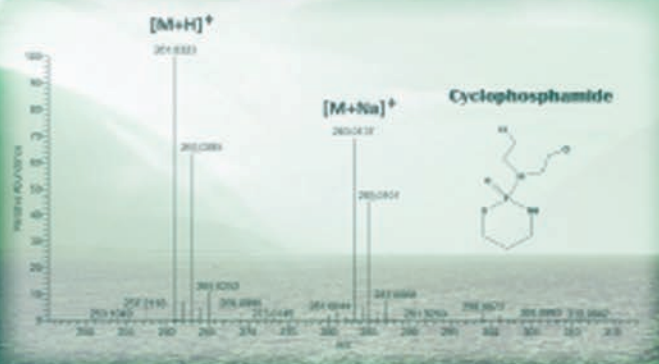


CHROMATOGRAPHIC SCIENCE SERIES

Chromatographic Analysis of the Environment

Mass Spectrometry Based Approaches

FOURTH EDITION



Edited by
Leo M.L. Nollet
Dimitra A. Lambropoulou



CRC Press
Taylor & Francis Group

Chromatographic Analysis of the Environment

Mass Spectrometry Based Approaches

F O U R T H E D I T I O N

Edited by
Leo M.L. Nollet
Dimitra A. Lambropoulou



CRC Press

Taylor & Francis Group

Boca Raton London New York

CRC Press is an imprint of the
Taylor & Francis Group, an **informa** business

CRC Press
Taylor & Francis Group
6000 Broken Sound Parkway NW, Suite 300
Boca Raton, FL 33487-2742

© 2017 by Taylor & Francis Group, LLC
CRC Press is an imprint of Taylor & Francis Group, an Informa business

No claim to original U.S. Government works

Printed on acid-free paper
Version Date: 20170110

International Standard Book Number-13: 978-1-4665-9756-3 (Hardback)

This book contains information obtained from authentic and highly regarded sources. Reasonable efforts have been made to publish reliable data and information, but the author and publisher cannot assume responsibility for the validity of all materials or the consequences of their use. The authors and publishers have attempted to trace the copyright holders of all material reproduced in this publication and apologize to copyright holders if permission to publish in this form has not been obtained. If any copyright material has not been acknowledged please write and let us know so we may rectify in any future reprint.

Except as permitted under U.S. Copyright Law, no part of this book may be reprinted, reproduced, transmitted, or utilized in any form by any electronic, mechanical, or other means, now known or hereafter invented, including photocopying, microfilming, and recording, or in any information storage or retrieval system, without written permission from the publishers.

For permission to photocopy or use material electronically from this work, please access www.copyright.com (<http://www.copyright.com/>) or contact the Copyright Clearance Center, Inc. (CCC), 222 Rosewood Drive, Danvers, MA 01923, 978-750-8400. CCC is a not-for-profit organization that provides licenses and registration for a variety of users. For organizations that have been granted a photocopy license by the CCC, a separate system of payment has been arranged.

Trademark Notice: Product or corporate names may be trademarks or registered trademarks, and are used only for identification and explanation without intent to infringe.

Library of Congress Cataloging-in-Publication Data

Names: Nollet, Leo M. L., 1948- editor. | Lambropoulou, Dimitra A., editor.
Title: Chromatographic analysis of the environment : mass spectrometry based approaches.
Description: Fourth edition / edited by Leo M. L. Nollet and Dimitra Lambropoulou. |
Boca Raton, FL : CRC Press, [2017]
Identifiers: LCCN 2016028978 | ISBN 9781466597563 | ISBN 9781315316208
Subjects: LCSH: Chromatographic analysis. | Environmental chemistry.
Classification: LCC QD79.C4 C48 2017 | DDC 628.5028/7--dc23
LC record available at <https://lcn.loc.gov/2016028978>

Visit the Taylor & Francis Web site at
<http://www.taylorandfrancis.com>
and the CRC Press Web site at
<http://www.crcpress.com>

*This book is dedicated to all victims of the attacks in
Brussels, Belgium, on March 22, 2016.*

*We hope it will compensate a very little bit for their
sufferances and the sorrows of their families.*

*It is also dedicated to the Greek people, who are going
through a very, very long period of uncertainty.*

“When the going gets tough, the tough gets going.”

