F.; Lin, J.-M. Application of carbon-based nanomaterials in sample preparation: A review. *Anal. Chim. Acta* **2013**, *784*, 1–17. [CrossRef]
3. Sajid, M. Magnetic ionic liquids in analytical sample preparation: A literature review. *TrAC Trends Anal. Chem.* **2019**, *113*, 210–223. [CrossRef]
4. Chatzimitakos, T.; Stalikas, C. Carbon-based nanomaterials functionalized with ionic liquids for microextraction in sample preparation. *Separations* **2017**, *4*, 14. [CrossRef]
5. Feng, J.; Loussala, H.M.; Han, S.; Ji, X.; Li, C.; Sun, M. Recent advances of ionic liquids in sample preparation. *TrAC Trends Anal. Chem.* **2020**, *125*, 115833. [CrossRef]
6. Ruiz-Aceituno, L.; Sanz, M.; Ramos, L. Use of ionic liquids in analytical sample preparation of organic compounds from food and environmental samples. *TrAC Trends Anal. Chem.* **2013**, *43*, 121–145. [CrossRef]
7. Yavir, K.; Konieczna, K.; Marcinkowski, Ł.; Kloskowski, A. Ionic liquids in the microextraction techniques: The influence of ILs structure and properties. *TrAC Trends Anal. Chem.* **2020**, *130*, 115994. [CrossRef]
8. Clark, K.D.; Emaus, M.N.; Varona, M.; Bowers, A.N.; Anderson, J.L. Ionic liquids: Solvents and sorbents in sample preparation. *J. Sep. Sci.* **2018**, *41*, 209–235. [CrossRef] [PubMed]
9. Chatzimitakos, T.G.; Pierson, S.A.; Anderson, J.L.; Stalikas, C.D. Enhanced magnetic ionic liquid-based dispersive liquid-liquid microextraction of triazines and sulfonamides through a one-pot, pH-modulated approach. *J. Chromatogr. A* **2018**, *1571*, 47–54. [CrossRef] [PubMed]
10. Trujillo-Rodríguez, M.J.; Anderson, J.L. In situ generation of hydrophobic magnetic ionic liquids in stir bar dispersive liquid-liquid microextraction coupled with headspace gas chromatography. *Talanta* **2019**, *196*, 420–428. [CrossRef]

11. Merib, J.; Spudeit, D.A.; Corazza, G.; Carasek, E.; Anderson, J.L. Magnetic ionic liquids as versatile extraction phases for the rapid determination of estrogens in human urine by dispersive liquid-liquid microextraction coupled with high-performance liquid chromatography-diode array detection. *Anal. Bioanal. Chem.* **2018**, *410*, 4689–4699. [CrossRef]
12. Trujillo-Rodríguez, M.J.; Nacham, O.; Clark, K.D.; Pino, V.; Anderson, J.L.; Ayala, J.H.; Afonso, A.M. Magnetic ionic liquids as non-conventional extraction solvents for the determination of polycyclic aromatic hydrocarbons. *Anal. Chim. Acta* **2016**, *934*, 106–113. [CrossRef] [PubMed]
13. Maximino, C.; de Brito, T.M.; da Silva Batista, A.W.; Herculano, A.M.; Morato, S.; Gouveia, A., Jr. Measuring anxiety in zebrafish: A critical review. *Behav. Brain Res.* **2010**, *214*, 157–171. [CrossRef] [PubMed]
14. Da Silva, A.C.; Mafra, G.; Spudeit, D.; Merib, J.; Carasek, E. Magnetic ionic liquids as an efficient tool for the multiresidue screening of organic contaminants in river water samples. *Sep. Sci. Plus* **2019**, *2*, 51–58. [CrossRef]
15. Yao, T.; Yao, S. Magnetic ionic liquid aqueous two-phase system coupled with high performance liquid chromatography: A rapid approach for determination of chloramphenicol in water environment. *J. Chromatogr. A* **2017**, *1481*, 12–22. [CrossRef] [PubMed]
16. Yao, T.; Li, Q.; Li, H.; Peng, L.; Liu, Y.; Du, K. Extractive resolution of racemic phenylalanine and preparation of optically pure product by chiral magnetic ionic liquid aqueous two-phase system. *Sep. Purif. Technol.* **2021**, *274*, 119024. [CrossRef]
17. Deng, N.; Li, M.; Zhao, L.; Lu, C.; de Rooy, S.L.; Warner, I.M. Highly efficient extraction of phenolic compounds by use of magnetic room temperature ionic liquids for environmental remediation. *J. Hazard. Mater.* **2011**, *192*, 1350–1357. [CrossRef]
18. Yu, H.; Merib, J.; Anderson, J.L. Faster dispersive liquid-liquid microextraction methods using magnetic ionic liquids as solvents. *J. Chromatogr. A* **2016**, *1463*, 11–19. [CrossRef]
