Recent molecularly imprinted polymers applications in bioanalysis

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Abstract
Molecular imprinted polymers (MIPs) as extraordinary compounds with unique features have presented a wide range of applications and benefits to researchers. In particular when used as a sorbent in sample preparation methods for the analysis of biological samples and complex matrices. Its application in the extraction of medicinal species has attracted much attention and a growing interest. This review focus on articles and research that deals with the application of MIPs in the analysis of components such as biomarkers, drugs, hormones, blockers and inhibitors, especially in biological matrices. The studies based on MIP applications in bioanalysis and the deployment of MIPs in high-throughput settings and optimization of extraction methods are presented. A review of more than 200 articles and research works clearly shows that the superiority of MIP techniques lies in high accuracy, reproducibility, sensitivity, speed and cost effectiveness which make them suitable for clinical usage. Furthermore, this review present MIP-based extraction techniques and MIP-biosensors which are categorized on their classes based on common properties of target components. Extraction methods, studied sample matrices, target analytes, analytical techniques and their results for each study are described. Investigations indicate satisfactory results using MIP-based bioanalysis. According to the increasing number of studies on method development over the last decade, the use of MIPs in bioanalysis is growing and will further expand the scope of MIP applications for less studied samples and analytes.

Keywords Molecular imprinted polymers · Bioanalysis · Extraction techniques · Biological samples

Abbreviations
MI-IPN  Molecular imprinted interpenetrating polymer network
MMST  Monolithic MIP sol–gel packed tips
INAT  Inside-needle adsorption trap

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Molecular imprinted polymers (MIPs) have been in focus due to their special properties in many fields during the last decade. Many optimizations and developments of MIP techniques have been achieved for a range of goals. The most common applications of MIPs are detecting and quantifying of special targets in the field of chemistry. Due to the importance of analyzing drugs, biomarkers and other analytes in biological samples, scientists have developed MIP-based techniques to make analysis procedures more selective, sensitive, rapid and cost-effective. These efforts will allow MIP-based extraction techniques to be used as common approaches for clinical usage.

According to BelBruno (2019), for the first time the phrase “imprinted polymer” has been reported by Andersson et al. (1984). However, Wulff (2013) has claimed that the molecularly imprinted synthetic polymers were discovered in 1972 in his laboratory and his first article related to imprinted polymers is published in 1985 (Wulff et al. 1985). For more details, Wulff, in his early researches, has applied imprinted polymers in catalytic reactions (Liu and Wulff 2004; Wulff et al. 2006; Wulff and Knorr 2001; Wulff and Liu 2012) like K. Shea as well, who has reported on rather unique biological applications, like a plastic antibody inserted into living mice (BelBruno 2019). By the way, the presence of numerous MIP approaches and the obvious attention paid to these techniques is the consequence of these early researchers’ evaluations.

Several methods are recommended for the preparation of MIPs, some of which include synthesis, phase inversion and soft lithography or surface stamping methods. The synthesis methods are the most popular technique among researchers. In such methods, functional monomers interact with target molecules for developing a network of covalently or non-covalently complexes. Pyrrole, methacrylic acid (MAA), aniline, methyl methacrylate (MMA) and acrylamide are some of the most common functional monomers (Fig. 1) (BelBruno 2019; Xu et al. 2020). Briefly, in a synthesis method, the component process mainly includes a porogen solvent, a cross linker, a
Each component in a synthesis process plays significant roles in which changing and improving one of items will lead to optimized MIPs as a result. For instance, choosing a good template for a special analyte is very determinative in sensitivity and selectivity of the extraction process, or finding the best way for removing templates and analytes (washing and eluting) in the last step is extremely important because an unsuccessful removal may affects the final results (BelBruno 2019). Polymerization is the first crucial level in MIP formation which monomers, initiators, cross-linkers and even every polymerization method impact on results. Hence, polymerization methodologies
and the optimal components for each analyte in different matrices must be investigated in order to obtain acceptable modifications (Souza et al. 2016; Asiabi et al. 2016; McKitterick et al. 2020a; Rajpal et al. 2020; Sartore et al. 2020; Gama and Bottoli 2017). Nanomaterials as sorbents are extensively applied in various extraction methods. Based on extensive researches, various nanomaterials are introduced and utilized in many extraction techniques. Among all nanomaterial sorbents, MIP nanoparticles have gained much attention of researchers to have prosperous usage in significant extraction techniques (Ahmadi et al. 2017). Some examples of utilizing these sorbents are presented in this review. Finally, synthesized polymers may have a good selectivity on target molecules in the reason of binding supplementary sites with template in shape, size and also in the position of the functional groups (He et al. 2007; Djozan et al. 2011, 2012; Song et al. 2014; Sellergren et al. 1988; Rachkov and Minoura 2000). MIP nanoparticles have been thoroughly reviewed by Fresco-Cala et al. (2020).

In addition to the many benefits of MIP sorbents and the different established synthesis techniques, the production of such polymers confronts other difficulties; there is no general procedure for synthesis of MIPs and it is difficult to achieve a stable molecular shape memory of a polymer matrix. (Bossi et al. 2007). These issues have recently led to using computational modeling to achieve higher performance by optimization of MIP’s structures with different computational methods such as molecular dynamics calculations, density functional theory, etc. which provide an opportunity to screen thousands of combinations (Gollowitzer and Ljubić 2011; Mazouz et al. 2020; Silva et al. 2021a; Rajpal and Mizaikoff 2022).

As a summary, MIP synthesis is a procedure in which a special functional monomer self-assembles by surrounding a chosen template and the process will continue by polymerization techniques (bulk, surface imprinting, precipitation, suspension and emulsion polymerizations) in a porogen solvent. The last step of the process is removing the template, resulting in the manifestation of a cavity complementary in chemical characteristic and shape to the structure (Gama and Bottoli 2017).

MIP techniques are significantly developed and used in many fields, such as food analysis, analytical chemistry, therapeutics, drug delivery, sensors, immunoassays, biomedical diagnosis and environmental studies (Otero-Pazos et al. 2014; Kou et al. 2020; Yang et al. 2014; He et al. 2021, 2020; Ciechanowska et al. 2020; Song et al. 2018; Bonatti et al. 2021; Gornik et al. 2021; Cennamo et al. 2018; Muhammad et al. 2017). For instance, efforts on finding the best method for detecting SARS-CoV-2 are very salient and applying MIP techniques is being considered. Nunzio Cennamo et al. (2021) reported about the sensitive on-site detection of SARS-CoV-2 by plasmonic optical fibers and molecularly imprinted polymers and Raziq et al. (2021) explained the development of a portable MIP-based electrochemical sensor for detection of SARS-CoV-2 antigen. Furthermore, Fresco-Cala et al. (2021) reported the development and preparation of magnetic molecularly imprinted polymers by using epitope approach and SARS-CoV-2 peptide as a template. In this study, we concentrate on the use of MIPs in analytical chemistry, specifically their use in the extraction/microextraction of specific targets from biological samples as a key step in sample preparation techniques.

Biological samples are complicated mixtures with exclusive and diverse compositions for each person and species. Advanced strategies of sample preparation for each matrix and analyte aid to elimination of extra components from a sample to come over disorders of matrices and leading to elevated selectivity and recovery (Georgi and Boos 2006). Each matrix has its own challenges. For instance; (a) Blood is a composition of diverse blood cells sling withinside the plasma (b) Plasma consists glucose, proteins, hormones, minerals, and blood cells as well. (c) Serum is the fluid and solute component of blood without fibrinogens. (d) Urine is composed of water (95%), urea, creatinine, proteins, pigmented products of breakdown and also inorganic salts such as sodium, phosphate, sulfate, and ammonia. (e) Human breast milk is composed of certain amount of fat, proteins, lactose and minerals and (f) Saliva includes about 99% of water portion, had compounds secreted within the salivary glands. Saliva also consists of numerous electrolytes such as bicarbonate, sodium, magnesium, phosphate, potassium and calcium (Inoue et al. 2006; Fernández-Peralbo and Luque de Castro 2012; Rosenthal 1948; Kohler 2014). Due to the high complexity of biological samples, some important factors must be considered during a bioanalysis process to be sure about the validation of results such as stability, spiking, nonspecific binding and using internal standards. Extra attention on the sample stability during the collection, storage, shipping, and processing are also important. Despite spiking into biological matrices, the “Nonspecific Binding” also should be noticed in some biofluids like urine and cerebrospinal fluid as other important factor to reflect the whole complexity of study samples. Nonspecific binding can be resolved by decreasing the concentration of analytes and leading to more accurate results. To improve the accuracy of biological sample results, Internal Standards (IS) are very effective. Choosing the best Internal Standard, on the other hand, is a challenging task, because it must have physicochemical properties similar to a specific analyte. The two common types of ISs are Structural analog and stable isotope-labeled internal standards which the second one, is more effective and highly recommended (Yadav and Shrivas-tav 2011; Viswanathan et al. 2007; Wang et al. 2020).

Efforts in developing bioanalytical methods for clinical samples are making good progress. In this regard, recent
research on MIP-based extraction techniques and MIP-based biosensors have presented satisfactory results due to their high selectivity, sensitivity and accuracy. In this paper, we have reviewed the most common MIP applications in bioanalysis and recent advances of MIP utility in extraction/microextraction techniques and biosensor methods. The analysis of many important compounds such as inhibitors, biomarkers, anesthetic drugs, antimicrobial substances and etc., in several biofluids are widely presented, covering published papers over the last decade.

MIP in bioanalysis

With regards to the development of extraction techniques, several kinds of sorbents have been investigated. Some of classic sorbents are chemically bonded silica with different functional groups, metal organic frameworks, metallic and metal oxide nanoparticles, carbon nanotubes and also fiber coating materials, each of which has been optimized for special analyte or analytes in special samples. Recently, MIP sorbents have attracted much more considerations due to their high selectivity, flexibility and capability of extracting various analytes from complicated matrices like biological samples (Hashemi et al. 2018).

Furthermore, biosensors are a kind of analytical techniques which are widely used in bioanalysis as a simple, real-time and effective approach. These high-selective techniques usually contain three key factors: the transducer, the signal processing system and the bio-receptor (Abid et al. 2021). Recently, MIP-based biosensors are developed for many types of analytes and samples. In this review, we have focused more on MIP-based extraction techniques and briefly on MIP-based biosensors.

MIP-based sample preparation techniques

Sample preparation, as a main step of bioanalysis approaches, has always been a challenge for analyzing analytes in various samples. Many routine methods of sample preparation are extraction, chromatographic sample purification, clean-up and enrichment, precipitation, etc. (Yang et al. 1998) The most common extraction techniques in analytical chemistry are solid-phase extraction, liquid–liquid extraction and membrane-based solid-phase extraction.

Researchers have always been attempting to develop extraction methods for various samples such as environmental, biological, foods and agricultural samples due to their unique complicated matrices. Biological samples have received the most attention due to their intricate matrices, which have always posed significant obstacles in preconcentration and extraction of unique analytes among other macromolecules and cells. Fortunately, researchers have devised a variety of approaches for dealing with complicated samples as well as selectively extracting special analytes with satisfactory results. Here the focus is more on MIP-based extraction techniques especially in biological matrices. MIPs (molecularly imprinted polymers) are known as selective separation materials. One of the benefits of such sorbents is the possibility to make polymers that are tailored to a certain target. The crucial stage is the polymerization of crosslinking and functional monomers in the attendance of a template or imprint sorts (Ashri and Abdel-Rehim 2011). There are several extraction/microextraction techniques that have been developed, including SPME, SPE, IT-SPME, MEPS, SBSE, Non-fiber SPME, and DSPME. The broad applicability and development of these techniques are thoroughly covered in our previous review paper (Daryanavard et al. 2021). Some of the developed MIP-based extraction approaches are widely covered in the following sections. The application rate of these techniques is shown in Fig. 3.

MIP-SPE

The capacity of solid-phase extraction (SPE) to extract analytes from a variety of matrices makes it a popular method for sample preparation. Its simplicity of use, capacity to handle large loads, ability to provide acceptable recoveries, consumption of relatively little amounts of organic solvents, automation, and availability of a broad variety of
MEPS or microextraction by packed sorbent is a developed method of solid-phase-extraction by packing sorbent bed into a liquid-handling syringe which causes great improvements in analyte extraction (Moein et al. 2015a). Most of existing SPE techniques could be applied by MEPS while scaling down of sample volumes and reagents. In other words, MEPS is the miniaturization of conventional SPE (Daryanavard et al. 2013). Since the first MEPS report was released in 2004, it has been regarded as a desirable option and successful sample preparation method that is suitable for fulfilling analytical and bioanalytical purposes (Abdel-Rehim 2004). The major difference between SPE and MEPS is the solution flow direction which in SPE is up to down but in MEPS is in both directions (up and down) which naturally leads to a difference in the optimization of elution and washing steps (Abdel-Rehim 2010). MEPS is a revolutionary technology in that it has allowed for the combination of extraction, clean-up and preconcentration in a single device. The device consists of a barrel insert and needle, which contains the packed MEPS bed (Moein et al. 2015a). Being fully automated, having short analysis time, using small sample volumes, convenient analyte enrichment and being both simple and inexpensive are the advantages of MEPS that has made it distinctive and superior compared to other methods (Abdel-Rehim and Abdel-Rehim 2013). Like SPE, MEPS can be used manually offline and also online by connecting it directly to an HPLC or GC autosampler (Moein et al. 2015a).

MIP-MEPS

MIP-MEPS is a recent advancement of MEPS technology by application of MIP sorbents to optimize the selectivity and efficiency in various samples such as plasma, urine and waters (Daryanavard et al. 2013; Prieto et al. 2011a, b). In 2019, Meng and Wang (2019) presented their findings on levofloxacin detection in human plasma using MEPS technique in conjunction with ultra-high-performance liquid chromatography. Deep eutectic solvents (DESs) were employed as pure porogen in this study to create DESs-MIPs. Please refer to our in-depth study for additional information about MEPS (Moein et al. 2015a).

MIP-SPME

For the first time, SPME was presented by Pawliszyn and Lord in the early 1990s (Arthur and Pawliszyn 1990). A thin polymer film coating on a fiber to extract analytes from various matrix samples is used in this kind of extraction technique. This approach has undergone several improvements, yielding in outstanding results that make it widely applicable for integrating extraction, sampling, sample preparation and preconcentration into a single step. This approach, like the others discussed in this study, is highly simple, quick, inexpensive, solvent-free, easily automated, and it has been used to analyze direct aqueous samples by remarkable selectivity and sensitivity. SPME efficiency can be influenced by a number of variables, including the kind of stationary phase and its thickness, sample volume, temperature and fiber exposure (Sarafrasz-Yazdi and Razavi 2015).

MIPs have been successfully employed as a selective and sensitive stationary (sorbent) phase in a variety of studies in...
recent years. In our previous studies (El-Beqqali et al. 2017; El-Beqqali and Abdel-Rehim 2016), we described a novel SPME development known as MIP-sol–gel tablet-SPME for determining methadone and amphetamine in human plasma. The MIP-sol–gel was created as a thin layer over polyethylene material in the shape of a tablet. According to the results, each tablet may be used twenty times with a short extraction time (10 min).

The polymeric tablet is a new microextraction approach based on a polyethylene tablet coated with a thin layer of molecularly imprinted polymer or graphene oxide for extraction, enrichment and analysis of analytes from a variety of matrices such as biological, environmental and food samples, according to the extended explanation in our previous overview. In these approaches, the surface of polyethylene is altered with sol–gel imprinted polymers or a graphene oxide/polyethylene glycol combination. Finally, the analytes separated from the tablet surface can be eluted and injected into the analytical equipment for measurement (Abdel-Rehim et al. 2020).

As a result, MIP-SPME solves several SPME concerns, such as the expense of commercial fibers, instability (chemical or thermal), and difficulties in fiber synthesis. MIP fibers are well-known for their ease of preparation and low cost while preserving stiffness and selectivity toward a given analyte (Sarafraz-Yazdi and Razavi 2015).

MMISPE

For the first time, monomer polymerization in liquid perfluoro chlorine was achieved in 1998 with the application of magnet iron oxide, an MMIP (magnetic molecularly imprinted polymer) with a mean diameter of 13 μm (Ansell and Mosbach 1998). Among nanoparticles as sorbents, the superparamagnetic iron oxide nanoparticles (SPIONs) in bioanalysis have recently received much more attention. This sophisticated sorbent can be used for (a) diagnostics, (b) separations, and (c) treatments such as hyperthermia, drug delivery and magnetofection. Magnetic nanoparticles’ sizes (MNPs) are related to the chosen synthesis method. For example, precipitation from microemulsions, surfactant or polymer solutions can readily form nanoparticles with diameters < 100 nm with giving superparamagnetic properties (Lee et al. 2010). Hung-Yin Lin et al. (Daryanavard et al. 2013) demonstrated the use of MIP-based nanoparticles to separate and sense lysozyme, urea and albumin-creatinine from urine sample. Magnetic separation technique is a batch-scale process based on functionalized magnetic materials (Lin et al. 2012). Due to the high biocompatibility, vast surface area, ease of manipulations, and ease of functionalization of magnetic separation techniques, these could be ideal for extraction of biological macromolecules. In a nutshell, the magnetic separation process involves combining magnetic materials with target analytes, which bind to the magnetic particles during a period of incubation. Finally, without filtering or centrifugation, all magnetic complexes will be isolated from the sample by another magnetic field (Toh et al. 2012; Li et al. 2011; Kubo and Otsuka 2016).

Magnetic molecularly imprinted solid-phase extraction (MMISPE), a newly developed magnetic extraction method, is gaining favor among researchers due to its benefits such as simplicity, convenience, fast and effective binding to target analytes, magnetically susceptible characteristics, and shorter pretreatment time. Its use in the extraction and pre-concentration of target components in a variety of matrices, including food, biological and environmental samples, backs up these assertions (Zhang et al. 2011; Li et al. 2017). One of the applications of MMISPE, was in the study of McKitterick et al. (2020a). They developed a technique for selective clean-up of Protein biomarker measurement. They created NLLGLIEAK-targeting MMIPs as well as a method for extracting tryptic peptides from serum which are both selective and rapid. Four distinct MMIPs were synthesized in this work and MMISPE method for extracting low quantities of tryptic peptides from human serum was devised and improved.

MIP-ITSPME

Eisert and Pawliszyn presented In-tube Solid Phase Micro-extraction (ITSPME) in 1997 as a simple operational approach for sample preparation in the laboratory (Eisert and Pawliszyn 1997). This method is an improvement on the previously stated conventional fiber SPME. The goal of this approach was to address issues such as limited sorption capacity, fragility and bleeding from fiber thick-film coatings. The goal was also to automate the SPME-HPLC process, allowing continuous extraction, desorption, and injection using a conventional autosampler. ITSPME is an online SPME by HPLC, GC or LC–MS with using open-tubular capillary column (Kataoka et al. 2009).

The utilization of monolithic MIPs on SPME is apparent due to their straightforward preparation and improved selectivity. ITSPMEs are methods that have benefited from MIPs to achieve special advantages (Ponce-Rodriguez et al. 2020). MIP-based ITSPME is used in many kinds of matrices and samples of purpose developing the method and also extracting special analytes by using different analytical methods (Souza et al. 2016; Chaves and Costa Queiroz 2013; Zhang...
et al. 2009; Djozan et al. 2009, 2010; Rajabi Khorrami and Narouenezhad 2011). Marchioni et al. (2020) described the determination of cannabinoids and Δ9-tetrahydrocannabinol in plasma by “dummy MIP-in-tube solid-phase microextraction”. In this study, an in-situ polymerization in a fused silica capillary yielded a new dummy molecularly imprinted monolithic capillary (MIP monolith) for in-tube SPME, with hydrogenated cannabidiol acting as the dummy template.