Contents

Preface.....	xi
Editors	xiii
Contributors	xv

SECTION I *Separation*

Chapter 1	Gas Chromatography–Mass Spectrometry: Basic Concepts and Instrumentation	3
	<i>Basil K. Munjanja</i>	
Chapter 2	LC-MS-Based Screening and Targeted Profiling Methods for Environmental Analysis: Focus on Pharmacologically Active Compounds in the Aqueous Environment and Critical Evaluation of Analytical Approaches.....	25
	<i>Barbara Kasprzyk-Hordern and Bruce Petrie</i>	
Chapter 3	High-Resolution Mass Spectrometric Techniques for Structural Characterization and Determination of Organic Pollutants in the Environment.....	47
	<i>Nuria Cortés-Francisco and Josep Caixach</i>	
Chapter 4	Application of Thermal Desorption–Mass Spectrometry for the Analysis of Environmental Pollutants.....	79
	<i>Steven Sai Hang Ho, Judith C. Chow, Jian Zhen Yu, John G. Watson, Jun-Ji Cao, and Yu Huang</i>	

SECTION II *Sample Preparation and Sampling Strategies*

Chapter 5	Sample Preparation Methods for Determination of Pollutants in Solid and Complex Environmental Matrices.....	111
	<i>Carlos Gonçalves, Maria Augusta D. Sousa, Vasilios G. Samaras, C. Marisa R. Almeida, and M. Clara P. Basto</i>	
Chapter 6	Application of Novel Materials in Sample Treatment and Separation: Cleanup and Chromatographic Improvements.....	199
	<i>Núria Fontanals</i>	
Chapter 7	Advances in Sample Preparation for Molecular Imprinting in Environmental Applications.....	221
	<i>George Z. Kyzas, Dimitrios Bikiaris, and Dimitra A. Lambropoulou</i>	

Chapter 8	Sample Preparation Methods for Determination of Pollutants in Air Samples.....	237
	<i>Francisco Pena-Pereira and Jacek Namieśnik</i>	
Chapter 9	Passive Sampling Strategies for Environmental Monitoring in Air and Aquatic Environment	265
	<i>Anna-Akrivi Thomatou and Ioannis Konstantinou</i>	

SECTION III *Quality Assurance*

Chapter 10	Quality Assurance and Validation: General Considerations and Trends.....	325
	<i>Roberta Galarini, Simone Moretti, and Giorgio Saluti</i>	
Chapter 11	Proficiency Testing in Environmental Analysis: Achievements and Challenges.....	371
	<i>Charalampos Alexopoulos, Elias Kakoulidis, and Eugenia Lampi</i>	
Chapter 12	Reference Methods for the Measurement of Pollutants in Environmental Matrices....	409
	<i>Leo M. L. Nollet</i>	

SECTION IV *Air Pollutants*

Chapter 13	Air Pollutants in the Outdoor Environment (NO _x , SO ₂ , VOCs, HAPs [CO, O ₃])....	427
	<i>Carolina Santamaría, David Elustondo, Esther Lasheras, and Jesús Miguel Santamaría</i>	

SECTION V *Residues in Different Matrices*

Chapter 14	Pharmaceuticals and Personal Care Products	453
	<i>Sergiane Souza Caldas, Ana Laura Venquiaruti Escarrone, and Ednei Gilberto Primel</i>	
Chapter 15	Endocrine-Disrupting Chemicals: Presence in Environmental Matrices	469
	<i>Ramiro Vallejo-Rodríguez, Mario Murillo-Tovar, Leonel Hernández-Mena, and Alberto López-López</i>	
Chapter 16	Analysis of Plasticizers in Food and Environment	491
	<i>Leo M. L. Nollet</i>	