19. Berton, P.; Siraj, N.; Das, S.; de Rooy, S.; Wuilloud, R.G.; Warner, I.M. Efficient low-cost procedure for microextraction of estrogen from environmental water using magnetic ionic liquids. *Molecules* **2020**, *26*, 32. [CrossRef]
20. Chatzimitakos, T.; Binellas, C.; Maidatsi, K.; Stalikas, C. Magnetic ionic liquid in stirring-assisted drop-breakup microextraction: Proof-of-concept extraction of phenolic endocrine disrupters and acidic pharmaceuticals. *Anal. Chim. Acta* **2016**, *910*, 53–59. [CrossRef]
21. Feng, X.; Xu, X.; Liu, Z.; Xue, S.; Zhang, L. Novel functionalized magnetic ionic liquid green separation technology coupled with high performance liquid chromatography: A rapid approach for determination of estrogens in milk and cosmetics. *Talanta* **2020**, *209*, 120542. [CrossRef] [PubMed]
22. Wang, Y.; Sun, Y.; Xu, B.; Li, X.; Jin, R.; Zhang, H.; Song, D. Magnetic ionic liquid-based dispersive liquid–liquid microextraction for the determination of triazine herbicides in vegetable oils by liquid chromatography. *J. Chromatogr. A* **2014**, *1373*, 9–16. [CrossRef] [PubMed]
23. García-Reyes, J.F.; Ferrer, C.; Thurman, E.M.; Fernández-Alba, A.R.; Ferrer, I. Analysis of herbicides in olive oil by liquid chromatography time-of-flight mass spectrometry. *J. Agric. Food Chem.* **2006**, *54*, 6493–6500. [CrossRef]
24. Ferrer, C.; Gómez, M.J.; García-Reyes, J.F.; Ferrer, I.; Thurman, E.M.; Fernández-Alba, A.R. Determination of pesticide residues in olives and olive oil by matrix solid-phase dispersion followed by gas chromatography/mass spectrometry and liquid chromatography/tandem mass spectrometry. *J. Chromatogr. A* **2005**, *1069*, 183–194. [CrossRef] [PubMed]
25. Fuentes, E.; Báez, M.E.; Quiñones, A. Suitability of microwave-assisted extraction coupled with solid-phase extraction for organophosphorus pesticide determination in olive oil. *J. Chromatogr. A* **2008**, *1207*, 38–45. [CrossRef] [PubMed]
26. Cai, M.; Chen, X.; Wei, X.; Pan, S.; Zhao, Y.; Jin, M. Dispersive solid-phase extraction followed by high-performance liquid chromatography/tandem mass spectrometry for the determination of ricinine in cooking oil. *Food Chem.* **2014**, *158*, 459–465. [CrossRef]
27. Wang, W.-X.; Yang, T.-J.; Li, Z.-G.; Jong, T.-T.; Lee, M.-R. A novel method of ultrasound-assisted dispersive liquid–liquid microextraction coupled to liquid chromatography–mass spectrometry for the determination of trace organoarsenic compounds in edible oil. *Anal. Chim. Acta* **2011**, *690*, 221–227. [CrossRef] [PubMed]
28. Li, Q.; Wu, S.; Wang, C.; Yi, Y.; Zhou, W.; Wang, H.; Li, F.; Tan, Z. Ultrasonic-assisted extraction of sinomenine from Sinomenium acutum using magnetic ionic liquids coupled with further purification by reversed micellar extraction. *Process Biochem.* **2017**, *58*, 282–288. [CrossRef]
29. Feng, X.; Zhang, W.; Zhang, T.; Yao, S. Systematic investigation for extraction and separation of polyphenols in tea leaves by magnetic ionic liquids. *J. Sci. Food Agric.* **2018**, *98*, 4550–4560. [CrossRef]
30. Mousavi, K.Z.; Yamini, Y.; Seidi, S. Dispersive liquid–liquid microextraction using magnetic room temperature ionic liquid for extraction of ultra-trace amounts of parabens. *New J. Chem.* **2018**, *42*, 9735–9743. [CrossRef]
31. Will, C.; Omena, E.; Corazza, G.; Bernardi, G.; Merib, J.; Carasek, E. Expanding the applicability of magnetic ionic liquids for multiclass determination in biological matrices based on dispersive liquid–liquid microextraction and HPLC with diode array detector analysis. *J. Sep. Sci.* **2020**, *43*, 2657–2665. [CrossRef]
32. Abdelaziz, M.A.; Mansour, F.R.; Danielson, N.D. A gadolinium-based magnetic ionic liquid for dispersive liquid–liquid microextraction. *Anal. Bioanal. Chem.* **2021**, *413*, 205–214. [CrossRef]