Miscellaneous

Stir bar sorptive extraction (SBSE) is a solvent-less micro-extraction technique presented by Baltussen et al. (1999). Nowadays, the common commercial coating for SBSE is available for non-polar compounds but because of notable deficiencies of this method such as lower selectivity and low extraction efficiency, application of MIPs as a coating for SBSE has enabled the analysis of various analytes and the application in many complex samples, such as the analysis of sulfonamides from animal feeds (Cui et al. 2021), extraction of carbenzazim and thiabendazole from orange samples (Díaz-Álvarez et al. 2019) as well as analysis of environmental estrogens in plastic and water samples (Xu et al. 2014).

The dispersive solid phase microextraction (DSPME) method is the result of improving non-fiber SPME method in order to overcome the limitations of traditional SPME. Instead of depositing sorbents on the fiber core, these are poured directly into the sample solution and dispersed, respectively, which leads to an increase in contact surfaces between sorbents and samples and causes a higher efficiency in extraction of analytes and a reduction of the procedures time (Tsai et al. 2009). Even though DSPME has many advantages such as being simple, fast, and inexpensive, as well as being applicable to concentrate, clean up and to extract variety of components in real samples, etc., it has many significant restrictions including the difficulty of sorbent separation from the sample solution, method automation limitations, and restrictions in its usage for in vivo analysis (Ghorbani et al. 2019). The MIP-DSPME technique is utilized to extract analytes with more efficiency and selectivity in many real samples (Asfaram et al. 2018; Wu et al. 2017; Cheng et al. 2017; Bazmandegan-Shamili et al. 2016). Besides the MIP method, there are many other assistant techniques which have been used to modify the extraction efficiency of this method; using special analyte absorber components with suitable functional groups or cavities, using magnetic components such as Magnetic iron oxide, using Vortex-assisted DSPME and ultrasonic-assisted DSPME techniques (Ghorbani et al. 2019).

MIP applications in bioanalysis

For the examination of biological samples, sampling, sample preparation and the storage of samples are critical. Plasma, blood, and urine are significantly more complex matrices including salts, proteins, bases, acids and other chemical components with chemistries comparable to analytes of interest, making target extraction from biological matrices challenging. These compounds would cause matrix effect which can dramatically influence analysis performance for both identification and quantification of an analyte. These may lead to false negative or positive results. Hence, the application of a clean-up step before analysis is essential to minimize the matrix effects especially for biologically active compounds in biological materials. Hence, it is impossible to inject drugs and metabolites in biological matrices directly into the analytical equipments before sample cleanup. The first and most important stage in the bioanalytical process is sample cleanup or sample preparation. Many significant factors should be considered while evaluating analytes in biological matrices, including: (1) Examination of the stability of analyte in blood and plasma. (2) The safe storage of samples in appropriate conditions, (3) Using suitable containers because unsuitable containers may cause medications to be lost or contaminated. Due to adsorption to the silica silanols, extremely polar compound glass tubes, for example, are not appropriate. (4) Reproducible sample preparation technique with excellent recovery. MIP methods may be the best choice for sample preparation since they are stable under a broad variety of circumstances and provide for flexibility in determining the optimal experimental conditions for sample cleanup (Ashri and Abdel-Rehim 2011; Zhou et al. 2017).

Measurement of biological components such as drugs, biomarkers, hormones and also pesticides is of outmost importance for medicine and environmental health. Hence, common methods development or inventing new methods in order to achieving high accuracy, reproducibility, simplicity and cost effectiveness are in the progress. MIP techniques have an extraordinary potential to be used as a clinical method for analysis of specific components. Below, we present some cases of their application in bioanalysis.

Inhibitors

Metabolic inhibitors and receptor antagonists are essential tools in molecular life sciences. Because enzymes carry out their tasks with fidelity, from aiding central route metabolism to driving signal transmission, catalysis is at the heart of most cellular activities. Simplification the study of
complex cellular processes using inhibitors and antagonists is extremely attractive, and this might be accomplished by inhibiting specific enzymes and/or receptor-mediated signaling. As a result of using inhibitors, a process will be connected to an inhibitor-sensitive enzyme or an antagonist-sensitive receptor, which provides an efficient method of limiting the influence of competitive pathways, which may otherwise conceal mechanistic properties of a reaction or experimental approach (Purich 2017). Various advancements for discovering a high selective extraction technique for a range of inhibitors such as venlafaxines, sitagliptin, fluoxetine, and others are thoroughly examined by scientists. As mentioned below, using techniques such as MISPE/UHPLC-MS/MS, magnetic adsorbents on MIP-SPE, MISPE coupled with ZIC-HILIC and MC/GO on MIP-SPE are highly appropriate for bioanalysis of inhibitors in plasma, urine and serum.

Venlafaxine (VEN) and its active metabolite, O-desmethylvenlafaxine (ODV), are selective inhibitors of serotonin-norepinephrine reuptake (SNRIs). VEN is generally used for adults to treat severe depression, generalized anxiety, phobias, and social anxiety disorders. VEN overdose, on the other hand, can induce symptoms such as hypertension, serotonin toxicity, seizures, or cardiac conduction disorders, necessitating therapeutic monitoring of this medication. VEN undergoes substantial metabolization to one main active O-desmethyl metabolite and two minor metabolites, which are subsequently combined to create O-desmethylvenlafaxine (ODV), N10 desmethylvenlafaxine (NDV), and N,O-didesmethylvenlafaxine (NDV) (Miranda et al. 2016). Analysis of VEN, ODV, and NDV in plasma samples by molecularly imprinted solid phase extraction coupled via UHPLC-MS/MS (MISPE/UHPLC-MS/MS) is performed by Miranda et al. (2016). Ethylene glycol dimethacrylate, metacrylic acid, 2,2-azobisisobutyronitrile, toluene and VEN were used as crosslinker, monomer, initiator, porogen solvent and template, respectively. A linear concentration interval was obtained as a result of MISPE/UHPLC-MS/MS approach ranging from 3 to 700 ng mL\(^{-1}\) of VEN, from 5 to 700 ng mL\(^{-1}\) of ODV, and from 3 to 500 ng mL\(^{-1}\) of NDV, with a correlation coefficient greater than 0.995. The method’s accuracy displayed relative standard error values (RSE\%) ranging from -11.8 to 16.01%. Analyzing of VEN in other biological samples such as serum and urine, is reported by using MIP-SPE as a selective extraction method and spectrofluorometric determination by Madrakian et al. (2015) which presented a VEN-imprinted polymer layer that was coated onto the surface of magnetite nanoparticles. The produced magnetic adsorbent dispersed well in water medium and could be readily magnetically isolated from the medium after loading with the adsorbate. The loaded VEN was readily desorbed with methanol and HCl and measured spectrofluorometrically at 598 nm in the linear concentration range of 2–400 ng mL\(^{-1}\).

Recently a new water-compatible molecularly imprinted solid-phase extraction (MISPE) technique coupled with zwitterionic hydrophilic interaction liquid chromatography (ZIC-HILIC) for selective extraction and detection of sitagliptin in urine and serum is developed by Rao et al. (2011). Sitagliptin is an orally active, strong, and specific inhibitor of dipeptidyl peptidase IV (DPP-IV) which is used to treat type 2 diabetes. It also leads to the growth of insulin-producing \(\beta\)-cells in pancreatic islets and improves glycemic control. The bulk of sitagliptin is eliminated in urine unchanged.

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**Fig. 4** Schematic illustration for preparation processes of MIP-GO/Chm (Barati et al. 2017). Permission License Number: 5264280668643
a result, developing analytical techniques capable of detecting sitagliptin at low biologically active concentrations is critical not just to comprehend its pharmacological mechanism but also for remedial medication monitoring.

Fluoxetine (FXT), another kind of inhibitors, is the most commonly used as a selective serotonin re-uptake inhibitor (SSRI) antidepressant medication in the world. It has a lengthy elimination half-life of one to several days, and approximately 11% of the dosage is excreted as unmodified fluoxetine. As a result of the excessive use of this drug, there is a risk of its residue spreading in natural waterways. For accurate examination the amount of this inhibitor in biofluids and waters, as illustrated in Fig. 4, Barati et al. (2017) synthesized and characterized MIPs on magnetic chitosan/graphene oxide (MC/GO) for selective isolation and preconcentration of fluoxetine from environmental and biological samples (Figs. 5, 6 and 7).

The aforementioned researches’ findings demonstrated that MIP sorbents may be utilized to successfully assess a variety of inhibitors with excellent accuracy and selectivity.

Natural compounds

The major phytocannabinoids found in cannabis sativa are cannabidiol (CBD) and Δ9-tetrahydrocannabinol (Δ9-THC). While Δ9-THC is the major psychoactive component, CBD has been studied for its potential to treat a variety of diseases including Depression, Parkinson, Multiple Sclerosis, Huntington, Epilepsy, Hypoxia–ischemia lesion, Anxiety, Pain and Alzheimer. Cannabidiol has been linked to neuroprotective qualities implicated in neurodegenerative disorders. Such qualities minimize anxiety, nightmares, and the prevalence of violent behavior. As a result, CBD may enhance the psychiatric degree of Parkinson’s disease patients, who do not have psychiatric comorbidities. CBD heating in some acidic solutions leads in certain acids catalyzing cyclization inside the CBD molecule, yielding Δ9-THC under experimental circumstances. However, the oral conversion of CBD to Δ9-THC in human beings does not seem to occur (Marchioni et al. 2020).

Many developments for the purpose of cannabinoids determination in body and biofluids are reported such as MIP-in-tube-SPME/UHPLC-MS/MS technique for detecting...
CBD and Δ9-THC in plasma (Marchioni et al. 2020) which could be reused over fifty times without affecting extraction efficiency significantly and also the development of MIP-MEPS for a successful extraction of 11-hydroxy-Δ9 tetrahydrocannabinol, Δ9-tetrahydrocannabinol and 11-nor-Δ9-tetrahydrocannabinol-9-carboxylic acid by liquid chromatography and tandem mass spectrometry (Sartore et al. 2020).

**Biomarkers**

Biomarkers are characteristics which can be extracted and analyzed as an indicator of biological responses to an exposure or intervention, including therapeutic interventions. Diverse applications such as risk estimates, disease screening and detection, diagnosis, prognostic estimates, therapeutic benefit predictions and disease monitoring have been introduced. Cancer-based proteins, gene mutations, deletions, rearrangements and additional copy numbers of the genes are the most popular biomarkers (Ou et al. 2021). Many researchers have made efforts to improve MIP-based bioanalysis methods for biomarkers (such as bilirubin (BR), L-tyrosine (Tyr), sarcosine, globotriaosylsphingosine (lysoGb3), glucosylsphingosine (GlcS), galactosylsphingosine (GalS), L-Hydroxyproline (Hyp) and Mandelic acid (MA). Some of which are presented in this section) which are summarized in the following.

Bilirubin (BR) is a bioactive molecule generated by the metabolism of hemoglobin. The serum BR level is an important liver function indicator and has recently been designated as a lung cancer biomarker by the American Association for Cancer Research. Hence, developing a selective, easy, and robust technique for extracting and detecting BR from biological fluids is critical. For this reason, besides other new techniques in recent years, the technique; a needle trap using a molecularly imprinted sol–gel xerogel for on-line microextraction of bilirubin combined with liquid chromatography tandem mass spectroscopy (On-line- NMSX-MEPS/ LC–MS/MS) is introduced by Moein et al. (2014a) in 2014. Needles prepared in this technique could be used for roughly 100 extractions. The detection limit and the minimum quantity limit were found by utilizing plasma or urine samples, respectively, to be 1.6 and 5 nM in the range of 5–1000 nM standard calibration curves by extraction recovery of approximately 80%.

Hippuric acid (HA) is a molecule that has been identified as a lung cancer biomarker in both urine and plasma. Many attempts have been made in order to discover high-accuracy methods for analyzing this biomarker to be as clinical method. In this regard, two developed methods are reported by Moein et al. (2014b) and Mehran Javanbakht et al. (2015b) such as MIP sol–gel polysulfone membrane-MEPS in the on-line connection with LC–MS/MS and three-phase molecularly imprinted sol–gel based hollow fiber membrane liquid-phase, respectively, for extraction and microextraction of HA from plasma and urine samples. Several critical factors were carefully examined throughout the membrane preparation process to find the optimum extraction conditions for the first developed method including; determining the best template-to-precursor ratio, using variety of template (HA) and precursor concentrations, the influence of varying quantities of TFA as a catalyst in the sol–gel process and also the solution's "pass-time" for developing a thin layer of imprinted sol–gel on the membrane surface which was determined to be 5 times with a 10-min duration for immersing the polysulfone membrane in the imprinting sol–gel solution. These optimizations gradually resulted recoveries higher than 91% in the linear range of 1–1000 nM in both plasma and urine. The modification of a polysulfone hollow fiber membrane using an in situ molecularly imprinted sol–gel process (as a novel and one-step technique) was created and examined in the second developed method. In this regard, the inorganic precursor, 3-(propylmethacrylate) trimethoxysilane (3PMTMOS) was utilized to create molecularly imprinted sol–gel. According to the results, this method can be used for at least 50 extractions without significantly reducing extraction efficiency by achieving recoveries more than 89% in the linear range of 1–2000 nM in both urine and plasma samples (Moein et al. 2014b, 2015b).

L-Tyrosine (Tyr) is an amino acid that plays a key function in a variety of biomedical processes. It was recently...
discovered to be effective as a lung cancer biomarker. Finding a dependable, robust, reproducible, and selective technique for separating Tyr from biological matrices is a significant issue. Therefore, for Tyr detection and extraction, many analytical equipment and sample clean-up techniques were devised. In this regard, in situ monolithic molecularly imprinted polymer sol–gel packed tips (MMSTs/LC–MS/MS) were developed and implemented for the extraction of the lung cancer biomarker L-tyrosine (Tyr) from human urine and plasma samples. Several extraction parameters were examined, including precondition, washing, and elution solutions, pH, and time. In addition, the extraction recovery (ER) and enrichment factor (EF) were investigated (Moein et al. 2014c). As a result, Tyr underwent total rebinding/elution at a pH of 6.0, which is close to its isoelectric point, providing a plausible explanation for the findings reported. The technique validation revealed good regression correlation coefficients ($R^2 = 0.996$) for urine and plasma samples with concentration ranges of 5–1000 and 1–1000 nM, respectively. The results demonstrated that the created approach is more convenient, stable, durable, and repeatable than earlier equivalent methods.

As prostate cancer is one of the most common kinds of tumor illness in men, scientists are paying close attention to prostate-cancer indicators like sarcosine, especially its extraction and analysis in blood or urine samples (Moein et al. 2015c). Recently two methods for extraction and analysis of sarcosine including DMMIP-MTCIL–MDSPE/UHPLC–MS/MS and DMIP-MEPS/LC–MS/MS are introduced by Chen et al. (2021) and (Moein et al. 2015c) respectively. The DMMIP–MTCIL–MDSPE/UHPLC–MS/MS method for the determination of sarcosine in human urine by is developed by utilizing 12-plex chemical isotope labeling (MTCIL360/361/362/363/364/365/375/376, and 378) which initially developed and synthesized by Chen et al. (2020). The above-studied analytes, Globotriaosylsphingosine (lyso-Gb3) as a biomarker in plasma. As an internal standard, LMT359-labeled lyso-Gb3 was employed. This technique has the benefits of excellent sensitivity, selectivity (triple recognition), accuracy (recovery 93.5–108.8%), and throughput (8 samples in a single run) (Hu et al. 2020). By this technique in other report, an 8-Plex Amine-reactive Mass Difference Tags (M360/361/362/373/375/378-AMDTs) were developed and synthesized, and gradually utilized to label glucosylsphingosine (GlcS) and galactosylsphingosine (GalS) in separate 8 plasma samples (Chen et al. 2020). The above studied analytes, Globobriaosylsphingosine (lyso-Gb3), glucosylsphingosine (GlcS) and galactosylsphingosine (GalS) are reliable biomarkers of fabry, gaucher and krabbe diseases. By promoting this approach, the extraction of L-Hydroxyproline (Hyp), a potential indicator for early clinical diagnosis of liver fibrosis, is investigated (Zhu et al. 2020). In this study, 4-plex stable isotope labeling derivatization combined with dummy magnetic molecularly imprinted polymers (QSILD-DMMIPs) was synthesized. The new series of QSILD reagents are in the format of d0/d1/d2/d3-6-N-methyl-rhodamine 6G-N-hydroxysuccinimidyl (d0/d1/d2/d3-MRSF). In the optimal condition, linearity (0.2–100 ng mL$^{-1}$), LOD & LOQ (0.05 and 0.2 ng mL$^{-1}$), precisions results (1.2–7.9%) and recoveries of Hyp (97.9–102.3%) are remarkable.

The International Agency for Research on Cancer (IARC) and the US Environmental Protection Agency (EPA) both classify benzene as a category I
carcinogen. Benzene is used in a variety of industries to create other compounds. As benzene can enter the body through the skin, biomonitoring should be regarded as an additional technique for determining the relative contributions from all exposure pathways when assessing a worker’s total exposure. Trans,trans-Muconic acid (tt-MA) is a second biomarker that has been used as a biological exposure index (BEI) (Soleimani et al. 2017). This issue has been considered by scientists, who have proposed three techniques such as MIP-SPE/HPLC–UV, MIP-DLLME/GC–MS and MIP-MEPS/HPLC–UV for extracting and analyzing this biomarker. For comparison MIP-SPE/HPLC–UV and MIP-MEPS/HPLC–UV are proposed as an additional technique for determining the relative contributions from all exposure pathways when assessing a worker’s total exposure.

For more in-depth study, in our earlier review paper, a comprehensive evaluation of MIP synthesis methods and their use in the extraction and microextraction of cancer biomarkers is provided (Suzaei et al. 2022).

Anesthetic drugs

The mechanisms of popular anesthesia represent one of the great unsolved troubles of classical neuropharmacology. The chemical, physical, and pharmacological characteristics of anesthetics vary greatly and because of the broad range of targets, it is clear that dealing with anesthetics pharmacologically is not the same as dealing with most other medicines used in pharmacology. There are several molecular targets of anesthetic action in the central nervous system, but many more are still to be identified. The identification of these novel targets may lead to the development of a new class of medicines that can be utilized to treat drug-resistant anesthesias (Bischoff et al. 2008).

Local anesthetics (LA) are weak bases with a lipophilic aromatic ring connected to a hydrophilic tertiary amine through an ester or amide bond. When administered to a nerve axon, LA produces a transient blockage of neuronal transmission. Cocaine was the first LA discovered by Albert Niemann in 1860, and many different types of LAs are now synthesized for clinical application (Perrin et al. 2020). Fentanyl (N-(1-phenethyl-4-piperidyl) propionanilide) is a powerful synthetic (man-made) narcotic analgesic that is widely applied in the operating room and intensive care unit for anesthesia and analgesia. It is used extensively during preoperative, induction, maintenance and postoperative surgeries for purposes of neuroleptic analgesia and sedation. Fentanyl has 50–100 times the potency of morphine. The blood concentration of these substances is below the limit of detection (LOD) of most analytical equipment. Because of the poor concentration of this analyte in plasma and urine, cleaning and sample preconcentration are required prior to instrumental analysis.