Chapter 17	Instrumental Analysis of Brominated Flame Retardants	515
	<i>Mohamed Abou-Elwafa Abdallah, Alin C. Dirtu, and Adrian Covaci</i>	

Chapter 18	Naphthenic Acids: Environmental Occurrence and Chromatographic Analysis.....	537
	<i>Adeola Adenugba, John V. Headley, Kerry Peru, and Dena McMartin</i>	

SECTION VI Transformation Products

Chapter 19	Occurrence of Transformation Products of Pharmaceutical and Personal Care Products in the Aquatic Environment	555
	<i>Myrsini Papageorgiou, Eleni Evgenidou, and Dimitra A. Lambropoulou</i>	

Outlook.....	605
---------------------	-----

Index.....	609
-------------------	-----

Preface

Considerable analytical progress in chromatographic analysis has been made over the past decade, when hyphenated techniques involving highly efficient separation and sensitive detection have become the techniques of choice. Among them, methods based on chromatographic separation with mass spectrometric detection have opened new perspectives in terms of identification and are acknowledged as the major useful and authoritative methods for the determination of pollutants in the environment.

Since the publication of the third edition of this book in 2005, the focus of chromatographic research has changed again, and the variety of application fields that have been addressed in the literature shows that, due to their versatility, chromatographic mass spectrometric techniques have proven themselves successful in virtually any analytical challenge that makes them robust and effectively applicable alternatives in pollutant analysis. Obviously, in comparison with different detection methods, mass spectrometry or tandem mass spectrometry appears to be the technique of choice in environmental analysis, as it provides reliable results at the subnanogram per liter or per gram level, while the use of other specific detectors, such as flame-ionization detector, nitrogen–phosphorus detector, and electron capture detector, has been in gradual decline. Mass spectrometric analysis has increased exponentially during this time, and important progress has been made in terms of instrumentation in order to increase the throughput, mass resolving power, mass accuracy, tandem mass spectrometry capabilities, and resolution for mass spectrometry.

In this context, the main scope of the book is to outline those developments, which are particularly relevant to environmental analysis, especially when using chromatographic mass spectrometric techniques. Accordingly, the fourth edition has been largely changed and updated in comparison with the previous ones to address these new issues, the new lines of discussions, and new findings.

This edition contains six sections. In Section I, an overview of principles, instrumental aspects, and conceptual case studies in chromatographic analysis is given. The basic concepts and instrumentation of gas chromatography and liquid chromatography combined with mass spectrometry are discussed. This section includes also a chapter on thermal desorption.

The five chapters in Section II detail sample preparation methods for the determination of pollutants in air, in solid and complex environmental matrices, and in the aquatic environment. The reader finds much information on novel materials and methods in sample treatment and separation.

Important aspects, such as quality assurance, validation, proficiency testing, and reference methods, are the elements of the contents of the three chapters of Section III.

Sections IV, V, and VI enumerate chromatographic methods on air pollutants (Section IV), on environmental residues in different matrices (Section V, five chapters), and on transformation products of pharmaceutical and personal care products (Section VI). The five chapters of Section V essentially deal with residues with endocrine-disrupting capacities.

Most of the data are compiled in tables and figures to elucidate the text. Presenting important theoretical and practical aspects from sample collection to laboratory analysis, *Chromatographic Analysis of the Environment, Fourth Edition*, is a unique resource of chromatographic techniques, data, and references that are useful to all scientists involved in the analysis of environmental compounds.

The redaction of this book was not without obstacles and difficulties. These obstacles were largely due to severe health issues and other less severe issues of both editors. These health issues have now been overcome.

We are very thankful to all the contributors for their excellent input and especially for their time and patience.

I would like to give a kiss to Dimitra for her help, wisdom, and courage.