33. Hassan, A.A.; Tanimu, A.; Alhooshani, K. Iron and cobalt-containing magnetic ionic liquids for dispersive micro-solid phase extraction coupled with HPLC-DAD for the preconcentration and quantification of carbamazepine drug in urine and environmental water samples. *J. Mol. Liq.* **2021**, *336*, 116370. [CrossRef]
34. Fiorentini, E.F.; Escudero, L.B.; Wuilloud, R.G. Magnetic ionic liquid-based dispersive liquid-liquid microextraction technique for preconcentration and ultra-trace determination of Cd in honey. *Anal. Bioanal. Chem.* **2018**, *410*, 4715–4723. [CrossRef]

35. Fiorentini, E.F.; Canizo, B.V.; Wuilloud, R.G. Determination of As in honey samples by magnetic ionic liquid-based dispersive liquid-liquid microextraction and electrothermal atomic absorption spectrometry. *Talanta* **2019**, *198*, 146–153. [CrossRef] [PubMed]
36. Fiorentini, E.F.; Oviedo, M.N.; Wuilloud, R.G. Ultra-trace Cr preconcentration in honey samples by magnetic ionic liquid dispersive liquid-liquid microextraction and electrothermal atomic absorption spectrometry. *Spectrochim. Acta Part B At. Spectrosc.* **2020**, *169*, 105879. [CrossRef]
37. Fiorentini, E.F.; Botella, M.B.; Wuilloud, R.G. A simple preconcentration method for highly sensitive determination of Pb in bee products by magnetic ionic liquid dispersive liquid-liquid microextraction and electrothermal atomic absorption spectrometry. *J. Food Compos. Anal.* **2020**, *95*, 103661. [CrossRef]
38. Wang, X.; Chen, P.; Cao, L.; Xu, G.; Yang, S.; Fang, Y.; Wang, G.; Hong, X. Selenium speciation in rice samples by magnetic ionic liquid-based up-and-down-shaker-assisted dispersive liquid-liquid microextraction coupled to graphite furnace atomic absorption spectrometry. *Food Anal. Methods* **2017**, *10*, 1653–1660. [CrossRef]
39. Yao, L.; Liu, H.; Wang, X.; Xu, W.; Zhu, Y.; Wang, H.; Pang, L.; Lin, C. Ultrasound-assisted surfactant-enhanced emulsification microextraction using a magnetic ionic liquid coupled with micro-solid phase extraction for the determination of cadmium and lead in edible vegetable oils. *Food Chem.* **2018**, *256*, 212–218. [CrossRef]
40. Wang, X.; Xu, G.; Guo, X.; Chen, X.; Duan, J.; Gao, Z.; Zheng, B.; Shen, Q. Effervescent tablets containing magnetic ionic liquids as a non-conventional extraction and dispersive agent for speciation of arsenite and arsenate in vegetable samples. *J. Mol. Liq.* **2018**, *272*, 871–877. [CrossRef]
41. Wang, X.; Xu, G.; Chen, P.; Liu, X.; Fang, Y.; Yang, S.; Wang, G. Arsenic speciation analysis in environmental water, sediment and soil samples by magnetic ionic liquid-based air-assisted liquid–liquid microextraction. *RSC Adv.* **2016**, *6*, 110247–110254. [CrossRef]
42. Oviedo, M.N.; Fiorentini, E.F.; Lemos, A.A.; Wuilloud, R.G. Ultra-sensitive Sb speciation analysis in water samples by magnetic ionic liquid dispersive liquid–liquid microextraction and multivariate optimization. *Anal. Methods* **2021**, *13*, 1033–1042. [CrossRef] [PubMed]
43. Aguirre, M.Á.; Canals, A.; López-García, I.; Hernández-Córdoba, M. Determination of cadmium in used engine oil, gasoline and diesel by electrothermal atomic absorption spectrometry using magnetic ionic liquid-based dispersive liquid-liquid microextraction. *Talanta* **2020**, *220*, 121395. [CrossRef] [PubMed]
44. Trujillo-Rodríguez, M.J.; Anderson, J.L. In situ formation of hydrophobic magnetic ionic liquids for dispersive liquid-liquid microextraction. *J. Chromatogr. A* **2019**, *1588*, 8–16. [CrossRef]
45. Will, C.; Huelsmann, R.D.; Mafra, G.; Merib, J.; Anderson, J.L.; Carasek, E. High-throughput approach for the in situ generation of magnetic ionic liquids in parallel-dispersive droplet extraction of organic micropollutants in aqueous environmental samples. *Talanta* **2021**, *223*, 121759. [CrossRef]
46. Bowers, A.N.; Trujillo-Rodríguez, M.J.; Farooq, M.Q.; Anderson, J.L. Extraction of DNA with magnetic ionic liquids using in situ dispersive liquid–liquid microextraction. *Anal. Bioanal. Chem.* **2019**, *411*, 7375–7385. [CrossRef]