In this regard, studies on many anesthetic drugs such as fentanyl, lidocaine, ropivacaine, mepivacaine and bupivacaine extracting from biofluids are reported by Bagheri et al. (2013) and Daryanavard et al. (2013). Fentanyl was extracted from urine and plasma. The Sol–gel method was utilized in this work to successfully produce a molecularly imprinted xerogel (MIX) for fentanyl on the inner surface of a copper tube. The tube was first treated with self-assembly monolayers of 3-(mercaptopropyl) trimethoxysilane, and then [3-(2,3-epoxypropoxy)-propyl]-trimethoxysilane was used as a precursor for acidic imprinting of the template molecule (MIX-SPME/HPLC–UV) (Bagheri et al. 2013). In other report, microextraction by packed syringe (MEPS)

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was coupled with LC–MS/MS especially for determination of local anesthetics such as lidocaine, ropivacaine, mepiva- 
caine and bupivacaine (four local anesthetics drugs) in plasma and urine samples (Daryanavard et al. 2013). For the first method, the linearity was in the range of 5–5000 µg L⁻¹, LOD and LOQ were found to be 3 µg L⁻¹ and 5 µg L⁻¹, respectively, and the proposed technique was easily applied to urine and plasma samples spiked with the analyte, with relative recovery percentages of up to 85 percent for the spiked samples. For the second method, pentycaine was employed as a template, and results demonstrated linearity in the range of 5.0–2000 nM for all targets, with a correlation coefficient (R²) of 0.999 or higher. Recoveries for all analytes investigated varied from 60 to 80%. Similar to earlier methods that combined MIPs and MEPS techniques, they may be used for 100 extractions before being abandoned.

**Antimicrobial substances**

According to a report by the London School of Economics, bacterial and parasitic diseases are the second cause of mortality in the globe. Due to the advent of drug-resistant "superbugs," such as staphylococcus aureus (MRSA) methi- 
cillin-resistant, traditional antibiotics including penicillin and its derived products may become obsolete. Pharmaceutical companies and researchers are continuing to investigate novel and effective antibacterial compounds to address this challenge (Bycroft and Payne 2013). Recently, there has been a notable increase in the use of high-efficiency novel methods for bioanalysis of antimicrobial compounds using MIP techniques, such as MMISPE, MIPF–SPME, MIP–MSPE, MIP–SPE–boronate affinity based, MIP–SPE, MMidSPME, MIP–SPE, and so on. These methods have been used to extract and analyze a variety of antimicrobial substances such as parabens, levofloxacin, chlorampheni- 
col, florfenicol, thiamphenicol, fluoroquinolones, linezolid, gatifloxacin, tylosin, amoxicillin, cefazidime, melatonin, 
cefotaxime, dapptomycin, ciprofloxacin, fluconazole, clinda- 
mycin, gentamicin, linezolid, moxifloxacin and metronida- 
zole in blood, plasma, urine and serum samples (Pajewska-
Szymt et al. 2020; Meng and Wang 2019; Wei et al. 2016; 
Mirzajani and Kardani 2016; Szultka et al. 2012; Xiao et al. 
2013; Zeng et al. 2021; Parisa and Ameneh Porpham 2020). The procedures that have been employed for bioanalysis of parabens and levofloxacin are explained in the following paragraphs.

Levofloxacin has a vast antibacterial action against both Gram-positive and Gram-negative bacteria. Infectious ill- 
nesses, such as community-acquired pneumonia and acute exacerbation of chronic bronchitis have widely been treated. This medication is one of the most widely used third-gener- 
ation quinines, with a very minimal risk of side effects (Meng and Wang 2019). Among all quantification methods for levofloxacin determination in human plasma, Meng and 
Wang (2019) reported Deep eutectic solvents (DESs) based 
MIP-MEPS coupled with UHPLC with satisfactory results. As a porogen, deep eutectic solvents (DESs) were utilized to 
preserve water-compatible molecularly imprinted polymers (MIPs) using a pseudotemplate. The DESs are made up of 
charged species and have intraliquid structural characteristics. Choline chlorideethylene was used as the porogen in this work to produce DESs–MIP’s. Levofloxacin’s highest 
binding capacity on DESs-MIPs in methanol and water was clearly 0.077 and 0.216 mol g⁻¹, respectively. The DESs- 
MIPs were used as adsorbing materials in microextraction by packed sorbent (MEPS), and the DESs-MIPs-MEPS set-
tings were optimized, yielding the following observations; 
the linearity over 0.05–10 µg mL⁻¹ with coefficient of correl-
ation equal to 0.9988., LOD and LOQ were 0.012 and 
0.04 µg mL⁻¹, respectively and the accuracy of the sug-
gested approach ranged between 95.3% and 99.7% at three 
spiking levels, with interday and intraday relative standard 
deviations of 8.9 percent. In the investigation of pH, the pH 
of the loading sample was optimally between 6.0 and 8.0, 
which corresponded to the pH of human plasma.

Parabens are esters of p-hydroxybenzoic acid with differ-
ent alkyl groups, including methyl-(MeP), ethyl-(EtP), prop-
ynyl-(PrP), and butyl-(BuP) paraben. According to studies, 
they may have harmful effects on the human body, producing 
hormone abnormalities or skin allergies. Since parabens are 
widely used as additives in personal care items such as sham-
poos, bath gels, and body lotions, there is a need to discover 
the best method for analyzing parabens and monitoring their 
presence in the environment and, in particular, biological 
samples (Pajewska-Szymt et al. 2020). Hence Souza et al. 
(2016) and Pajewska-Szymt et al. (2020) separately reported 
two developed methods including MIP-RAM-in-tube-SPME/
UHPLC-MS/MS and MIPs-HPLC-FLD by, respectively. The method, MIP-RAM-in-tube-SPME/UHPLC-MS/MS is 
developed for detecting parabens in breast milk samples. This new molecularly imprinted polymer is modified with 
restricted access material (a hydrophilic external layer) 
(MIP-RAM) which is synthesized via polymerization in situ 
in an open fused silica capillary. MIP-RAM capillary, used 
as sorbent for in-tube SPME, established specific interac-
tions with parabens present in milk samples. This technique produced linear ranges ranging from 10 (LLOQ) to 
400 ng mL⁻¹ with coefficients of determination greater than 0.99. The last method, MIMPs- HPLC-FLD is also de-
developed for isolation of parabens from breast milk. Magnetic 
molecularly imprinted polymers (MMIPs) are synthesized 
as a sorbent in solid phase extraction with 17β-estradiol as 
a template molecule in the production of imprinted poly-
mers. After determination in optimum condition by HPLC-
FLD, the LOD and LOQ were very low in the range of 1.1–2.7 ng mL⁻¹ and 3.6–8.1 ng mL⁻¹, respectively.
Anti-inflammatory drugs

Nonsteroidal anti-inflammatory medicines (NSAIDs) are a class of medications with varying structural and pharmacological characteristics but a common method of action. Despite their comparable toxicity profiles and mechanisms of action, they interact with the cyclooxygenase enzyme in somewhat different ways. Aryl alkanoic acids (indomethacin, diclofenac, sulindac, nabumetone), 2-arylpropionic acids (profens) and salicylates (aspirin) are the four types of NSAIDs (Al-kaf 2017). Many developed methods are used for a selective extraction of anti-inflammatory drugs including 3-D MI-IPN sorbent MEPS/HPLC–UV, On-line-EC-MIP-in-tube SPME/HPLC–UV, MIP-SPE/HPLC–DAD, EC-MIP-SPME/IMS and Chitosan-MIP-SPE/UV-Spec separately and respectively by Asgari et al. (2017), Asiabi et al. (2016), Martinez-Sena et al. (2016), Alizadeh et al. (2014) and Mabrouk et al. (2020).

The 3-D Molecular imprinted interpenetrating polymer network sorbent-MEPS method (3-D MI-IPN sorbent MEPS/HPLC–UV) developed in order to measuring and determining carbamazepine, dexamethasone and naproxen as anti-inflammatory drugs in urine samples. Carbamazepine, as the MIP template along with naproxen and dexamethasone were examined to prove the MI-IPN selectivity and efficiency by analyzing urine samples. Due to the presence of two-separated interlocked polymeric networks, suitable gaps inside the 3-D structure were formed to precisely assign the necessary template for a convenient MIP operation (Asgari et al. 2017). Selective extraction and determination of indomethacin as an anti-inflammatory drug in urine, blood and plasma is done by on-line-electrochemically controlled-MIP-in-tube-solid phase micro extraction (On-line-EC-MIP-in-tube SPME) combined with HPLC–UV method. Using an electrical potential can enhance extraction efficiency and allow for more straightforward modification of extraction system parameters such as clean-up, selectivity, efficiency and rate. A new molecularly imprinted polymer coated tube was created and used for indomethacin extraction to improve the selectivity and application of this technique (Asiabi et al. 2016). The method MIP-SPE/HPLC–DAD is utilized to analysis of ketoprofen, naproxen, diclofenac, and ibuprofen as anti-Inflammatory targets. By above method in the linearity ranged 0.05–10 mg L⁻¹ in urine sample, recoveries ranges obtained 80–137%, 86–131%, 93–128% and 80–114% for ketoprofen, naproxen, ibuprofen and diclofenac, respectively (Martinez-Sena et al. 2016). Gradually methods EC-MIP-SPME/IMS and Chitosan-MIP-SPE/UV-Spec were used for microextraction of ibuprofen and ketorolac, respectively (Mabrouk et al. 2020; Alizadeh et al. 2014).

Addictive drugs

Addiction is a chronic disease characterized by a three-stage cycle of binging/intoxication, withdrawal/negative affect, and preoccupation/anticipation. These levels respectively include neuroadaptations in brain circuits involved in incentive salience and addiction development, stress overload and reward deficit, and executive function (McGinn et al. 2021).

Methamphetamine (MAMP) and Amphetamine (AMP) are stimulants of the central nervous system that cause euphoria, hallucinations, enhanced alertness, and wakefulness. The drug’s powerful reinforcing and addictive effects lead to drug addiction as well as tolerance to the drug’s psychotropic effects, which leads to the usage of hazardous doses. Most nations classify 3,4-methylenedioxymethamphetamine (MDMA or ecstasy) as an illegal drug due to the warnings of permanent harm to the central nervous system. Methadone, on the other hand, is primarily utilized as a synthetic opioid in the treatment of opiate addiction. It is critical for patients to have their plasma concentrations monitored in order to correctly adjust their daily dosage. MIPs researchers are actively developing a fast, selective, and low-cost method for extracting and identifying methadone in routine and clinical analyses of these medicines. Such developed methods for determination of addictive drugs are SPME-fiber-based MIP, MIP-INAT, MIP-MEPS and MIP-sol–gel tablet-μSPE/LC–MS/MS. The two first methods are developed by Djozan et al. (2011, 2012) for detecting of MAMP from human saliva and determination of MAMP, AMP and ecstasy in human urine, respectively. The second method is based on a solvent-free and on the usage of a molecularly imprinted polymer (MIP) and an inside-needle adsorption trap (INAT).

Mohamed Abdel-Rehim et al. reported many papers to indicate their efforts on leading to a selective, rapid, inexpensive and fast approach appropriate for forensic and clinical bioanalysis of amphetamine and methadone in most common biofluids. Determination of methadone in human plasma (El-Beqqali and Abdel-Rehim 2016) and amphetamine in human urine (El-Beqqali et al. 2017) have been analyzed by MIP-sol–gel-tablet toward μSPE using liquid chromatography and tandem mass spectroscopy (MIP-sol–gel tablet-μSPE/LC–MS/MS) in Mohamed Abdel-Rehim group. The MIP-sol–gel was produced as a thin layer on polyethylene material in tablet form in these investigations. The template was methadone-d₉, and the precursor was 3-(propylmethacrylate)-trimethoxysilane. Each tablet may be utilized twenty times for the extraction and desorption durations of just 10 and 6 min, respectively.
Hormones

Hormones are chemical messengers that transmit a signal from point A (secretion) to point B (organic action) inside a physiological system. The hormone is biosynthesized (and perhaps, but no longer always, stored) inside distinct cells associated with an anatomically defined endocrine gland. It flows via the bloodstream to one or more target cells, which are distinguished by the presence of a particular high affinity receptor (Norman et al. 2015). Application of molecularly imprinted polymers as sorbents for extraction of hormones from various matrices has been widely investigated (Mpupa et al. 2021). Here, we summarize recent studies specifically extracted from biological samples.

Endocrine disrupting chemicals (EDCs) have piqued the interest of the scientific community. Endocrine disruptors are implicated in a broad variety of negative health consequences, including fertility disorders, cardiovascular disease, obesity, diabetes, and cancers. A unique concern is associated with the low-dose, long-term and combination effects of EDCs subsequently to early exposure in the

Table 1  Validation parameters in serum and urine (Bousoumah et al. 2015)

| Serum | Linearity $R^2$ | Intra-day precision RSD (%) | LOD µg L$^{-1}$ | LOQ µg L$^{-1}$ |
|-------|----------------|----------------------------|----------------|----------------|
|       | 0.1–50 µg L$^{-1}$ | $1^a $ µg L$^{-1}$ | $5 $ µg L$^{-1}$ |       |       |
| $n = 5$ | $n = 3$ | $n = 5$ | $n = 3$ |       |       |
| E1    | 0.962          | 8.7                      | 10.7           | 0.07           |
| α-E2  | 0.9858         | 5.8                      | 15.4           | 0.08           |
| E3    | nd             | 16.7                     | 11.6           | 1              |
| β-E2  | 0.9924         | 1.7                      | 14.9           | 0.04           |
| EE2   | 0.999          | 5.9                      | 17.4           | 0.06           |
| OP    | nd             | nd                       | 9              | 0.04           |
| NP    | nd             | nd                       | 7.4           | 0.06           |
| BPA   | 0.9893         | 4.8                      | 10.9           | 0.01           |
| BPS   | nd             | 33.3                     | 49.2           | 0.09           |
| COU   | nd             | 54                       | 27.3           | 0.51           |
| ENT   | 0.9986         | 10                       | 11.9           | 0.16           |
| GEN   | nd             | 59.4                     | 34.3           | 0.7            |
| DES   | 0.975          | 13.9                     | 13.1           | 0.03           |
|       | 0.25           | 0.9953                   | 4.7            | 28.6           |
|       | 0.3            | 0.9964                   | 1.4            | 24.8           |
|       | 3.4            | 0.9889                   | 15.7           | 11.9           |
|       | 0.15           | 0.9989                   | 2              | 23.4           |
|       | 0.2            | 0.9937                   | 2.5            | 27.5           |
|       | 0.15           | nd                       | nd             | 25.6           |
|       | 0.2            | nd                       | nd             | 19.7           |
|       | 0.04           | 0.9982                   | 4.4            | 35.1           |
|       | 0.3            | nd                       | 35.2           | 20             |
|       | 1.7            | nd                       | nd             | nd             |
|       | 0.55           | 0.9799                   | 24.1           | 17.5           |
|       | 2.4            | nd                       | nd             | nd             |
|       | 0.1            | 0.9966                   | 3.6            | 16.2           |

nd not determined

$^a$20 µg L$^{-1}$ for estrone, β-estradiol, estriol and enterolactone

$^b$20 µg L$^{-1}$ for enterolactone and 50 µg L$^{-1}$ for estriol

Fig. 8 Recovery profile for targeted estrogenic compounds in serum a and urine b at 5 µg mL$^{-1}$(Bousoumah et al. 2015). Permission License Number: 5264300065359

Hormones are chemical messengers that transmit a signal from point A (secretion) to point B (organic action) inside a physiological system. The hormone is biosynthesized (and perhaps, but no longer always, stored) inside distinct cells associated with an anatomically defined endocrine gland. It flows via the bloodstream to one or more target cells, which are distinguished by the presence of a particular high affinity receptor (Norman et al. 2015). Application of molecularly imprinted polymers as sorbents for extraction of hormones from various matrices has been widely investigated (Mpupa et al. 2021). Here, we summarize recent studies specifically extracted from biological samples.

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course of the perinatal period (fetus, pregnant women, newborn). Estrogenic compounds are a particular source of concern among EDCs. Natural estrogens, synthetic estrogens, phytoestrogens, and several types of environmental contaminants are all included (Bousoumah et al. 2015). Attempts to discover and develop extraction methods for estrogenic compounds led to an increase in multi-residue methods that allow for the high throughput and minimal cost simultaneous determination of a broad variety of EDCs with decreased analytical time and cost, which is critical in order to characterize a large number of bioactive compounds. The MIP-SPE technique has been used to extract estrogenic endocrine disruptors from urine and serum with excellent results in both matrices, having recoveries above 70% for the majority of components; reported by Bousoumah et al. (2015). The linearity was determined at three levels of concentration ranging from 0.1 to 50 μg L⁻¹ by spiking urine and serum samples. LOD was in the range of 0.01–1 μg L⁻¹ for both matrices and the LOQ for urine and serum were 0.04–1.8 μg L⁻¹ and 0.04–3.4 μg L⁻¹, respectively. Results are presented in Table 1 and Fig. 8 for all studied estrogenic compounds in this group (Bousoumah et al. 2015) in both serum and urine samples.

Oliveira et al. (2019a, 2019b) in 2019 reported two new methods in different papers for successfully determination of estrogens such as estriol (E3) and estrone (E1) from human urine by Restricted Access Mesoporous Molecularly Imprinted Polymer double coated with Hydrophilic Monomer and Bovine Serum Albumin (RA-MMIP-HM-BSA/HPLC–UV) method and ethinylestradiol (EE2) and estradiol (E2) from human urine by Restricted Access Material combined to Molecularly Imprinted Polymer for selective Magnetic Solid-Phase Extraction (RAM-MIP-MSPE/HPLC–UV) method. The first developed method was linear for each hormone in the concentration range of 100–1100 ng mL⁻¹, with correlation coefficients of 0.9952 and 0.9954 for E3 and E1, respectively and the second improved technique produced linearity for each hormone across the concentration range of 80–1100 ng mL⁻¹, with correlation coefficients of 0.9954 and 0.9971 for E2 and EE2, respectively.

Blockers

Beta-blockers are a class of medications that are widely used to treat cardiovascular diseases such as irregular heartbeats, high blood pressure, and angina pectoris. The occurrence of β-blockers has raised significant worry about their potential chronic toxicity on aquatic species, emphasizing the importance of extensive research into their environmental distribution, destiny, and toxicity (Yi et al. 2020).

Atenolol (ATE) is a cardio-selective β-blocker that is used to treat high blood pressure for lengthy periods of time. However, ATE, like propranolol, has the greatest potential for abuse as a performance-enhancing substance in a variety of sports. As a result, an effective and selective separation approach is required to detect and expose the quantity of ATE within the body. Determination of atenolol from biological samples is considered (Hasanah et al. 2019). Gorbani et al. (2017), reported a determination of atenolol from human urine by using ethylene glycol dimethacrylate, acrylic acid, dichloroethane and dibenzoyl peroxide as a cross-linker, functional monomer, porogen and initiator, respectively. In this study the molecular imprinted solid phase extraction (MI-SPE) was used as sample preparation method. The linearity of calibration curve was in the range of 0.10–2.0 μg mL⁻¹ for the developed method by recoveries of 74.5–75.3%. The LOD and LOQ values were 0.032 and 0.099 μg mL⁻¹, respectively. Efforts on measuring ATE in blood serum are done and many methods have been developed for analyzing atenolol in plasma and urine samples using molecular imprinted solid phase extraction (MI-SPE) (Gorbani et al. 2017; Bodoki et al. 2018; Alizadeh 2014), as example; Hasanah et al. (2019) developed MIP-SPE method and application of UV–Vis spectrophotometry by recoveries of 93.65 ± 1.29%.