Leo M. L. Nollet
Dimitra A. Lambropoulou

7 Advances in Sample Preparation for Molecular Imprinting in Environmental Applications

*George Z. Kyzas, Dimitrios Bikiaris,
and Dimitra Lambropoulou*

CONTENTS

7.1	Introduction	219
7.2	Synthesis of Molecularly Imprinted Polymers	221
7.3	Sample Preparation for Molecularly Imprinted Polymers.....	223
7.3.1	Solid-Phase Extraction for Molecularly Imprinted Polymers (Molecularly Imprinted Solid-Phase Extraction)	223
7.3.1.1	Molecularly Imprinted Solid-Phase Extraction for Environmental Applications	225
7.3.1.2	Molecularly Imprinted Solid-Phase Microextraction for Environmental Applications	228
	Acknowledgments.....	229
	References.....	229

7.1 INTRODUCTION

Molecular imprinting is a modern technique and not quite common. It is a specific enough technique according to which the selective binding/isolation of target species (molecules or ions/metals) from a mixture can be achieved (Whitcombe et al., 1995). The ability to selectively recognize a target molecule in a vast pool of similar molecules is essential to biological and chemical processes. This process is called molecular recognition, and it is an event that occurs everywhere in nature. It occurs when two molecules are both geometrically and chemically complementary; that is, when they can both ‘fit together’ spatially and bind to each other by using noncovalent forces, including hydrogen bonds, electrostatic interactions, hydrophobic interactions, and weak metal coordination (Chen et al., 2002). Therefore, a specific technology has been bloomed and redesigned in the last 40 years, which is called molecular imprinting. The whole process is based on adsorption/rebinding/separation technology, which is already one of the most successful techniques for pollutant removal (Srinivasan, 2011; Balogh et al., 2012; Jiang et al., 2012; Alahmadi et al., 2013; Mobarak et al., 2013; Radenović et al., 2013; Sasaki et al., 2013). The targets-for-isolation species (usually called templates or template molecules) are compounds of high-added value, which their isolation from mixture can lead to future recovery and exploitation.

Some of the basic application areas of molecular imprinting include separation processes (chromatography, SPE, membrane separations), artificial antibodies, and sensor recognition elements (Bergemann et al., 1999; Chen et al., 2011). Molecular imprinting presents wide recognition due to some properties such as stability and easy and low-cost preparation (Liu and Wulff, 2004). It is

worth noting the impressive increase number of research groups which employ this technique since the increasing number of publications can confirm it. The simplicity of use, the relatively low cost, and the broad range of possible guest molecules (small organic molecules, ions but also biological macromolecules) have since led to the important development of this technique, as illustrated by the increasing number of publications over recent years (Figure 7.1).

As it was said previously, the major applications of MIPs belong to the analytical field with targets (templates) of environmental pollutants. Therefore, special mention should be done for the existing analytical instrumentation for the determination of the compounds/species under separation. In general, the target molecules (analytes) are determined using techniques of chromatography, which are coupled to common detectors (UV, fluorescence). More recently, MS or MS/MS was applied for the same purpose. But in the case of MS, the direct injections of crude/nonmodified sample extracts are allowed but not recommended, because matrix components can inhibit or even enhance the analyte ionization, hampering accurate quantification. For this reason, sample preparation is even now a procedure of the whole chain of analytical process that is under investigation.

The main targets of sample preparation are the following: (i) removal of potential interferents, (ii) analyte preconcentration, (iii) converting (if this is necessary) the analyte into a more suitable form for detection or separation, and (iv) providing a robust and reproducible method which will be independent of variations in the sample matrix. Recently, other targets (more specific) have been addressed about sample preparation: (i) using smaller initial sample sizes, (ii) improving the selectivity in extraction, (iii) facilitating the automation, and (iv) minimizing the amount of glassware and organic solvents to be used (Smith, 2003).