47. Yao, T.; Du, K. Simultaneous determination of sulfonamides in milk: In-situ magnetic ionic liquid dispersive liquid-liquid microextraction coupled with HPLC. *Food Chem.* **2020**, *331*, 127342. [CrossRef]
48. Cao, D.; Xu, X.; Xue, S.; Feng, X.; Zhang, L. An in situ derivatization combined with magnetic ionic liquid-based fast dispersive liquid-liquid microextraction for determination of biogenic amines in food samples. *Talanta* **2019**, *199*, 212–219. [CrossRef]
49. Chen, P.; Liu, X.; Wang, L.; Wang, C.; Fu, J. Weighing paper-assisted magnetic ionic liquid headspace single-drop microextraction using microwave distillation followed by gas chromatography-mass spectrometry for the determination of essential oil components in lavender. *J. Sep. Sci.* **2021**, *44*, 585–599. [CrossRef]
50. An, J.; Rahn, K.L.; Anderson, J.L. Headspace single drop microextraction versus dispersive liquid-liquid microextraction using magnetic ionic liquid extraction solvents. *Talanta* **2017**, *167*, 268–278. [CrossRef]
51. Trujillo-Rodríguez, M.J.; Pino, V.; Anderson, J.L. Magnetic ionic liquids as extraction solvents in vacuum headspace single-drop microextraction. *Talanta* **2017**, *172*, 86–94. [CrossRef] [PubMed]
52. Jahromi, Z.; Mostafavi, A.; Shamspur, T.; Mohamadim, M. Magnetic ionic liquid assisted single-drop microextraction of ascorbic acid before its voltammetric determination. *J. Sep. Sci.* **2017**, *40*, 4041–4049. [CrossRef] [PubMed]
53. Fernández, E.; Vidal, L.; Canals, A. Hydrophilic magnetic ionic liquid for magnetic headspace single-drop microextraction of chlorobenzenes prior to thermal desorption-gas chromatography-mass spectrometry. *Anal. Bioanal. Chem.* **2017**, *410*, 4679–4687. [CrossRef] [PubMed]
54. Wang, Y.; Sun, Y.; Xu, B.; Li, X.; Wang, X.; Zhang, H.; Song, D. Matrix solid-phase dispersion coupled with magnetic ionic liquid dispersive liquid–liquid microextraction for the determination of triazine herbicides in oilseeds. *Anal. Chim. Acta* **2015**, *888*, 67–74. [CrossRef]
55. Chatzimitakos, T.G.; Anderson, J.L.; Stalikas, C.D. Matrix solid-phase dispersion based on magnetic ionic liquids: An alternative sample preparation approach for the extraction of pesticides from vegetables. *J. Chromatogr. A* **2018**, *1581–1582*, 168–172. [CrossRef]
56. Peng, S.; Xiao, J.; Cheng, J.; Zhang, M.; Li, X.; Cheng, M. Ionic liquid magnetic bar microextraction and HPLC determination of carbamate pesticides in real water samples. *Microchim. Acta* **2012**, *179*, 193–199. [CrossRef]
57. Benedé, J.L.; Anderson, J.L.; Chisvert, A. Trace determination of volatile polycyclic aromatic hydrocarbons in natural waters by magnetic ionic liquid-based stir bar dispersive liquid microextraction. *Talanta* **2018**, *176*, 253–261. [CrossRef]

58. Chisvert, A.; Benedé, J.L.; Anderson, J.L.; Pierson, S.A.; Salvador, A. Introducing a new and rapid microextraction approach based on magnetic ionic liquids: Stir bar dispersive liquid microextraction. *Anal. Chim. Acta* **2017**, *983*, 130–140. [CrossRef]
59. Zhu, S.; Wang, L.; Su, A.; Zhang, H. Dispersive liquid-liquid microextraction of phenolic compounds from vegetable oils using a magnetic ionic liquid. *J. Sep. Sci.* **2017**, *40*, 3130–3137. [CrossRef]
60. Li, H.; Wang, Q.; Gao, N.; Fu, J.; Yue, X.; Lv, X.; Zhong, F.; Tang, J.; Wang, T. Facile synthesis of magnetic ionic liquids/gold nanoparticles/porous silicon composite SERS substrate for ultra-sensitive detection of arsenic. *Appl. Surf. Sci.* **2021**, *545*, 148992. [CrossRef]
61. Tashakkori, P.; Erdem, P.; Bozkurt, S.S. Molecularly imprinted polymer based on magnetic ionic liquid for solid phase extraction of phenolic acids. *J. Liq. Chromatogr. Relat. Technol.* **2017**, *40*, 657–666. [CrossRef]