Carvedilol, which known as 1-(9H-carbazol-4-yl-oxy)-3-[2-(2-methoxyphenoxy) ethyl] amino]-2-propanol, is a medication authorized for the treatment of congestive heart failure having b- and α1-receptor blocking action (CHF). Carvedilol is effective at protein oxidation, suppressing lipid peroxidation and inhibiting the formation of reactive oxygen species due to its antioxidant activity. It is useful for patients with CHF because it protects the heart. Azodi-Deilami et al. (2014) reported a magnetic molecularly imprinted polymers (m-MIPs) by usage of a magnetic component (Fe₃O₄), and carvedilol as a template molecule for in the solid-phase extraction (MISPE) technique combined with high-performance liquid chromatography (HPLC) for analysis of carvedilol from human blood and plasma samples. The calibration curve for this method was in the 2–350 μg L⁻¹ concentration range with the LOD and LOQ 0.13 and 0.45 μg L⁻¹, respectively and recoveries between 85 and 93%.

Sotalol is a β-blocker that is used to treat rhythm abnormalities (cardiac arrhythmias) and is also used to treat hypertension in certain people. It is an antagonist at both β1 and β2 adrenoceptors. A new technique for extracting tiny amounts of sotalol from human urine samples was reported by Ansari and Karimi (2017). The development of molecularly imprinted solid-phase extraction (MIP-SPE/HPLC–UV) method resulted high recoveries (97–102%) and RSD (<5%) in the linearity of 0.05–100 μg mL⁻¹. LOD and LOQ were 0.01 and 0.04 μg mL⁻¹.

The development of a molecularly imprinted solid-phase extraction sorbent by Yilmaz and Basan (2015) resulted in
the selective extraction of telmisartan from human urine. Telmisartan is a kind of angiotensin II receptor antagonist that is used to treat heart failure and hypertension. Urinary excretion of telmisartan is in the range of 0.1–4%. Results presented good recovery values (76.1–79.1%) and precision values (0.11–1.6%) in the linearity of 0.04–1.40 μg mL⁻¹.

**Multi-functional drugs**

There are many components which have abilities to treat several disorders or may have this potential that we could put them here in multi-functional drugs category. The bioanalysis of multi-functional drugs has been in the consideration of scientists due to excessive usage of some of them and as common drugs in therapeutics. Techniques such as MIP-in-tube SPME/LC-FD, HKUST-1-MOF-Fe3O4-GA-MIP/UV–Vis, MMWCNTs/HPLC–UV, water-compatible-MMISPE/HPLC–DAD, PT-DMIP/HPLC–UV, MIP-SPE/HPLC and PT-MIP-SPME/HPLC–UV are developed in order to extract and analyzing interferon alpha 2a (Chaves et al. 2011), gallic acid (Asfaram et al. 2017), curcumin (Bahrani et al. 2017), risperidone and 9-hydroxyrisperidone (Ji et al. 2018), prednisolone (Arabi et al. 2016), dextromethorphan (Moein et al. 2011) and enkephalind (Li and Li 2015) respectively in biofluids.

The method MIP-in-tube SPME/LC-FD is a fused silica capillary packed with restricted access materials (RAM, C18-BSA) as well as an immunosorbent (monoclonal anti-interferon alpha 2a). It is designed to detect interferon alpha 2a in plasma samples with the goal of therapeutic drug monitoring. In this reason, glycoprotein-imprinted biomaterials that preferentially bind to interferon alpha 2a molecules, were synthesized using a sol–gel method (Chaves et al. 2011). Interferon alpha 2a is a recombinant form of the natural protein and comprises 165 amino acids. A wide range of illnesses such melanoma, hepatitis B and C, leukemia and carcinomas of the renal cells have been under the treatment of these protein (Chaves and Costa Queiroz 2013).

In the interpretation of the second method, HKUST-1-MOF-Fe3O4-GA-MIP/UV–Vis, it was used for measuring gallic acid from urine, plasma and water samples by application of magnetite (Fe3O4 nanoparticles (NPs)) HKUST-1 metal organic framework (MOF) composite as a support for surface imprinting of gallic acid imprinted polymer (HKUST-1-MOF-Fe3O4-GA-MIP) by using vinyltrimethoxysilane (VTMOS) as a cross-linker. This type of MIP was used for the rapid, selective, and sensitive ultrasound aided dispersive magnetic solid phase microextraction of gallic acid (GA) using the UV–Vis’s detection technique (UA DMSPME-UV–Vis). Gallic acid (GA) known as bioactive phenolic acid, has a variety of applications including mutation-resistance, anti-inflammatory, anti-oxygen-free-radical’s, strong anticancer efficacy toward prostate, breast, and lung cancer, and a few commercial applications such as the manufacture of the antibiotic trimethoprim. On the other hand, GA is generated from the basic hydrolysis of tannic acid, which produces toxic effluents that pollute the environment. This large use placed greater emphasis on the researchers to design and develop new material and/or methods to be able to measure GA in an accurate and repeatable manner (Asfaram et al. 2017).

In the method, water-compatible-MMISPE/HPLC–DAD, which is utilized for extraction and measurement of 9-hydroxyrisperidone and risperidone from urine, the water-compatible magnetic molecularly imprinted polymer was used as a sorbent for solid phase extraction coupled with HPLC–DAD. Results display this method as an appropriate saturation magnetization for magnetic separation (< 30 s) with a high selectivity and high adsorption capacity (18 mg g⁻¹). The achieved linearity for both 9-hydroxyrisperidone and risperidone was in the range 1–2000 ng mL⁻¹ with correlation coefficient ≥ 0.991. The detection limit of 9-hydroxyrisperidone and risperidone were 0.24 ng mL⁻¹ and 0.21 ng mL⁻¹, respectively and the recovery rates at three different spike levels varied from 94.6% to 102.4% (Ji et al. 2018).

The purification and analysis of prednisolone from urine by creating a new pipette-tip based on nano-sized dummy molecularly imprinted polymer (PT-DMIP) assisted by ultrasonication was reported by Mehrorang Ghaedi and co-workers. Prednisolone is a synthetic glucocorticoid that is widely used to treat acute rejection episodes in inflammatory diseases including colitis, arthritis, asthma, bronchitis and certain skin rashes. Furthermore, prednisolone is used in organ transplants to reduce the danger of organ injection. The PT-DMIP cartridge was created by filling the tip of the micropipette with a dummy molecularly imprinted polymer (Arabi et al. 2016). The pipette tip-based molecularly imprinted solid-phase microextraction monolith technique was used by Li and Li (2015) to determine enkephalins in human cerebrospinal fluid. In this work, a new molecularly imprinted polymer (MIP) monolith for highly selective extraction of enkephalins was synthesized and produced in a micropipette tip utilizing the epitope imprinting technique. Enkephalins were first recognized as a kind of endogenous opioid around the middle of the 1970s. The first two enkephalins discovered were Leu-enkephalin and Met-enkephalin, two pentapeptides that varied only at the C-terminus. Enkephalins' role in physiological and pathological procedures in the central nervous system (CNS) necessitates the advancement of specialized and ultrasensitive analytical techniques to assist clinical research.
Heavy metals

Occupational toxicologists pay specific attention to determining heavy metals among other hazardous contaminants. Global worry exists as a result of fast industrial growth and the discharge of hazardous chemicals into the environment. Most businesses nowadays utilize heavy metals directly or indirectly, exposing a significant number of people to such elements, particularly heavy metals, through food, water, air, smoking and workplace. For instance, cadmium is mostly utilized in the battery, plating, welding, alloying sectors and semi-conductive. Cadmium is also a non-essential material element in the human body (Panjali et al. 2015). Hence, metal analysis techniques for human matrices have been developed and improved, resulting in excellent accuracy and recovery. Panjali et al. (2015) developed an ion imprinted polymer (IIP), based on coating of a polymer on a Fe3O4 nanoparticle (NP) core, is used as a magnetic sorbent for the preconcentration and determination of the Cd(II) ion level in human urine samples. In optimal condition by applying flame atomic absorption spectrophotometry, recoveries were higher than 80 and lower than 100%. In other report, Fazelirad et al. (2019) explained preconcentration of Cu(II) in water, biological (hair) and agricultural samples by using nanoporous Cu(II) ion imprinted polymer method. The measurement procedure was completed by electrothermal atomic absorption spectrometry. The linearity of this method obtained 0.03–33 µg L−1 by LOD of 0.0087 µg L−1 and RSD 4.3%. Cui et al. (2013) also reported the determination of free Cu(II) in urine and serum samples by restricted accessed material-copper(II) ion imprinted polymer solid phase extraction combined with inductively coupled plasma-optical emission spectrometry. In optimized conditions, the adsorption capacity was 15.9 mg g−1. The linearity ranged from 1 to 100 µg L−1 with LOD 0.17 µg L−1.

Other target compounds

6-mercaptopurine (6-MP), that is extremely utilized as an immunosuppressive and anti-leukemic agent, has necessitated its selective detection in biofluids with its active metabolite 6-thioguanine (TG). Healing drug monitoring of 6-mercaptopurine and its metabolite 6-thioguanine is generally conducted to examine toxicity and effectiveness, particularly when the therapy is not reaching the intended therapeutic effects at the recommended dosages for treatment. As a result, several methods for determining 6-MP and its metabolites in biofluids to disclose their kinetics have been presented (Attallah et al. 2018). Attallah et al. (2018) reported their studies on Extraction and determination of 6-mercaptopurine and its active metabolite thioguanine in plasma, a novel bioanalysis technique (MMI-SPE/LC–MS/MS) has been synthesized as a magnetic molecularly imprinted nanoparticles. The presented MMI-SPE in pH = 5 and via 100 mg amount of Fe3O4@MIP NPs offered as the best technique in comparison to other documented approaches for achieving high extraction recoveries (85.94–103.03%).

Buprenorphine (Bup), a semisynthetic opioid, is commonly utilized for chronic pain treatment and opioid addiction maintenance therapy. The analgesic effect of Bup, which has a molecular structure comparable to morphine, is 20–25 times stronger than morphine. The therapeutic concentration in body fluids is quite low due to modest dosages in typical prescriptions and, on the other hand, the wide tissue dispersion produced by Bup's remarkably high lipophilicity (log P of 4.98). In this study for analysis of Bup in human urine, Habibi et al. (2018) reported a satisfactory result by applying magnetic molecularly imprinted polymer nanoparticles based dispersive micro solid-phase extraction method for extraction and high performance liquid chromatography connected with fluorescence detector for measuring (MMIPNP-d-µSPE/HPLC-FL method). Recoveries of Bup were between 97.4 and 100.3%, in the linear dynamic range of 1–1000 ng mL−1 (R2 = 0.9998).

Coenzyme Q10 (CoQ10) is a powerful endogenous antioxidant and an important cofactor in the mitochondrial respiratory chain. CoQ10 insufficiency is now linked to a variety of diseases, including neurodegenerative and mitochondrial disorders, making early diagnosis and remedy with CoQ10 supplementation critical for patient care. As a result, determining CoQ10 levels in various biofluids is an efficient process. Analysis of CoQ10 through MIP-SPE pretreatment approach is accomplished in urine and liver extract matrices (García Becerra et al. 2019; Contin et al. 2014). In order to measuring CoQ10 from liver extract (Contin et al. 2014), the coenzyme Q0 is used as a template and methacrylic acid, acetonitrile and ethylene glycol dimethacrylate as functional monomer, porogen and crosslinker, respectively. By using HPLC–UV for measurement step, the extraction recoveries were higher than 73.7% with good precision (3.6–8.3%). Analysis of CoQ10 from urine (García Becerra et al. 2019) is done by using HPLC–MS/MS. Results showed recoveries more than 90%.

The most major trace biogenic amine produced in the mammalian brain and peripheral nervous tissues is tyramine (2-(4-hydroxyphenyl) ethylamine). Trace biogenic amines are biologically related to the dopamine, norepinephrine, and serotonin neurotransmitter systems, and have been linked to a wide range of mood, emotion, attention, and cognition problems in humans. Tyramine is a product of tyrosine metabolism after the activation of tyrosine decarboxylase and functions as a biosynthetic intermediate precursor of octopamine. New tyramine receptors have recently been identified. This discovery sparked a flurry of research into the possibility that tyramine has its own neurotransmitter system. Tyramine is found in the mammalian brain at
extremely low levels, ranging from 0.1 to 100 ng g\(^{-1}\) of tissue. After consuming tyramine-rich foods, the intracorporal concentration of tyramine may rise. For the purpose of bioanalysis of tyramine, MIP-SPE/HPLC-FLD method is developed by Dorota Maciejewska et al. specially for analysis of tyramine from bovine serum albumin sample. A computational analysis was utilized in this work to estimate the affinity of the polymer matrix toward tyramine, and a preliminary experimental assessment for the target analyte was performed. The polymer’s experimental analysis toward tyramine was then proceeded. In comparison, the imprinted, non-imprinted, and commercial C18 sorbents recovered 95 ± 2%, 14 ± 3%, and 1.9 ± 0.4% of tyramine from spiked bovine serum albumin samples, respectively, demonstrating significantly higher efficiency than previous techniques. The linearity of the calibration curve was in the range of 2.5–50 µmol·L\(^{-1}\) (\(R^2 = 0.998\)) under optimal conditions (Lulinski et al. 2014).

**MIP-based biosensors**

Biosensors are a strong instrument that is frequently utilized in the examination of biological samples, and they provide several advantages. Biosensors are useful instruments for detecting different analytes, particularly viruses, in clinical diagnosis, food processing, and environmental monitoring. Biosensors are quick and effective tools for detecting illnesses in real time, both qualitatively and quantitatively. The most frequent biosensors used for viral detection are electrochemical and optical (e.g., Surface plasmon resonance (SPR), surface-enhanced Raman scattering (SERS)) and even the usefulness of biosensors on SARS-CoV-2 (the causative agent of COVID-19) has recently been studied (Abid et al. 2021; Zhu et al. 2021). The first biosensor created by Clark and Lyons (1962) to quantify glucose in biological matrices.

Biosensor development has recently been the most appealing research topic due to its ease of use, rapidity, low price, sensitivity, and selectivity in contributing to advancements in next-generation medications such as personalized therapy and ultrasensitive point-of-care detection of disease markers. Biosensors are categorized based on the mechanism of physicochemical transduction or the type of biorecognition element used. Biosensors are categorized as optical, electrochemical, piezoelectric, and thermal based on the transducer. Optical biosensors rely on a variety of optical methods, including fluorescence, absorption, luminescence, surface plasmon resonance (SPR), and others. Electrochemical biosensors have received the greatest attention because of their low detection limit, selectivity, ease of fabrication and operation (Sawant 2017).

MIPs, as a type of sensor identification element, have several commercial applications and a great practical application value in the field of sensor analysis. Because electrochemical sensors offer the distinct benefits of high sensitivities, quick analytical rates, simple device operation, and simplicity of miniaturization, they are ideal for use in medical applications. As a result, molecularly imprinted electrochemical sensors that use MIPs as recognition elements have garnered broad interest and have become a global research hotspot. For instance, various types of magnetic molecularly imprinted electrochemical sensors (MIECS) have been widely developed which are divided into two categories; (1) MIECS based on traditional electrodes (such as; electrochemical sensors coupled with magnetic molecularly imprinted solid-phase extraction, electrochemical sensors with MIP membranes prepared directly on electrodes modified with magnetic nanomaterials and electrochemical sensors with MMIPs modified on electrodes by drop-casting, spin coating, or filling) and (2) MIECS based on magnetically controlled electrodes (such as; MIECS based on self-made magnetically controlled electrodes or devices, MIECS based on commercially available magnetically controlled electrodes and MIECS achieving high-throughput detection using magnetically controlled electrodes) which each of them have been optimized for special analytes and matrices (Yang et al. 2020).

Recently, MIP-based biosensors are highly considered for determination drugs, biomarkers, hormones and etc. in human fluids. For instance, Gajda et al. (2020) determined aripiprazole antipsychotic drug by electropolymerization of new thiophene-carbazole functional and cross-linking monomers used in molecular imprinting polymer. MIP-ari piprazole film-coated electrodes were utilized as extended gates in this study for selective aripiprazole determination using the extended-gate field-effect transistor (EG-FET) chemosensor. In the optimum condition, the dynamic linearity obtained 30–300 pM with LOD of 22 fM. In another report, Abbasy et al. (2020) created a dependable bioanalytical technique based on prostate-specific antigen entrapment in the cavity of molecularly imprinted polymers. As an artificial receptor, electrically-conducting poly [Toluidine Blue] was used in this investigation. It was put together using molecular imprinting techniques and an electrochemical method. Using the DPV method, the bio-device also demonstrated linear response from 1 to 60 µg L\(^{-1}\) and LLOQ of 1 µg L\(^{-1}\),
allowing Prostate-Specific Antigen monitoring in clinical samples. MIP sensors have been used in determination of pain medications. Diouf et al. (2021) described the use of MIP sensors to detect tramadol in spiked saliva and urine. Tramadol (TRA) is a weak opioid analgesic that is used to treat mild to moderately severe pain. However, TRA overdose adverse effects from moderate to death were frequently reported. An electrochemical sensor based on molecularly imprinted conductive polymer was initially improved in this study for non-invasive and quantitative detection, and a voltammetric electronic tongue (VE-Tongue) combined with chemometric techniques was utilized for qualitative analysis TRA. The obtained LOD was 9.42 µg mL\(^{-1}\) in the linear range of 0.01–100 µg mL\(^{-1}\) with a significant recovery more than 90%.

Tryptophan (Trp) is a subset of the 18 essential amino acid groups of human body, and it is a key precursor for the formation of neurotransmitters such as serotonin and niacin, as well as neurohormones such as melatonin. It is worth noting that they cannot be produced in the human body, and according to current studies an excess of Trp in the human body may lead to parkinson’s and alzheimer’s sicknesses. The measurement of Trp in the body prompted scientists to develop a suitable method in this regard. Jingting Luo et al. a satisfactory analysis of Trp in urine excellent recoveries ranging 97–104%. They optimized MIP pre-polymer solution coated on quartz crystal microbalance (QCM) electrode surface for a selective biosensing. The LOD was determined 0.73 ng mL\(^{-1}\) (Prabakaran et al. 2021).

In short, many kinds of MIP-based biosensor analysis developments have been reported for special targets such as paracetamol (acetaminophen) in plasma (Alanazi et al. 2021), glycoprotein in human serum sample (You et al. 2017), uric acid in serum and urine (Göçenoğlu Sarıkaya et al. 2017), heart-fatty acid binding protein in human serum, human plasma, and bovine serum (Sanati et al. 2021), \(\beta\)-amyloid in serum (Pereira et al. 2020) and \(\alpha\) synuclein in human brain organoids (Lee et al. 2020) with high accuracy and recovery which may lead to clinical usage as fast and reproducible approaches. The use of MIPs in biological sensing has also been the subject of recent several review studies (Batista et al. 2021; Kadhem et al. 2021; Ramana-vicius et al. 2022) (Fig. 9).

### Conclusion and future perspectives

MIP techniques have shown high potential of bioanalysis as fast, selective and ultrasensitive in a range of great interest. Hence, the dose of biological components in body is an essential factor in physical and mental human health, monitoring and controlling of these components rate in body either due to the health maintaining and preventing diseases or for treatment purposes are seriously significant. So, the MIP applications in bioanalysis of many important components have been reviewed from literature covering the last decade. To achieve the considered goal of this study, the analyzed components in complex biofluids are categorized into different classes and the prepared Table 2 presents satisfactory results in recoveries, repeatability and wide linearity range with low LODs and LOQs. In addition, the applied MIP-based extraction techniques and MIP based biosensors have been summarized due to their ability of overcoming interfering species in biological samples and evaluating high selectivity and recoveries. Through all MIP-based extraction techniques, SPE, MSPE, SPME and MEPS are the most applied techniques respectively (Fig. 3). Despite The growing trend of papers entitled with MIP applications presented significant results, it is far from the expected rate state. The results of this study and review of published sources shows hormones and antimicrobial substances had...
Table 2: Recent application of MIP based extraction methods in biological analysis of inhibitors, biomarkers, antimicrobial substances, hormones, blockers, multi-functional compounds, natural compounds, heavy metals and kinds of drugs

| Sample Matrix | Target | Template | Extraction method | Analytical techniques | (RSD) % | Recovery % | Linear range (ng mL⁻¹) | References |
|---------------|--------|----------|-------------------|-----------------------|---------|------------|------------------------|------------|
| **Biomarkers** |        |          |                   |                       |         |            |                        |            |
| 1             | Plasma | Galactosyphosphingosine, Glucosylsphingosine | M387-AMDTs-GlcS | DMMIP-dSPE 8-plex | UHPLC-MS/MS | 2.3–11.4 | 96.1–107.2 | 0.009 - 369.31 | Chen et al. (2020) |
| 2             | Serum  | L-Hydroxyproline | ERSF-Hyp | QSILD-DMMIPs-SPE (4-plex) | LC–MS/MS | 1.2–7.9 | 97.9–102.3 | 0.2–100 | Zhu et al. (2020) |
| 3             | Blood  | 2-Aminothiazole-4-carboxylic acid | 2-Aminothiazole-4-carboxylic acid | MIP-HI-d-SPE | LC–MS/MS | 2–5 | – | 30–900 | Giebułtowicz et al. (2019) |
| 4             | Blood  | 2-Aminothiazoline-4-carboxylic acid | 2-Aminothiazole-4-carboxylic acid | MIP-dispersive SPE | HPLC | 1.5–2.7 | 81–89 | – | Luliński et al. (2015) |
| 5             | Urine  | Mandelic acid | Mandelic acid | MIP-MEPS | HPLC–UV | <5.2 | 88.8 | 200–20,000 | Soleimani et al. (2018) |
| 6             | Urine  | Trans, trans-muconic acid | Trans, trans-muconic acid | MIP-SPE | HPLC–UV | 3.3–3.7 | 87–112 | 300–10,000 | Vieira et al. (2012) |
| 7             | Urine  | trans, trans-muconic acid | Trans, trans-muconic acid | MIP-MEPS | HPLC–UV | 3.4–6.6 | >89.8 | 15–2000 | Soleimani et al. (2017) |
| 8             | Urine  | 8-hydroxy-2′-deoxyguanosine | Guanosine | MIP-In-Tube-SPME | HPLC/UV | 1.1–6.8 | 84 ± 3% | 2.83–1501.17 | Zhang et al. (2009) |
| 9             | Serum  | NLLGLIEAK | Z-NLLGLIEA[Nle] | MIP-MSPE | LC–MS/MS | – | – | – | McKitterick et al. (2020a) |
| 10            |        | Z-NLLGLIEA-Nle-OH | Z-NLLGLIEA[Nle] | MIP-RAFT-SPE | – | 100.8 ± 6.2% | – | – | Rossetti et al. (2014) |
| 11            | Plasma | Bilirubin | Bilirubin | On-line-MIP-SPE | On-line-MIP-SPME | LC–MS/MS | 1.2–7.0 | 80 | 2.92–584.66 | Moein et al. (2014a) |
| 12            | Urine  | Bilirubin | Bilirubin | On-line-MIP-SPME | LC–MS/MS | 1.1–6.7 | >91 | 0.18–180 | Moein et al. (2014b) |
| 13            | Plasma | Hippuric acid | Hippuric acid | Online-MIP-PSM | LC–MS/MS | 1.2–4.5 | >89 | 0.18–360 | Moein et al. (2015b) |
| 14            | Plasma | Hippuric acid | Hippuric acid | 3-MSHM | LC–MS/MS | 1.0–6.0 | 88–90 | 0.9–180 | Moein et al. (2014c) |
| 15            | Plasma | L-Tyrosine | L-Tyrosine | MMSTs | LC–MS/MS | 1.0–6.0 | 88–90 | 0.9–180 | Moein et al. (2014c) |
| 16            | Plasma | Sarcosine | Glycine | Online-DMIP-MEPS | LC–MS/MS | 2.9–7.1 | 87 | 3–10,000 | Moein et al. (2015c) |
| 17            | Plasma | Sarcosine | Sarcosine | DMMIPs-12-Plex-Tcil-MDSPE | UHPLC-MS/MS | 2.6–11.5 | 96.1–107.4 | 0.89–1781.86 | Chen et al. (2021) |
| 18            | Serum  | neuron-specific enolase | Z-NLLGLIEA[Nle] | Online-MIP-SPE | HPLC–MS/MS | – | 100.8 ± 6.2% | 7.5–375 | McKitterick et al. (2020b) |
Table 2 (continued)

| Sample Matrix | Target                      | Template                  | Extraction method | Analytical techniques | (RSD) % | Recovery % | Linear range (ng mL⁻¹) | References                        |
|---------------|-----------------------------|---------------------------|-------------------|-----------------------|---------|------------|------------------------|-----------------------------------|
| 19 Urine      | 4-hydroxyphenylacetic acids | 4-hydroxyphenylacetic acid| MIP-SPE           | UPLC-MS/MS            | <4.5    | –          | 25–1000                | Janczura et al. (2021)            |
|               |                             | Phenylacetic acid         |                   |                       |         |            |                        |                                   |
|               |                             | 3-nitrobenzoic acid       |                   |                       |         |            |                        |                                   |
|               |                             | 2-nitrophenol             |                   |                       |         |            |                        |                                   |
| Antimicrobial substances                      |                             |                           |                   |                       |         |            |                        |                                   |
| 20 Plasma    | Levofloxacin                | Levofloxacin              | DESs-MIP-MEPS     | UHPLC                 | ≤8.9    | 95.3–99.7  | 50–10,000              | Meng and Wang (2019)              |
| 21 Breast Milk | Parabens                  | Benzylparaben             | MIP-RAM-in tube-  | UHPLC-MS/MS           | -1.0– 19.0 | 55–80       | 10–400                 | Souza et al. (2016)              |
| 22 Breast Milk | Methylparabens             | 17β-Estradiol             | MMISPE            | LC-FLD                | >8      | 92–102     | 10.28–411.20           | Pajewska-Szmyt et al. (2020)     |
|               | Ethylparaben                |                           |                   |                       |         |            | 9.98–399.20           |                                   |
|               | Propylparaben               |                           |                   |                       |         |            | 19.95–798.00          |                                   |
|               | Butylparaben                |                           |                   |                       |         |            | 20.20–808.00          |                                   |
|               | Benzylparaben               |                           |                   |                       |         |            | 20.16–806.40          |                                   |
| 23 Blood     | Chloramphenicol             | Chloramphenicol           | MMISPE            | HPLC–UV               | 2.7–7.9 | 83.3–99.1  | 0.25–25                | Wei et al. (2016)                 |
|               | Florfenicol                 |                           |                   |                       |         |            |                        |                                   |
|               | Thiamphenicol               |                           |                   |                       |         |            |                        |                                   |
| 24 Plasma    | Fluoroquinolones            | Ciprofloxacin             | MIPF-SPME         | HPLC–UV               | 1.3–6.7 | 97.81–102  | 0.1–40                 | Mirzajani and Kardani (2016)     |
| 25 Plasma    | Linezolid                   | Linezolid                 | MIPF-SPME         | HPLC–MS               | 3.4–11.2| –          | 1000–20,000            | Szulatka et al. (2012)           |
| 26 Serum     | Gatifloxacin                | Gatifloxacin              | MIP-MSPE          | HPLC                  | 3.3–4.9 | 79.1–85.3  | 800–450,000            | Xiao et al. (2013)               |
| 27 Biological samples | Tylosin | Tylosin | MIP-SPE | HPLC–UV | – | 75.6 ± 5.6% | – | Zeng et al. (2021) |
| 28 Urine     | Ceftazidime                 | Ceftazidime               | MIP-SPE           | HPLC–DAD              | 4.1     | >90        | 25–800                 | Parisa and Ameneh Porgham (2020) |
| 29 Urine     | Melatonin                   | Melatonin                 | MMIdSPME          | HPLC–UV               | 0.71–6.02 | 93.07–104.1 | 0.2–4200               | Dil et al. (2021)                |
Table 2 (continued)

| Sample Matrix | Target | Template | Extraction method | Analytical techniques | (RSD) % | Recovery % | Linear range (ng mL⁻¹) | References |
|---------------|--------|----------|------------------|-----------------------|---------|------------|------------------------|------------|
| 30 Blood      | Amoxicillin, Cefatoxime – Ciprofloxacin, Daptomycin Fluconazole, Gentamicin Clindamycin, Linezolid Metronidazole, Moxifloxacin | – | MIP-SPME | HPLC–MS/MS | 0.58–5.01 | 96.08–101.87 | 1000–50,000 | Szultka et al. (2013) |
| 31 Plasma Urine | Meropenem | Meropenem | MIP-SPE | HPLC–PDA | 2.8–5.6 | 83.6–100.6 | 120–800 | Amlashi et al. (2019) |
| Anesthetic Drugs | Fentanyl | Fentanyl | MIX-SPME | HPLC–UV | 5.5–6.5 | > 85 | 5–5000 | Bagheri et al. (2013) |
| 32 Plasma Urine | Lidocaine Ropivacaine | Pentycaine | MIP-MEPS | LC–MS/MS | < ± 14 | 60–80 | 1.17–468.67 | Daryanavard et al. (2013) |
| 33 Plasma Urine | Estrone (E1) Estriol (E3) | Estrone (E1) | RA-MMIP-HM–BSA | HPLC–UV | 1.76 | 79.5±7.1% | 69.5±1.5% | Oliveira et al. (2019a) |
| Hormones | E1, α-E2, E3, B-E2, EE2, OP, NP, BPA, BPS, COU, ENT, GEN, DES | Phenolic template | MIP-SPE | LC–MS/MS | > 70 for a majority of compounds | 100–50,000 | Bousoumah et al. (2015) |
| 34 Urine Serum | EE2, E2 | E2 | RAM-MIP-MSPE | HPLC–UV | > 15 | 98.75±4.02% | 95.73±0.24% | 80–1100 | Oliveira et al. (2019b) |
| 35 Plasma Urine | Catecholamines | 3-Phenylpropylacrylate | MIP-dSPE | UHPLC-MS/MS | – | 58–92 | – | Podjava and Šilaks (2021) |
| 36 Urine Serum | Androsterone Stanolone Androstenedione Methyltestosterone | Testosterone | MIP-SPME | GC–MS | 4.2–14.7 | 80.1–108.4 | 0.08–0.8 | Qiu et al. (2010) |
| 37 Plasma Urine | Epinephrine Norepinephrine Dopamine | Epinephrine | MIPF-SPME | Capillary electrophoresis | 6.0–11.1 | 86–96 | 1.83–109.92 | Zhang et al. (2012) |
Table 2 (continued)

| Sample Matrix | Target | Template | Extraction method | Analytical techniques | (RSD) % | Recovery % | Linear range (ng mL⁻¹) | References |
|---------------|--------|----------|-------------------|-----------------------|---------|------------|-----------------------|------------|
| Urine         | Insulin| Insulin  | MIP-SPE           | HPLC–PDA              | 3.4–4.6 | > 87       | 0.1–270               | Moein et al. (2014d) |
| Serum         | Atenolol| Atenolol | MIP-SPE           | Spectrophotometer     | 0.38–2.05 | 74.5–75.3 | 100–2000             | Gorbani et al. (2017) |
| Plasma        | Sotalol| Sotalol  | MIP-SPE           | HPLC–UV               | 1.85–4.84 | 97.4–102.5 | 50–100,000           | Ansari and Karimi (2017) |
| Urine         | Telmisartan | Telmisartan | MIP-SPE   | Spectrophotometer     | 0.11–1.6 | 76.1–79.1 | 40–1400              | Yılmaz and Basan (2015) |
| Bovine serum  | Propranolol | Propranolol | MIP-dSPME | HPLC                  | 2.3–3.7  | 85.2–97.4 | 0.03–25.93           | Tu et al. (2021) |
| Urine         | Risperidone 9-Hydroxy-risperidone | Risperidone | Water compatible-MMISPE | HPLC–DAD              | > 5.3    | 94.6–102.4 | 1–2000               | Ji et al. (2018) |
| Plasma        | Gallic acid | Gallic acid | Ultra-assisted DMSPME | UV–Vis               | > 3.5    | 98.13      | 8–6000               | Asfaram et al. (2017) |
| Plasma        | Curcumin trace | Curcumin | MMWCNTs          | HPLC–UV               | 0.94–4.44 | > 98       | 0.1–1200             | Bahrami et al. (2017) |
| Plasma        | Dextromethorphan | Dextromethorphan | MIP-SPE  | HPLC                  | 3.2–4.4  | > 87       | 0.3–150              | Moein et al. (2011) |
| Urine         | Prednisolone | Betamethasone | PT-DMIP-SPE | HPLC–UV              | 2.2–8.8  | 89–96.1    | 0.22–220             | Arabi et al. (2016) |
| Human cerebrospinal fluid | Met-Enkephalin | Leu-Enkephalin (Tyr–Gly–Gly–Phe) | Pipet tip-MIP-SPME | HPLC–UV | 1.28–5.9 | 85.1–95.7 | 0.17–286.83 | Li and Li (2015) |
| Plasma        | Interferon alpha 2a | Interferon alpha 2a | MIP-in tube-SPME | HPLC–FD              | 3.0–9.2  | –         | 8–300                | Chaves and Costa Queiroz (2013) |
| EBC           | Valproic acid | Valproic acid | MIP-SPE-DLLME | GC–MS                 | 1.6–5.8  | 82±5       | 0.06–250            | Jouyban et al. (2021) |
| Plasma        | Baicalein | Baicalein | MIP-SPE (SBA-15@MIP) | HPLC–UV             | 2.9      | 94.4       | 20–7990             | He et al. (2015) |
| Urine         | Buprenorphine | Buprenorphine | MMIPNP-d-µSPE | HPLC–FL              | > 10     | 97.4–100.3 | 1–1000              | Habibi et al. (2018) |
| Urine         | Coenzyme Q10 | Coenzyme Q10 | – | MIP-SPE | HPLC–MS/MS              | 4.4–11.1 | > 90      | 3–500                | García Becerra et al. (2019) |
| Sample Matrix | Target | Template | Extraction method | Analytical techniques | (RSD) % | Recovery % | Linear range (ng mL⁻¹) | References |
|---------------|--------|----------|-------------------|-----------------------|--------|-----------|------------------------|-----------|
| Liver         | Coenzyme Q10 | Coenzyme Q0 | MIP-SPE | HPLC-UV | 3.6–8.3 | 70–89 | 7.5–150 µg g⁻¹ | Contin et al. (2014) |
| Plasma        | Amiodarone | Amiodarone | MMIP-SPE Bulk MIP-SPE | HPLC | – | 97.33 | – | Banan et al. (2022) |
| Plasma        | Neurotensin, Neuromedin N | Pro-Tyr–Ile–Leu | Molecularly imprinted monolithic-capillary microextraction | HPLC-UV | 3.7–4.6 | 82.5 | 17–16729 | Lei et al. (2022) |
| Urine         | Phenobarbital | – | MIP-SPME | HPLC-UV | – | – | 20–100000 | Rahimi and Bahar (2022) |
| Urine         | Ribavirin | Ribavirin | MIP-SPE | HPLC-UV | <5 | 93–102 | 500–80000 | Zafarghandi et al. (2022) |
| Plasma        | 6-Mercaptopurine Thioguanine | 6-Mercaptopurine | MMISPE | LC–MS/MS | 0.68–7.99 | 85.94–103.03 | – | Attallah et al. (2018) |
| Serum         | Tyramine | Tyramine | MIP-SPE | HPLC-FLD | – | 95 ± 2 | 342.95–6858.95 | Luliniński et al. (2014) |
| Urine         | Abacavir | Abacavir | MIP-SPME fiber | LC/MS | 3.7–9.7 | – | 0.05–1 | Terzopoulou et al. (2016) |
| Plasma        | Zolpidem | Zolpidem | MIP-SPE | HPLC-FLD | 0.45–2.86 | >90 | 10–100 | Alimohammadi and Pourmosleim (2021) |
| Fetal bovine serum | Proteins | Bovine serum albumin | MIP based on magnetic graphene microspheres | – | – | – | – | Yang et al. (2021) |
| Urine         | p-Aminosalicylic acid | p-Aminosalicylic acid | MMISPE | HPLC-UV | 7.8–10.8 | 92 ± 8.3% | 3–1000 | Bagheri et al. (2016) |
| Plasma        | Haloperidol | Haloperidol | MIP-SPE | HPLC–DAD | 3.8–6.9 | >98 | 2–10,000 | Ebrahimzadeh et al. (2013) |
| Plasma        | Antazoline, Hydroxyantazoline | 2-(4-imidazolyl) ethylamine dihydrochloride | magnetic-MIP-dSPE | LC–MS/MS | >12 | – | 30–3000 | Giebułtowicz et al. (2021) |
| Plasma        | Tricyclic antidepressants | benzyl (3-(10,11-dihydro-5H-dibenzo[b,f]azepin-5-yl) propyl(methyl) carbamate | Thin Film-MIP | LC–MS/MS | >15 | – | 1–500 | Shahhosseini et al. (2021) |
| Urine         | Indomethacin | indomethacin | MIP-EC-In-Tube-SPME | HPLC–UV | 4.3–5.8 | 0.998 | 1–200 | Asiabi et al. (2016) |
| Plasma        | Indomethacin | indomethacin | MIP-EC-In-Tube-SPME | HPLC–UV | 5.8–7.5 | 0.998 | 2–200 | Asiabi et al. (2016) |
| Blood         | Indomethacin | indomethacin | MIP-EC-In-Tube-SPME | HPLC–UV | 7.1–8.4 | 0.996 | 4–200 | Asiabi et al. (2016) |

**Anti-inflammatory drugs**
| Sample Matrix | Target | Template | Extraction method | Analytical techniques | (RSD) % | Recovery % | Linear range (ng mL⁻¹) | References |
|---------------|--------|----------|-------------------|-----------------------|---------|------------|------------------------|------------|
| 76 Plasma     | Ketorolac | Ketorolac | Chitosan-MIP-SPE  | UV-Spectrophotometer  | 7.3–12.86 | > 80       | 2000–20000 | Mabrouk et al. (2020) |
| 77 Urine      | Ketoprofen, Naproxen, Diclofenac, Ibuprofen | – | SupelMIP SPE-NSAIDs (Commercially available) | HPLC–DAD | >20 | 80–131 | 50–10000 | Martinez-Sena et al. (2016) |
| 78 Serum      | Ibuprofen | Ibuprofen | EC-MIP-SPME | IMS | > 6 | 89–128 | 5–100 and 100–1000 | Alizadeh et al. (2014) |
| 79 Serum      | Carbamazepine | Carbamazepine | MIP-MSPE | HPLC–UV | 1.4–2.0 | About 95 | 50–12000 and 200–12000 | Alvani-Alamdari et al. (2019) |
| 80 Urine      | Carbamazepine, Dexamethasone, Naproxen | Carbamazepine, Dexamethasone, Naproxen | 3-D MI-IPN sorbent-MEPS | HPLC–UV | 2.4–6.3 | 91 | 5–500 | Asgari et al. (2017) |
| 81 Urine      | Methamphetamine | Methamphetamine | MIP-INAT | GC-FID | 4.9–5.8 | 81–93 | 40–3000 | Djozan et al. (2012) |
| 82 Urine      | Amphetamine and Ecstasy | Amphetamine | MIP-sol-gel tablet-μSPE | LC–MS/MS | 3.3–8.5 | > 80 | 5–5000 | El-Beqqali et al. (2017) |
| 83 Plasma     | Methadone | Methadone-d9 | MIP-sol–gel tablet-μSPE | LC–MS/MS | 4.0–8.0 | > 80 | 5–5000 | El-Beqqali and Abdel-Rehim (2016) |
| 84 Salvia     | Methamphetamine | Methamphetamine | MIP-SPME | GC-FID | <5.5 | 7.8 | 50–3500 | Djozan et al. (2011) |
| 85 Urine      | Morphine | Morphine | MMISPE | UHPLC-DAD | 1.7–5.2 | > 84.8 | 100–30000 | Ebrahimi Rahmani et al. (2018) |
| 86 Saliva     | Cocaine, Methamphetamine | Cocaine, Methamphetamine | MIP papers | DI-ESI-MS/MS | <5.9 | 84.3–98 | 1–100 | Díaz-Liñán et al. (2021) |
| 87 Plasma     | Cannabinoids (CBD) | Hydrogenated cannabidiol | MIP-in tube-SPME | UHPLC-MS/MS | 0.2–19.1 | > 50 | 10–300 | Marchioni et al. (2020) |
| 88 Urine      | Δ⁹-tetrahydrocannabinol and 11-hydroxy-Δ⁹-tetrahydrocannabinol and 11-nor-Δ⁹-tetrahydrocannabinol-carboxylic acid | Catechin-hydrate | MIP-MEPS | LC–MS/MS | – | 3.45–17.8 | 25–250 | Sartore et al. (2020) |
| Sample Matrix | Target | Template | Extraction method | Analytical techniques | (RSD) % | Recovery % | Linear range (ng mL⁻¹) | References |
|---------------|--------|----------|-------------------|-----------------------|---------|------------|------------------------|------------|
| Urine         | Cannabinoids | JWH007, JWH015 and JWH098 | MIP-µSPE | HPLC–MS/MS         | > 8     | > 75       | 50–2500                | Sánchez-González et al. (2018) |
| Heavy metals  |        |          |                   |                       |         |            |                        |            |
| 90 Urine      | Cd(II) | Cd(II)   | MIIP-SPE          | FAAS                  | –       | 80 < x < 100 | –                      | Panjali et al. (2015) |
| 91 Hair       | Cu(II) | Cu(II)   | MIIP-SPE          | EAAS                  | 4.3     | 96 ± 4.2%  | 0.03–33                | Fazelirad et al. (2019) |
| 92 Urine Serum | Cu(II) | Cu(II)   | Restricted access-Cu(II) MIP-SPE | Plasma-optical emission spectrometry | 2.2     | 90–108     | 1–100                  | Cui et al. (2013) |
| 93 Hair       | Pb²⁺   | Pb²⁺     | MIP-MNS-SPE       | FAAS                  | –       | 99.7–109   | 0.5–850                | Kiani and Ghorbani (2017) |
| Inhibitors    |        |          |                   |                       |         |            |                        |            |
| 94 plasma     | Venlafaxine, O-desmethylvenlafaxine, N-desmethylvenlafaxine | venlafaxine | MISPE | UHPLC-MS/MS | – | 99 | 3–700 | Miranda et al. (2016) |
| 95 Urine Serum | venlafaxine | venlafaxine | Magnetite MIP-SPE | HPLC | – | 97–102.4 | 2.0–400 | Madrakian et al. (2015) |
| 96 Urine Serum | Sitagliptin | sitagliptin | MISPE | MISPE | – | > 98 | 100–1000 | Rao et al. (2011) |
| 97 Urine      | Fluoxetine | Fluoxetine | MIP-SPE | Spectrophotometry | 2.5 | 95.7–104 | 0.8–10 | Barati et al. (2017) |
the most attentions unlike natural components and heavy metals (Fig. 10). However, several challenges remain to be overcome to expand the variety range of components in biomatrices. Going further, the more application of MIPs on bioanalysis of other important components such as pollutants (like mycotoxins, heavy metals, and pesticides), other kinds of drugs, biomarkers, inhibitors and hormones can be expected. Complete and expand studies in these areas will facilitate the development and optimization of approaches in trace analysis and clinical assessments.

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Conflict of interest The all authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Abbasy L, Mohammadzadeh A, Hasanzadeh M, Razmi N (2020) Development of a reliable bioanalytical method based on prostate specific antigen trapping on the cavity of molecular imprinted polymer towards sensing of PSA using binding affinity of PSA-MIP receptor: a novel biosensor. J Pharm Biomed Anal 188:113447. https://doi.org/10.1016/j.jpba.2020.113447

Abdel-Rehim M (2004) Recent advances in microextraction by packed sorbent for bioanalysis. J Chromatogr A 1217:2569–2580. https://doi.org/10.1016/j.chroma.2009.09.053

Abdel-Rehim A, Abdel-Rehim M (2013) Evaluation of microextraction by packed sorbent and micro-liquid chromatography–tandem mass spectrometry as a green approach in bioanalysis. Biomed Chromatogr 27:1225–1233. https://doi.org/10.1002/bmc.2839

Abdel-Rehim M, Pedersen-Bjergaard S, Abdel-Rehim A, Lucena R, Moein MM, Cárdenas S, Miró M (2020) Microextraction approaches for bioanalytical applications: an overview. J Chromatogr A 1616:460790. https://doi.org/10.1016/j.chroma.2019.460790

Abid SA, Ahmed Muneer A, Al-Kadmy IMS, Sattar AA, Beshbisy AM, Batíha GE-S, Hetta HF (2021) Biosensors as a future diagnostic approach for COVID-19. Life Sci 273:119117. https://doi.org/10.1016/j.lfs.2021.119117

Ahmadi M, Elmony Y, Madrakian T, Abdel-Rehim M (2017) Nanomaterials as sorbents for sample preparation in bioanalysis: a review. Anal Chim Acta 958:1–21. https://doi.org/10.1016/j.aca.2016.11.062

Alanazi K, Garcia Cruz A, Di Massi S, Voorhaar A, Ahmad OS, Cowen T, Piletska E, Langford N, Coats TJ, Sims MR, Piletsky SA (2021) Disposable paracetamol sensor based on electroactive molecularly imprinted polymer nanoparticles for plasma monitoring. Sens Actuators, B Chem 329:129128. https://doi.org/10.1016/j.snb.2020.129128

Alimohammadi Z, Pourmoslemi S (2021) Disposable paracetamol sensor based on electroactive molecularly imprinted polymer nanoparticles for plasma monitoring. Sens Actuators, B Chem 329:129128. https://doi.org/10.1016/j.snb.2020.129128

Alizadeh T (2014) Synthesis of a nano-sized chiral imprinted polymer and its use as an (S)-atenolol carrier in the bulk liquid membrane. J Sep Sci 37:1887–1895. https://doi.org/10.1002/jssc.201400088

Alizadeh N, Samaei E, Kalhor H (2014) Electrochemically controlled solid phase microextraction of ibuprofen based on nanoscale conducting molecular imprinted polypyrrole and selective analysis in biological and formulation samples using ion mobility spectrometry. Anal Methods 6:2909–2915. https://doi.org/10.1039/C4AY42090F

Al-kaf AG (2017) Nonsteroidal anti-inflammatory drugs. InTech, Jan-eza Trdine 9, 51000 Rijeka, Croatia

Alvani-Alamdari S, Jouyban A, Khoubnasabjafari M, Nokhodchi A, Rahimpour E (2019) Efficiency comparison of nylon-6-based solid-phase and stir bar sorptive extractors for carbamazepine extraction. Bioanalysis 11:899–911. https://doi.org/10.4155/bio.2018-0321

Amlashi HS, Daryasari AP, Soleimani M (2019) Molecularly imprinted polymer solid phase extraction followed by high-performance liquid chromatography as an efficient and sensitive technique for determination of meropenem in human plasma and urine. S Afr J Chem 72:32–39

Andersson L, Sellergren B, Mosbach K (1984) Imprinting of amino acid derivatives in macroporous polymers. Tetrahedron Lett 25:5211–5214. https://doi.org/10.1016/S0040-4039(01)81566-5

Ang QY, Low SC (2019) Feasibility study on molecularly imprinted polymer beads for drug radioligand binding assay. Analyst 144:3790–3797. https://doi.org/10.1039/C9AN00965D

Ansari S, Karimi M (2017) Synthesis and application of molecularly imprinted polymer for highly selective solid phase extraction of methylprednisolone. Microchim Acta 184:664–670. https://doi.org/10.1007/s00604-017-2147-1

Ansel RJ, Mosbach K (1998) Magnetic molecularly imprinted polymer beads for drug radioligand binding assay. Analyst 123:1611–1616. https://doi.org/10.1039/A801903G

Arabi M, Ghaedi M, Ostovar A, Wang S (2016) Synthesis of lab-in-a-pipette-tip extraction using hydrophilic nano-sized dummy
molecularly imprinted polymer for purification and analysis of phospholipids. J Colloid Interface Sci 480:232–239. https://doi.org/10.1016/j.cis.2016.07.017

Arthur CL, Pawliszyn J (1990) Solid phase microextraction with thermal desorption using fused silica optical fibers. Anal Chem 62:2145–2148. https://doi.org/10.1021/ac00218a019

Asfaram A, Ghaedi M, Dastkian K (2017) Rapid ultrasound-assisted magnetic microextraction of gallic acid from urine, plasma and water samples by HKUST-1-MOF-Fe3O4-GA-MIP-NPs: UV–vis detection and optimization study. Ultrason Sonochem 34:561–570. https://doi.org/10.1016/j.ultsonch.2016.06.033

Asfaram A, Arabi M, Ostovan A, Sadeghi H, Ghaedi M (2018) Simple and selective detection of quercetin in extracts of plants and food samples by dispersive micro-solid phase extraction based on core–shell magnetic molecularly imprinted polymers. New J Chem 42:16144–16153. https://doi.org/10.1039/C8NJ03349H

Asgari S, Bagheri H, Es-haghhi A, AminiTabrizi R (2017) An interpenetrating polymer network for microextraction in packed syringe of carbamazepine. J Chromatogr A 1491:1–8. https://doi.org/10.1016/j.chroma.2017.02.033

Ashri NY, Abdel-Rehim M (2011) Sample treatment based on extraction techniques in biological matrices. Bioanalysis 3:2003–2018. https://doi.org/10.4155/bio.11.201

Asiabi H, Yamini Y, Seidi S, Ghahramanifard F (2016) Preparation and evaluation of a novel molecularly imprinted polymer coating for selective extraction of indomethacin from biological samples by electrochemically controlled in-tube solid phase microextraction. Anal Chim Acta 913:76–85. https://doi.org/10.1016/j.aca.2016.01.060

Attallah OA, Al-Ghobashy MA, Ayoub AT, Nebsen M (2017) Magnetic molecularly imprinted polymer nanoparticles for simultaneous extraction and determination of 6-mercaptopurine and its active metabolite thioguanine in human plasma. J Chromatogr A 1561:28–38. https://doi.org/10.1016/j.chroma.2018.05.038

Azodi-Deilami S, Abdouss M, Asadi E, Hassan Najafabadi A, Sadeghi S, Farzanesh S, Asadi S (2014) Magnetic molecularly imprinted polymer nanoparticles coupled with high performance liquid chromatography for solid-phase extraction of carvedilol in serum samples. J Appl Polym Sci. https://doi.org/10.1002/app.41209

Bagheri H, Pirio-Moghadam H, Bayat P, Balalaie S (2013) Application of sol–gel based molecularly imprinted xerogel for on-line capillary microextraction of fentanyl from urine and plasma samples. Anal Methods 5:7096–7101. https://doi.org/10.1039/C3AY41559G

Bagheri H, Molaei K, Asgharinezhad AA, Ebrahimzadeh H, Sham sipur M (2016) Magnetic molecularly imprinted composite for the selective solid-phase extraction of p-aminosalicylic acid followed by high-performance liquid chromatography with ultraviolet detection. J Sep Sci 39:4166–4174. https://doi.org/10.1002/jssc.201600865

Bahrani S, Ghaedi M, Khoshnood Mansoorkhani MJ, Ostovan A (2017) A highly selective nanocomposite based on MIP for curcumin trace levels quantification in food samples and human plasma following optimization by central composite design. J Chromatogr B 1040:129–135. https://doi.org/10.1016/j.jchromb.2016.12.011

Baltussen E, Sandra P, David F, Cramers C (1999) Stir bar sorptive extraction (SBSE), a novel extraction technique for aqueous samples: theory and principles. J Microcolumn Sep 11:737–747. https://doi.org/10.1021/sl990667x(1999)11:10.3%737::aid-mcs%3e3.0.co;2-4

Banak K, Ghorbani-Bidkorbeh F, Afsharaha H, Hatamabadi D, Landi B, Kecili R, Selligren B (2022) Nano-sized magnetic core-shell and bulk molecularly imprinted polymers for selective extraction of amiodarone from human plasma. Anal Chim Acta 1198:339548. https://doi.org/10.1016/j.aca.2022.339548

Barati A, Kazemi E, Dadfarinia S, Haji Shabani AM (2017) Synthesis/characterization of molecular imprinted polymer based on magnetic chitosan/graphene oxide for selective separation/pre-concentration of fluoxetine from environmental and biological samples. J Ind Eng Chem 46:212–221. https://doi.org/10.1016/j.jiec.2016.10.033

Batista AD, Silva WR, Mizaikoff B (2021) Molecularly imprinted materials for biomedical sensing. Med Dev Sensors 4:10166. https://doi.org/10.1002/mds.31066

Bazmmandegan-Shamili A, Dadfarinia S, Haji Shabani AM, Saeedi M, Rohani Moghadam M (2016) High-performance liquid chromatographic determination of diazoin after its magnetic dispersive solid-phase microextraction using magnetic molecularly imprinted polymer. Food Anal Methods 9:2621–2630. https://doi.org/10.1007/s12161-016-0456-z

BelBruno JJ (2019) Molecularly imprinted polymers. Chem Rev 119:94–119. https://doi.org/10.1021/acs.chemrev.b800171

Schneider G, Bischoff P, Kochs E (2008) Anesthetics drug pharmacodynamics. Handbook of experimental pharmacology, Springer, Berlin, Heidelberg

Bodoki AE, Iacob B-C, Gliga LE, Oprean SL, Spivak DA, Gariano NA, Bodoki E (2018) Improved enantioselectivity for atenolol employing pivot based molecular imprinting. Molecules 23:1875

Bonatti AF, De Maria C, Vozzi G (2021) Molecular imprinting strategies for tissue engineering applications: a review. Polymers 13:548

Bosi A, Bonini E, Turner APF, Piletsky SA (2007) Molecularly imprinted polymers for the recognition of proteins: the state of the art. Biosens Bioelectron 22:1131–1137. https://doi.org/10.1016/j.bios.2006.06.023

Bousoumah R, Antignac JP, Camel V, Grimaldi M, Balague P, Cour rant F, Bichon E, Morvan M-L, Le Bizec B (2015) Development of a molecular recognition based approach for multi-residue extraction of estrogenic endocrine disruptors from biological fluids coupled to liquid chromatography-tandem mass spectrometry measurement. Anal Bioanal Chem 407:8713–8723. https://doi.org/10.1007/s00216-015-0924-4

Bycroft BW, Payne DJ (2013) Dictionary of antibiotics and related substances: with CD-ROM (2nd edn). CRC Press

Caro E, Marcé RM, Borrell F, Cormack PAG, Sherrington DC (2006) Application of molecularly imprinted polymers to solid-phase extraction of compounds from environmental and biological samples. TrAC Trends Anal Chem 25:143–154. https://doi.org/10.1016/j.trac.2005.05.008

Cennamo N, D’Agostino G, Porto G, Biasiolo A, Perri C, Arcadio F, Zeni L (2018) A molecularly imprinted polymer on a plasmic plastic optical fiber to detect perfluorinated compounds in water. Sensors 18:1836

Cennamo N, D’Agostino G, Perri C, Arcadio F, Chiaretti G, Parisio EM, Camarlinghi G, Vettori C, Di Marzo F, Cennamo R, Porto G, Zeni L (2021) Proof of concept for a quick and highly sensitive on-site detection of SARS-CoV-2 by plasmic optical fibers and molecularly imprinted polymers. Sensors 21:1681

Chapus F, Pichon V, Lanza F, Selligren S, Hennion MC (2003) Optimization of the class-selective extraction of triazines from aqueous samples using a molecularly imprinted polymer by a comprehensive approach of the retention mechanism. J Chromatogr A 999:23–33. https://doi.org/10.1016/S0021-9673(03)00552-1

Chaves AR, Costa Queiroz ME (2013) In-tube solid-phase microextraction with molecularly imprinted polymer to determine interferon alpha 2a in plasma sample by high performance liquid chromatography. J Chromatogr A 1318:43–48. https://doi.org/10.1016/j.chroma.2013.10.018

Chaves AR, Silva BJG, Lanças FM, Queiroz NEC (2011) Biocompatible in-tube solid phase microextraction coupled with liquid chromatography-fluorescence detection for determination of
interferon α in plasma samples. J Chromatogr A 1218:3376–3381. https://doi.org/10.1016/j.chroma.2010.11.039

Chen S-E, Zhu S, Hu J, Sun J, Zheng Z, Zhao X-E, Liu H (2020) 8-Plex stable isotope labeling absolute quantitation strategy combined with dual-targeted recognizing function material for simultaneous separation and determination of glucosylphingosine and galactosylsphingosine in human plasma. Anal Chim Acta 1124:40–51. https://doi.org/10.1016/j.aca.2020.05.032

Chen S-E, Hu J, Yan P, Sun J, Jia W, Zhu S, Zhao X-E, Liu H (2021) 12-Plex UHPLC-MS/MS analysis of sarcosine in human urine using integrated principle of multiplex tags chemical isotope labeling and selective imprint enriching. Talanta 224:121788. https://doi.org/10.1016/j.talanta.2020.121788

Cheng L, Pan S, Ding C, He J, Wang C (2017) Dispersive solid-phase microextraction with graphene oxide based molecularly imprinted polymers for determining bis(2-ethylhexyl) phthalate in environmental water. J Chromatogr A 1511:85–91. https://doi.org/10.1016/j.chroma.2017.07.012

Ciechanowska A, Popiolek-Barczyk K, Pawlik K, Ciapała K, Oggioni M, Mercurio D, De Simoni M-G, Mika J (2020) Changes in macrophage inflammatory protein-1 (MIP-1) family members expression induced by traumatic brain injury in mice. Immunobiology 225:151911. https://doi.org/10.1016/j.imbio.2020.151911

Clark LC Jr, Lyons C (1962) Electrode systems for continuous monitoring in cardiovascular surgery. Ann N Y Acad Sci 102:29–45. https://doi.org/10.1111/j.1749-6632.1962.tb13623.x

Contin M, Flor S, Martinfeski M, Lucangioli S, Tripodi V (2014) The use of coenzyme Q0 as a template in the development of a molecularly imprinted polymer for the selective recognition of coenzyme Q10. Anal Chim Acta 807:67–74. https://doi.org/10.1016/j.aca.2013.11.030

Cui Y, Jiang L, Li H, Meng D, Chen Y, Ding L, Xu Y (2021) Molecularly imprinted electrosprten nanofibre membrane assisted stir bar sorptive extraction for trace analysis of sulfonamides from animal feeds. J Ind Eng Chem 96:382–389. https://doi.org/10.1016/j.jiec.2021.01.045

da Silva ATM, Pires BC, Dinali LAF, Maia ACFC, dos Santos CJ, Sanches C, Borges WdS, Borges KB (2021) Terephthalic acid-based molecularly imprinted polymer for enantioselective capillary electrophoresis determination of atenolol in human plasma. Sep Purif Technol 261:118257. https://doi.org/10.1016/j.seppur.2021.118257

Daryanavard SM, Jeppsson-Dadoun A, Andersson LI, Hashemi M, da Silva ATM, Pires BC, Dinali LAF, Simões NS, Borges KB (2019a) Microextraction by packed sorbent using a new restricted molecularly imprinted polymer for the determination of estrogens from human urine samples. Microchem J 150:104162. https://doi.org/10.1016/j.microc.2019.104162

de Oliveira HL, Pires BC, Teixeira LS, Dinali LAF, Simões NS, Wd.S, Borges KB, Borges, (2019b) Novel restricted access material combined to molecularly imprinted polymer for selective magnetic solid-phase extraction of estrogens from human urine. Microchem J 149:104043. https://doi.org/10.1016/j.microc.2019.104043

Díaz-Alvarez M, Turiel E, Martín-Esteban A (2019) Molecularly imprinted polymer monolith containing magnetic nanoparticles for the stir-bar sorptive extraction of thiabendazole and carbendazim from orange samples. Anal Chim Acta 1045:117–122. https://doi.org/10.1016/j.aca.2018.09.001

Díaz-Liñán MC, García-Valverde MT, Lucena R, Cárdenas S, López-Lorente AI (2021) Dual-template molecularly imprinted paper for the determination of drugs of abuse in saliva samples by direct infusion mass spectrometry. Microchem J 160:105686. https://doi.org/10.1016/j.microc.2020.105686

Dil EA, Doustimotlagh AH, Javadian H, Asfaram A, Ghaedi M (2021) Nano-sized Fe3O4@SiO2-molecular imprinted polymer as a sorbent for dispersive solid-phase microextraction of melatonin in the methanolic extract of Portulaca oleracea, biological, and water samples. Talanta 221:121620. https://doi.org/10.1016/j.talanta.2020.121620

Diouf A, Aghoutane Y, Burhan H, Sen F, Bouchikhi B, El Bari N (2021) Tramadol sensing in non-invasive biological fluids using a voltammetric electronic tongue and an electrochemical sensor based on biomimetic recognition. Int J Pharm 593:120114. https://doi.org/10.1016/j.ijpharm.2020.120114

Djouzlan D, Mahkam B, Ebrahimi B (2009) Preparation and binding study of solid-phase microextraction fiber on the basis of ametryn-imprinted polymer: application to the selective extraction of persistent triazine herbicides in tap water, rice, maize and onion. J Chromatogr A 1216:2211–2219. https://doi.org/10.1016/j.chroma.2008.12.101

Djouzlan D, Ebrahimi B, Mahkam M, Farajzadeh MA (2010) Evaluation of a new method for chemical coating of aluminum wire with molecularly imprinted polymer layer. Application for the fabrication of triazines selective solid-phase microextraction fiber. Anal Chim Acta 674:40–48. https://doi.org/10.1016/j.aca.2010.06.006

Djouzlan D, Farajzadeh MA, Sorouraddin SM, Baheri T (2011) Synthesis and application of high selective monolithic fibers based on molecularly imprinted polymer for SPME of trace methamethamine. Chromatographia 73:975–983. https://doi.org/10.1007/s10337-011-1984-8

Djouzlan D, Farajzadeh MA, Sorouraddin SM, Baheri T (2012) Determination of methamethamine, amphetamine and ecstasy by inside-needle adsorption trap based on molecularly imprinted polymer followed by GC-FID determination. Microchem Acta 179:209–217. https://doi.org/10.1007/s00604-012-0879-1

Ebrahim Rahmani M, Ansari M, Kazemipour M, Nateghi M (2018) Selective extraction of morphine from biological fluids by magnetic molecularly imprinted polymers and determination using UHPLC with diode array detection. J Sep Sci 41:958–965. https://doi.org/10.1002/jssc.201701018

Ebrazimzadeh H, Dehghani Z, Asgharinezhad AA, Shekari N, Molaei K (2013) Determination of haloperidol in biological samples using molecular imprinted polymer nanoparticles followed by HPLC-DAD detection. Int J Pharm 453:601–609. https://doi.org/10.1016/j.ijpharm.2013.05.054

Eisert R, Pawliszyn J (1997) Automated in-tube solid-phase microextraction coupled to high-performance liquid chromatography. Anal Chem 69:3140–3147. https://doi.org/10.1021/ac970319a

El-Aal MAA, Al-Ghobasby MA, El-Saharty YS (2021) Preparation and characterization of 96-well microplates coated with molecularly imprinted polymer for determination and biosimilarity assessment of recombinant human erythropoietin. J Chromatogr A 1641:462012. https://doi.org/10.1016/j.chroma.2021.462012
4-hydroxyphenylacetic acid conversion. J Mater Sci 56:8439–8460. https://doi.org/10.1007/s10853-021-05847-9

Ji W-H, Guo Y-S, Wang X, Guo DS (2018) A water-compatible magnetic molecularly imprinted polymer for the selective extraction of risperidone and 9-hydroxyrisperidone from human urine. Talanta 181:392–400. https://doi.org/10.1016/j.talanta.2018.01.025

Jouyban A, Farajzadeh MA, Afshar Mogaddam MR, Nemati M, Khoubasabafjari M, Jouyban-Gharamaleki (2021) Molecularly imprinted polymer-based solid-phase extraction combined with dispersive liquid–liquid microextraction using new deep eutectic solvent; selective extraction of valproic acid from exhaled breath condensate samples. Microchem J 161:105772. https://doi.org/10.1016/j.microc.2020.105772

Kadhem AJ, Gentile GJ, Fidalgo de Cortalezzi MM (2021) Molecularly imprinted polymers (MIPs) in sensors for environmental and biomedical applications: a review. Molecules 26:6233

Kadirvel P, Combès A, Bordron L, Pichon V (2019) Development and application of water-compatible molecularly imprinted polymers for the selective extraction of carbamazepine from environmental waters. Anal Bioanal Chem 411:1525–1536. https://doi.org/10.1007/s00216-019-01586-8

Kataoka H, Ishizaki A, Nonaka Y, Saito K (2009) Developments and applications of capillary microextraction techniques: a review. Anal Chim Acta 655:8–29. https://doi.org/10.1016/j.aca.2009.09.032

Kiani A, Ghorbani M (2017) Synthesis of core–shell magnetic ion-imprinted polymer nanospheres for selective solid-phase extraction of Pb2+ from biological, food, and wastewater samples. J Dispers Sci Technol 38:1041–1048. https://doi.org/10.1080/01932691.2016.1219666

Kohler IG, D. (2014) Multi-target screening of biological samples using LC-MS/MS: focus on chromatographic innovations. Bioanalysis 6:1255–1273

Kou Y, Wu T, Zheng H, Kadasala NR, Yang S, Guo C, Chen L, Liu Y, Yang J (2020) Recyclable magnetic MIP-based SERS sensors for selective, sensitive, and reliable detection of paclitaxel residues in complex environments. ACS Sustain Chem Eng 8:14549–14556. https://doi.org/10.1021/acssuschemeng.0c05065

Kubo T, Otsuka K (2016) Recent progress in molecularly imprinted polymers (MIPs) in sensors for environmental and bio-medical applications: a review. Molecules 26:6233

Li Y, Ding M-J, Wang S, Wang R-Y, Wu X-L, Wen T-T, Yuan L-H, Dai P, Lin Y-H, Zhou X-M (2011) Preparation of imprinted polymers at surface of magnetic nanoparticles for the selective extraction of Tadalafil from medicines. ACS Appl Mater Interfaces 3:3308–3315. https://doi.org/10.1021/am2007855

Li Y-F, Sun Y-M, Beier RC, Lei H-T, Gee S, Hammock BD, Wang H, Wang Z, Sun X, Shen Y-D, Yang J-Y, Xu Z-L (2017) Immunochemical techniques for multianalyte analysis of chemical residues in food and the environment: a review. TrAC Trends Anal Chem 88:25–40. https://doi.org/10.1016/j.trac.2016.12.010

Li Z, Wang J, Chen X, Hu S, Gong T, Xian Q (2019) A novel molecularly imprinted polymer-solid phase extraction method coupled with high performance liquid chromatography tandem mass spectrometry for the determination of nitrosamines in water and beverage samples. Food Chem 292:267–274. https://doi.org/10.1016/j.foodchem.2019.04.036

Lian Z, Wang J (2018) Selective detection of chloramphenicol based on molecularly imprinted solid-phase extraction in seawater from Jiaozhou Bay, China. Mar Pollut Bull 133:750–755. https://doi.org/10.1016/j.marpolbul.2018.06.041

Lin Z, Cheng W, Li Y, Liu Z, Chen X, Huang C (2012) A novel super-paramagnetic surface molecularly imprinted nanoparticle adopting dummy template: an efficient solid-phase extraction adsorbent for bisphenol A. Anal Chim Acta 720:74–753. https://doi.org/10.1016/j.aca.2012.01.020

Liu J-Q, Wulf G (2004) Functional mimicry of the active site of carboxypeptidase a by a molecular imprinting strategy: cooperativity of an amidinium and a copper ion in a transition-state imprinted cavity giving rise to high catalytic activity. J Am Chem Soc 126:7452–7453. https://doi.org/10.1021/ja048372i

Lulinski P, Sobiech M, Zolek T, Maciejewska D (2014) A separation of tyramine on a 2-(4-methoxyphenyl)ethylamine imprinted polymer: An answer from theoretical and experimental studies. Talanta 129:155–164. https://doi.org/10.1016/j.talanta.2014.05.029

Lulinski P, Giebultowicz J, Wrocyzniski P, Maciejewska D (2015) A highly selective molecularly imprinted sorbent for extraction of 2-aminothiazoline-4-carboxylic acid: synthesis, characterization and application in post-mortem whole blood analysis. J Chromatogr A 1420:16–25. https://doi.org/10.1016/j.chroma.2015.09.083

Mabrouk M, Hammad SF, Abdella AA, Mansour FR (2020) Chitosan-based molecular imprinted polymer for extraction and spectrophotometric determination of ketorolac in human plasma. Spectrochim Acta Part A Mol Biomol Spectrosc. 241:118668. https://doi.org/10.1016/j.saa.2020.118667

Madrakian T, Haryani R, Ahmadi M, Afkhami A (2015) Spectrofluorometric determination of venlafaxine in biological samples after selective extraction on the superparamagnetic surface molecularly imprinted nanoparticles. Anal Methods 7:428–435. https://doi.org/10.1039/C4AY021444D

Maranata GJ, Surya NO, Hasana AN (2021) Optimising factors affecting solid phase extraction performances of molecular imprinted polymer as recent sample preparation technique. Helijon 7:e05934. https://doi.org/10.1016/j.helijon.2021.e05934

Marchioni C, Vieira TM, Miller Crotti AE, Crippa JA, Costa Queiroz ME (2020) In-tube solid-phase microextraction with a dummy molecularly imprinted monolithic capillary coupled to ultra-performance liquid chromatography-tandem mass spectrometry to determine cannabinoids in plasma samples. Anal Chim Acta 1099:145–154. https://doi.org/10.1016/j.aca.2019.11.017

Martinez-Seña TA, Armenta S, Guardia Mdl, Esteve-Turrillas FA (2016) Determination of non-steroidal anti-inflammatory drugs in water and urine using selective molecular imprinted polymer extraction and liquid chromatography. J Pharm Biomed Anal 131:48–53. https://doi.org/10.1016/j.jpba.2016.08.006

 Springer
Mazou Z, Mokni M, Fourati N, Zerrouki C, Barbault F, Seydou M, Kalliat R, Yaakoubi O, Omezzine A, Bousslama A, Othmane A (2020) Computational approach and electrochemical measurements for protein detection with MIP-based sensor. Biosens Bioelectron 151:111978. https://doi.org/10.1016/j.bios.2019.111978

McGinn MA, Pantazis CB, Tunstall BJ, Marchette RCN, Carlson ER, Said N, Koob GF, Vendruscolo LF (2021) Chapter 9-Drug addiction co-morbidity with alcohol: neurobiological insights. In: Calipari ES, Gilpin NW (Eds) International review of neurobiology. Academic Press, pp 409–472

McKitterick N, Braathen F, Swinicka-Plak MA, Cormack PAG, Reubsat L, Halvorsen TG (2020a) Magnetic synthetic receptors for selective clean-up in protein biomarker quantification. J Proteome Res 19:3573–3582. https://doi.org/10.1021/acs.jproteome.0c00258

McKitterick N, Bicak TC, Cormack PAG, Reubsat L, Halvorsen TG (2020b) Facilitating serum determination of neuron specific enolase at clinically relevant levels by coupling on-line molecularly imprinted solid-phase extraction to LC-MS/MS. Anal Chim Acta 1140:210–218. https://doi.org/10.1016/j.aca.2020.10.022

Meng J, Wang X (2019) Microextraction by packed molecularly imprinted polymer combined ultra-high-performance liquid chromatography for the determination of levofloxacin in human plasma. J Chem 2019:4783432. https://doi.org/10.1155/2019/4783432

Michailof C, Manesiotis P, Panayiotou C (2008) Synthesis of caffeic acid and p-hydroxybenzoic acid molecularly imprinted polymers and their application for the selective extraction of polyphenols from olive milk waste waters. J Chromatogr A 1182:25–33. https://doi.org/10.1016/j.chroma.2008.01.001

Miranda LFC, Domingues DS, Queiroz MEC (2016) Selective solid-phase extraction using molecularly imprinted polymers for analysis of venlafaxine, O-desmethyvenlafaxine, and N-desmethylen- venlafaxine in plasma samples by liquid chromatography–tandem mass spectrometry. J Chromatogr A 1458:46–53. https://doi.org/10.1016/j.chroma.2016.06.024

Mirzajani R, Kardani F (2016) Fabrication of ciprofloxacin molecularly imprinted polymer coating on a stainless steel wire as a selective solid-phase microextraction fiber for sensitive determination of fluoroquinolones in biological fluids and tablet formulation using HPLC-UV detection. J Pharm Biomed Anal 122:98–109. https://doi.org/10.1016/j.jpba.2016.01.046

Moein MM, Javanbakhht M, Akbari-adergani B (2014) Molecularly imprinted polymer cartridges coupled on-line with high performance liquid chromatography for simple and rapid analysis of human insulin in plasma and pharmaceutical formulations. Talanta 121:30–36. https://doi.org/10.1016/j.talanta.2013.12.011

Moein MM, Abdel-Rehim A, Abdel-Rehim M (2015a) Microextraction by packed sorbent (MEPS). TrAC Trends Anal Chem 67:34–44. https://doi.org/10.1016/j.trac.2014.12.003

Moein MM, Javanbakhht M, Karimi M, Akbari-adergani B, Abdel-Rehim M (2015b) Three-phase molecularly imprinted sol–gel based hollow fiber liquid-phase microextraction combined with liquid chromatography–tandem mass spectrometry for enrichment and selective determination of a tentative lung cancer biomarker. J Chromatogr B 995–996:38–45. https://doi.org/10.1016/j.jchromb.2015.05.005

Moein MM, Abdel-Rehim A, Abdel-Rehim M (2015c) On-line determination of sarcosine in biological fluids utilizing dummy molecularly imprinted polymers in microextraction by packed sorbent. J Sep Sci 38:788–795. https://doi.org/10.1002/jssc.201401116

Mpupa A, Selahle SK, Mizaikoff B, Nommongco PN (2021) Recent advances in solid-phase extraction (SPE) based on molecularly imprinted polymers (MIPs) for analysis of hormones. Chemosensors 9:151

Mudiam MKR, Chauhan A, Singh KP, Gupta SK, Jain R, Ch R, Murthy KC (2013) Determination of t, t-muconic acid in urine samples using a molecularly imprinted polymer combined with simultaneous ethyl chloroformate derivatization and pre-concentration by dispersive liquid–liquid microextraction. Anal Bioanal Chem 405:341–349. https://doi.org/10.1007/s00216-012-6474-9

Muhammad P, Tu X, Liu J, Wang Y, Liu Z (2017) Molecularly imprinted plasmonic substrates for specific and ultrasensitive immunoassay of trace glycoproteins in biological samples. ACS Appl Mater Interfaces 9:12082–12091. https://doi.org/10.1021/acsami.7b00628

Ncube S, Madikizela LM, Nindi MM, Chimuka L (2019) Chapter 3-Solid phase extraction technique as a general field of application of molecularly imprinted polymer materials. In: Març M (Ed) Comprehensive Analytical Chemistry. Elsevier, pp 41–76

Nezhadali A, Es haghi Z, Khatibi A (2016) Selective extraction of progesterone hormones from environmental and biological samples using a poly(pyrrrole) molecularly imprinted polymer and determination by gas chromatography. Anal Methods 8:1813–1827. https://doi.org/10.1039/C5AY02174f

Norman AW, Henry HL (2015) Chapter 1-Hormones: an introduction. In: Norman AW, Henry HL (eds) Hormones, 3rd edn. Academic Press, San Diego, pp 1–25

Otero-Pazos P, Rodríguez-Bernaldo de Quiros A, Sendón R, Benito-Peña E, González-Vallejo V, Moreno-Bondi MC, Angulo I, Paseiro-Losada P (2014) Active food packaging based on molecularly imprinted polymers: study of the release kinetics of ferulic acid. J Agric Food Chem 62:11215–11221. https://doi.org/10.1021/jf5035042

Ou FS, Michiels S, Shyr Y, Adjei AA, Oberg AL (2021) Biomarker discovery and validation: statistical considerations. J Thorac Oncol 16:537–545. https://doi.org/10.1016/j.jtho.2021.01.1616

Pajewska-Szmyt M, Biniewska E, Buszewski B, Gadzala-Kopciuch P (2013) Determination of oestradiol and their application for the selective extraction of polyphenols and tandem mass spectrometry. In: Març M (Ed) Comprehensive Analytical Chemistry. Elsevier, pp 41–76

Panjali Z, Asgharinezhad AA, Ebrahimzadeh H, Karami S, Loni M, Rezvani M, Yarahmadi R, Shatatheri SJ (2015) Development of a selective sorbent based on a magnetic ion imprinted polymer for the preconcentration and FAAS determination of urinary...
cadmium. Anal Methods 7:3618–3624. https://doi.org/10.1039/C4AY03066D
Parisa J, Ameneh Porgham D (2020) Synthesis of molecularly imprinted polymer and its application as solid-phase extraction sorbent for cetazidime determination in human serum and urine samples. J Anal Chem 75:1108–1115. https://doi.org/10.1134/S1061934820090129
Pereira MV, Marques AC, Oliveira D, Martins R, Moreira FTC, Sales MGF, Fortunato E (2020) Paper-based platform with an in situ molecularly imprinted polymer for β-amyloid. ACS Omega 5:12057–12066. https://doi.org/10.1021/acsomega.0c00062
Perrin SL, Bull C, Black S (2020) Local anaesthetic drugs. Anaesthesia & Intensive Care Medicine 21:113–117. https://doi.org/10.1016/j.mpai.2019.12.003
Pichon V (2007) Selective sample treatment using molecularly imprinted polymers. J Chromatogr A 1152:41–53. https://doi.org/10.1016/j.chroma.2007.02.109
Pichon V, Chapuis-Hugon F (2008) Role of molecularly imprinted polymers for selective determination of environmental pollutants: a review. Anal Chim Acta 622:48–61. https://doi.org/10.1016/j.aca.2008.05.057
Podjava A, Šilaks A (2021) Synthesis and sorptive properties of molecularly imprinted polymer for simultaneous isolation of catecholamines and their metabolites from biological fluids. J Liq Chromatogr Relat Technol. https://doi.org/10.1080/10826076.2021.1874980
Ponce-Rodríguez HD, Verdú-Andrés J, Herráez-Hernández R, Camps-Falcó P (2020) Innovations in extractive phases for in tube solid-phase microextraction coupled to miniaturized liquid chromatography: a critical review. Molecules 25:2460. https://doi.org/10.3390/molecules25102460
Prabakaran K, Jandas PJ, Luo J, Fu C, Wei Q (2021) Molecularly imprinted poly(methacrylic acid) based QCM biosensor for selective determination of L-tryptophan. Colloids Surf A 611:125859. https://doi.org/10.1016/j.colsurfa.2020.125859
Prieto A, Vallejo A, Zuloaga O, Paschke A, Sellergen B, Schillinger E, Schrader S, Möder M (2011a) Selective determination of estrogens in compounds by water by microextraction coupled with large volume injection-in-port-derivatization gas chromatography–mass spectrometry. Anal Chim Acta 703:41–51. https://doi.org/10.1016/j.aca.2011.07.007
Prieto A, Schrader S, Bauer C, Möder M (2011b) Synthesis of a molecularly imprinted polymer and its application for microextraction by packed sorbent for the determination of fluoroxquinlone related compounds in water. Anal Chim Acta 685:146–152. https://doi.org/10.1016/j.aca.2010.11.038
Purich D (2017) The inhibitor index: a desk reference on enzyme inhibitors, receptor antagonists, drugs, toxins, poisons, biologics, and therapeutic leads (1st edn), CRC Press
Qiu L, Liu W, Huang M, Zhang L (2010) Preparation and application of solid-phase microextraction fiber based on molecularly imprinted polymer for determination of anabolic steroids in complicated samples. J Chromatogr A 1217:7461–7470. https://doi.org/10.1016/j.chroma.2010.08.056
Rachkov A, Minoura N (2000) Recognition of oxytocin and oxytocin-related peptides in aqueous media using a molecularly imprinted polymer synthesized by the epiptide approach. J Chromatogr A 889:111–118. https://doi.org/10.1016/S0021-9673(00)00568-9
Rahimi M, Bahar S (2022) Preparation of a new solid-phase micro-extraction fiber based on molecularly imprinted polymers for monitoring of phenobarbital in urine samples. J Chromatogr Sci. https://doi.org/10.1093/chromsci/bmaa001
Rajabi Khorrami A, Naroueenzhad E (2011) Synthesis of molecularly imprinted monolithic fibers for solid-phase microextraction of acetaldehyde from head-space of beverages stored in PET bottles. Talanta 86:58–63. https://doi.org/10.1016/j.talanta.2011.08.002
Rajpal S, Miziaikoff B (2022) An in silico predictive method to select multi-monomer combinations for peptide imprinting. J Mater Chem B. https://doi.org/10.1039/D2TB00418F
Ramanavicius S, Samukaite-Bubniene U, Ratautaitė V, Bechelany M, Ramanavicius A (2022) Electrochemical molecularly imprinted polymer based sensors for pharmaceutical and biomedical applications (review). J Pharm Biomed Anal 215:114739. https://doi.org/10.1016/j.jpba.2022.114739
Ramos L (2012) Chapter 1-Basics and advances in sampling and sample preparation. In: Picó Y (ed) Chemical analysis of food: techniques and applications. Academic Press, Boston, pp 3–24
Rao RN, Maurya PK, Khalid S (2011) Development of a molecularly imprinted polymer for selective extraction followed by liquid chromatographic determination of sitagliptin in rat plasma and urine. Talanta 85:950–957. https://doi.org/10.1016/j.talanta.2011.05.002
Raziq A, Kidakova A, Boroznjak R, Reut J, Říška A, Syrštski V (2021) Development of a portable MIP-based electrochemical sensor for detection of SARS-CoV-2 antigen. Biosens Bioelectron 178:113029. https://doi.org/10.1016/j.bios.2021.113029
Rosenthal TB (1948) THE effect of temperature on the pH of blood and plasma in vitro. J Biol Chem 173:25–30. https://doi.org/10.1016/S0021-9258(18)35552-2
Rossetti C, Abdêl Qader A, Halvorsen TG, Sellergren B, Reubsæt L (2014) Antibody-free biomarker determination: exploring molecularly imprinted polymers for pro-gastrin releasing peptide. Anal Chem 86:12291–12298. https://doi.org/10.1021/ac503559c
Rossetti C, Švítinicka-Plak MA, Gonhaug Halvorsen T, Cormack PAG, Sellergren B, Reubsæt L (2017) Automated protein biomarker analysis: on-line extraction of clinical samples by molecularly imprinted polymers. Sci Rep 7:44298. https://doi.org/10.1038/srep44298
Sanati A, Siavash Moakhar R, Hosseini II, Raeissi K, Karimzadeh F, Jalali M, Khazrazi M, Sheibani S, Shariati L, Presley JF, Vahi H, Mahshid S (2021) Gold nano/micro-islands overcome the molecularly imprinted polymer limitations to achieve ultra-sensitive protein detection. ACS Sensors 6:797–807. https://doi.org/10.1021/acssensors.0c01701
Sánchez-González J, Odoardi S, Bermejo AM, Bermejo-Barrera P, Romolo FS, Moreda-Piñeiro A, Strano-Rossi S (2018) Development of a tracor-solid-phase extraction molecularly imprinted polymer technique for synthetic cannabinoids assessment in urine followed by liquid chromatography–tandem mass spectrometry. J Chromatogr A 1550:8–20. https://doi.org/10.1016/j.chroma.2018.03.049
Sarafray-Yazdi A, Razavi N (2015) Application of molecularly-imprinted polymers in solid-phase microextraction techniques. TrAC Trends Anal Chem 73:81–90. https://doi.org/10.1016/j.trac.2015.05.004
Sartore DM, Vargas Medina DA, Costa JL, Lanças FM, Santos-Neto ÁJ, Romolo FS, Moreda-Piñeiro A, Strano-Rossi S (2020) Automated microextraction by packed sorbent of cannabinoids from human urine using a lab-made device packed with molecularly imprinted polymer. Talanta 219:121185. https://doi.org/10.1016/j.talanta.2020.121185
S.N. Sawant (2017) Development of biosensors from biopolymer composites. In: Sadasivuni KK, Ponnamma D, Kim J, Cabibihan JJ, AIMaaded MA (Eds) Biopolymer composites in electronics. Elsevier, pp 353–383
Sellergren B, Lepistoe M, Mosbach K (1998) Highly enantioselective and substrate-selective polymers obtained by molecular imprinting utilizing noncovalent interactions. NMR and chromatographic studies on the nature of recognition. J Am Chem Soc 110:5853–5860. https://doi.org/10.1021/ja00225a041
Shahhoseini F, Langille EA, Azizi A, Bottaro CS (2021) Thin film molecularly imprinted polymer (TF-MIP), a selective and single-use extraction device for high-throughput analysis of biological samples. Analyst 146:3157–3168. https://doi.org/10.1039/D0AN02228D

Shi Y, Peng D-D, Shi C-H, Zhang X, Xie Y-T, Lu B (2011) Selective determination of trace 17β-estradiol in dairy and meat samples by molecularly imprinted solid-phase extraction and HPLC. Food Chem 126:1916–1925. https://doi.org/10.1016/j.foodchem.2010.12.020

Silva CF, Menezes LF, Pereira AC, Nascimento CS (2021a) Molecularly imprinted polymer (MIP) for thiamethoxam: a theoretical and experimental study. J Mol Struct 1231:129980. https://doi.org/10.1016/j.molstruc.2021.129980

Soleimani E, Bahrami A, Afkhami A, Shahna FG (2017) Determination of urinary trans, trans-muconic acid using molecularly imprinted polymer in microextraction by packed sorbent followed by liquid chromatography with ultraviolet detection. J Chromatogr B 1061–1062:65–71. https://doi.org/10.1016/j.jchromb.2017.07.008

Soleimani E, Bahrami A, Afkhami A, Shahna FG (2018) Selective determination of mandelic acid in urine using molecularly imprinted polymer in microextraction by packed sorbent. Arch Toxicol 92:213–222. https://doi.org/10.1007/s00204-017-2057-z

Song B, Zhou Y, Jin H, Jing T, Zhou T, Hao Q, Zhou Y, Mei S, Lee Y-I (2014) Selective and sensitive determination of erythromycin in honey and dairy products by molecularly imprinted polymers based electrochemical sensor. Microchem J 116:183–190. https://doi.org/10.1016/j.microc.2014.05.010

Song X, Zhou T, Li J, Zhang M, Xie J, He L (2018) Determination of ten macrolide drugs in environmental water using molecularly imprinted solid-phase extraction coupled with liquid chromatography-tandem mass spectrometry. Molecules 23:1172

Souza ID, Melo LP, Jardim ICSF, Monteiro JCS, Nakano AMS, Queiroz MEC (2016) Selective molecularly imprinted polymer combined with restricted access material for in-tube SPME/UHPLC-MS/MS of parabens in breast milk samples. Anal Chim Acta 932:49–59. https://doi.org/10.1016/j.aca.2016.05.027

Sun X, Peng J, Wang M, Wang J, Tang C, Yang L, Lei H, Li F, Wang X, Chen J (2018) Determination of nine bisphenols in sewage and sludge using dummy molecularly imprinted solid-phase extraction coupled with liquid chromatography tandem mass spectrometry. J Chromatogr A 1552:10–16. https://doi.org/10.1016/j.chroma.2018.04.004

Suzaei FM, Batista AD, Miziaikoff B, Rahimi S, Daryanavard SM, Abdel-Rehim M (2022) Molecularly imprinted polymers for selective extraction/microextraction of cancer biomarkers: a review. Microchim Acta 189:255. https://doi.org/10.1007/s00604-022-05356-9

Sztulka M, Szelig J, Jackowski M, Buszewski B (2012) Development of novel molecularly imprinted solid-phase microextraction fibers and their application for the determination of antibiotic drugs in biological samples by SPME-LC/MSn. Anal Bioanal Chem 403:785–796. https://doi.org/10.1007/s00216-012-5901-2

Sztulka M, Krzeminski R, Jackowski M, Buszewski B (2013) Simultaneous determination of selected chemotherapeutics in human whole blood by molecularly imprinted polymers coated solid phase microextraction fibers and liquid chromatography–tandem mass spectrometry. J Chromatogr B 940:56–76. https://doi.org/10.1016/j.jchromb.2013.09.009

Terzopoulou Z, Papageorgiou M, Kyzas GZ, Bikiasis DN, Lambropoulou DA (2016) Preparation of molecularly imprinted solid-phase microextraction fiber for the selective removal and extraction of the antiviral drug abacavir in environmental and biological matrices. Anal Chim Acta 913:63–75. https://doi.org/10.1016/j.aca.2016.01.059

Toh PY, Yeap SP, Kong LP, Ng BW, Chan DIC, Ahmad AL, Lim JKH (2012) Magnetophoretic removal of microalgae from fishpond water: feasibility of high gradient and low gradient magnetic separation. Chem Eng J 211–212:22–30. https://doi.org/10.1016/j.cej.2012.09.051

Tsai W-H, Huang T-C, Huang J-J, Hsu Y-H, Chuang H-Y (2009) Dispersive solid-phase microextraction method for sample extraction in the analysis of four tetracyclines in water and milk samples by high-performance liquid chromatography with diode-array detection. J Chromatogr A 1216:2263–2269. https://doi.org/10.1016/j.chroma.2009.01.034

Tu X, Shi X, Zhao M, Zhang H (2021) Moleculally imprinted dispersive solid-phase microextraction sorbents for direct and selective drug capture from the undiluted bovine serum. Talanta 226:122142. https://doi.org/10.1016/j.talanta.2021.122142

Vieira AC, Zampieri RA, de Siqueira MEBP, Martins I, Figueiredo EC (2012) Molecularly imprinted solid-phase extraction and high-performance liquid chromatography with ultraviolet detection for the determination of urinary trans, trans-muconic acid: a comparison with ionic exchange extraction. Analyst 137:2462–2469. https://doi.org/10.1039/C2AN16215F

Viswanathan CT, Bansal S, Booth B, DeStefano AJ, Rose MJ, Sailstad J, Shah VP, Skelly JP, Swann PG, Weiner R (2007) Quantitative bioanalytical methods validation and implementation: best practices for chromatographic and ligand binding assays. Pharm Res 24:1962–1973. https://doi.org/10.1007/s11095-007-9291-7

Wang L, Yuan L, Pan L, Ji QC (2020) Chapter 24-Bioanalysis of biological matrix samples using liquid chromatography–tandem mass spectrometry detection. In: Riley CM, Rosanske TW, Reid G (Eds) Specification of drug substances and products (Second Edn), Elsevier, pp 641–659

Wei S, Li J, Liu Y, Ma J (2016) Development of magnetic molecularly imprinted polymers with double templates for the rapid and selective determination of amphenicol antibiotics in water, blood, and egg samples. J Chromatogr A 1473:19–27. https://doi.org/10.1016/j.chroma.2016.10.067

Wu X, Li Y, Zhu X, He C, Wang Q, Liu S (2017) Dummy molecularly imprinted magnetic nanoparticles for dispersive solid-phase extraction and determination of bisphenol A in water samples and orange juice. Talanta 162:57–64. https://doi.org/10.1016/j.talanta.2016.10.007

Wulff G (2013) Fortyfour years of molecular imprinting in synthetic polymers: origin, features and perspectives. Microchim Acta 180:1359–1370. https://doi.org/10.1007/s00604-013-0992-9

Wulff G, Knorr K (2001) Stoichiometric noncovalent interaction in molecular imprinting. Bioseparation 10:257–276. https://doi.org/10.1023/A:1021585185922

Wulff G, Liu J (2012) Design of biomimetic catalysts by molecular imprinting in synthetic polymers: the role of transition state stabilization. Acc Chem Res 45:239–247. https://doi.org/10.1021/ar200146m

Wulff G, Oberkobusch D, Minarik M (1985) Enzyme-analogue built polymers, 18 chiral cavities in polymer layers coated on wide-pore silica. React Polym 1:261–275. https://doi.org/10.1016/0167-6989(85)90019-0

Xiao D, Dramou P, Xiong N, He H, Li H, Yuan D, Dai H (2013) Development of novel molecularly imprinted magnetic solid-phase extraction materials based on magnetic carbon nanotubes and their application for the determination of gatifloxacin in serum samples coupled with high performance liquid chromatography. J Chromatogr A 1274:44–53. https://doi.org/10.1016/j.chroma.2012.12.011
Xu J, Yang Z, Liu Z (2014) Development of dual-templates molecularly imprinted stir bar sorptive extraction and its application for the analysis of environmental estrogens in water and plastic samples. J Chromatogr A 1358:52–59. https://doi.org/10.1016/j.chroma.2014.06.093

Xu J, Miao H, Wang J, Pan G (2020) Molecularly imprinted synthetic antibodies: from chemical design to biomedical applications. Small 16:1906644. https://doi.org/10.1002/smll.201906644

Yadav M, Shrivastav PS (2011) Incurred sample reanalysis (ISR): a decisive tool in bioanalytical research. Bioanalysis 3:1007–1024. https://doi.org/10.4155/bio.11.76

Yang Y, Yu J, Yin J, Shao B, Zhang J (2014) Molecularly imprinted solid-phase extraction for selective extraction of bisphenol analogues in beverages and canned food. J Agric Food Chem 62:11130–11137. https://doi.org/10.1021/jf5037933

Yang Y, Yan W, Guo C, Zhang J, Yu L, Zhang G, Wang X, Fang G, Sun D (2020) Magnetic molecularly imprinted electrochemical sensors: A review. Anal Chim Acta 1106:1–21. https://doi.org/10.1016/j.aca.2020.01.044

Yang Z, Yang K, Cui Y, Shah T, Ahmad M, Zhang Q, Zhang B (2021) Synthesis of surface imprinted polymers based on wrinkled flower-like magnetic graphene microspheres with favorable recognition ability for BSA. J Mater Sci Technol 74:203–215. https://doi.org/10.1016/j.jmst.2020.10.012

Yang Q, Tomlinson AJ, Naylor S (1998) Chapter 3-Sample preparation. In: Deyl Z, Mikišk I, Tagliaro F, Tesárová E (Eds) Journal of Chromatography Library. Elsevier, pp 95–140

Yi L-X, Fang R, Chen G-H (2013) Molecularly imprinted solid-phase extraction in the analysis of agrochemicals. J Chromatogr Sci 51:608–618. https://doi.org/10.1093/chromsci/bmt024

Yi M, Sheng Q, Sui Q, Lu H (2020) β-blockers in the environment: Distribution, transformation, and ecotoxicity. Environ Pollut 266:115269. https://doi.org/10.1016/j.envpol.2020.115269

Yilmaz H, Basan H (2015) Development of a molecularly imprinted solid-phase extraction sorbent for the selective extraction of temisartan from human urine. J Sep Sci 38:1433–1439. https://doi.org/10.1002/jssc.201401349

You M, Yang S, Tang W, Zhang F, He P-G (2017) Ultrasensitive electrochemical detection of glycoprotein based on boronate affinity sandwich assay and signal amplification with functionalized SiO2@Au nanocomposites. ACS Appl Mater Interfaces 9:13855–13864. https://doi.org/10.1021/acsami.7b00444

Zafarghandi SS, Panahi HA, Nezhati MN (2022) Preparation of pH-sensitive molecularly imprinted polymer via dual-monomer for selective solid-phase extraction of ribavirin from human urine and pharmaceutical samples. ChemistrySelect 7:e202104038. https://doi.org/10.1002/slct.202104038

Zeng H, Yu X, Wan J, Cao X (2021) Synthesis of molecularly imprinted polymers based on boronate affinity for diol-containing macrolide antibiotics with hydrophobicity-balanced and pH-responsive cavities. J Chromatogr A 1642:461969. https://doi.org/10.1016/j.chroma.2021.461969

Zhang S-W, Xing J, Cai L-S, Wu C-Y (2009) Molecularly imprinted monolith in-tube solid-phase microextraction coupled with HPLC/UV detection for determination of 8-hydroxy-2′-deoxyguanosine in urine. Anal Bioanal Chem 395:479–487. https://doi.org/10.1007/s00216-009-2964-9

Zhang Z, Tan W, Hu Y, Li G (2011) Simultaneous determination of trace sterols in complicated biological samples by gas chromatography–mass spectrometry coupled with extraction using β-sitosterol magnetic molecularly imprinted polymer beads. J Chromatogr A 1218:4275–4283. https://doi.org/10.1016/j.chroma.2011.05.022

Zhang X, Xu S, Lim J-M, Lee Y-I (2012) Molecularly imprinted solid phase microextraction fiber for trace analysis of catecholamines in urine and serum samples by capillary electrophoresis. Talanta 99:270–276. https://doi.org/10.1016/j.talanta.2012.05.050

Zhou W, Yang S, Wang PG (2017) Matrix effects and application of matrix effect factor. Bioanalysis 9:1839–1844. https://doi.org/10.4155/bio-2017-0214

Zhu S, Zheng L, Sun L, Jia W, Sun J, Zhao X-E, Liu H (2020) Derivatization-based magnetic dummy molecularly imprinted polymers integrated with 4-plex stable isotope labeling derivatization strategy for specific and rapid determination of t-hydroxyproline in human serum. Anal Chim Acta 1127:57–68. https://doi.org/10.1016/j.aca.2020.06.045

Zhu X, Chen H, Zhou Y, Wu J, Ramakrishna S, Peng X, Nanda HS, Zhou Y (2021) Recent advances in biosensors for detection of exosomes. Curr Opin Biomed Eng 18:100280. https://doi.org/10.1016/j.cobme.2021.100280

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