Based on the previous discussion, the common and ‘traditional’ liquid–liquid extraction is now not applicable and cannot ‘satisfy’ the recent requirements. Therefore, analytical laboratories and industries have substituted it with other new extraction techniques. Nowadays, the most used techniques are the (i) SPE, (ii) SPME, (iii) SBSE, (iv) matrix solid-phase dispersion (MSPD), (v) microsolid-phase extraction, (vi) liquid-phase microextraction, etc.

Until now, many research and review articles were published emphasizing the importance of sample preparation in the whole analytical process. A very interesting special issue (‘Advances in Sample Preparation—Part I and Part II’) was published by *Journal of Chromatography A* (Elsevier) showing some updates on this topic (Ramos and Smith, 2007a, 2007b). However, all of these techniques do not present such high selectivity, and, therefore, further optimization of typical steps

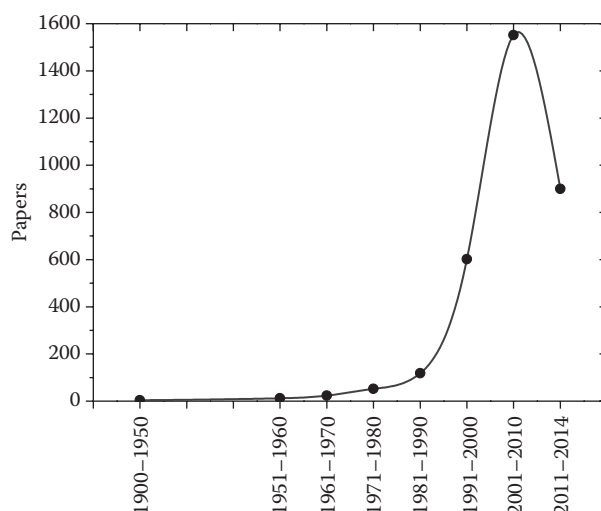


FIGURE 7.1 Works published using the term *molecular imprinted polymers* (data after search in Scopus).

needs to be realized. Unfortunately, even after careful optimization (conditioning, sample loading, washing and elution during the extraction, and cleanup of target analytes), some matrix components are co-eluted with target analytes, making it difficult to reach limits of detection in line with the stringent regulations nowadays.

In the near past, antibodies immobilized on an adequate support, namely, immunosorbents, were proposed as an alternative for use in SPE applications (Martín-Esteban et al., 1997; Pichon et al., 1999) in order to overcome the aforementioned drawbacks associated with typical nonspecific sorbents. Different immunosorbents have been employed for the determination of pesticides, drugs, and polyaromatic hydrocarbons, among others, showing an excellent degree of cleanup, owing to the inherent selectivity of the antibodies used. However, the obtainment of antibodies is difficult, time consuming, and expensive, so it is difficult to guarantee its success. Also, it is important to say that after the antibodies have been obtained, they need to be immobilized on an adequate support, which may result in poor antibody orientation or even complete denaturation.

The use of MIPs as selective sorbent materials allows customized sample treatment prior to the final determination. Thus, their use in SPE, so-called MISPE, is, by far, the most advanced technical application of MIPs (Caro et al., 2006; Pichon and Haupt, 2006; Tamayo et al., 2007; Haginaka, 2009; Lasáková and Jandera, 2009). An increasing interest in the combination of MIPs with other sample-preparation techniques is presented nowadays (i.e., polymeric membrane extraction, SBSE, and MSPD).

The scope of this work is to highlight the updates in MIPs for sample preparation (especially for SPE and SPME), describing the different approaches employed in selected applications in environmental targets (i.e., pharmaceuticals, biomedical, biological, etc.).

7.2 SYNTHESIS OF MOLECULARLY IMPRINTED POLYMERS

The preparation of MIPs starts by positioning the functional monomers around a template molecule. The monomers interact with sites on the template via interactions that can be reversibly covalent or noncovalent (hydrogen, ionic, van der Waals, π - π , etc.). Then, they are polymerized and cross-linked around the template in order to fix their position and to 'freeze' the geometry of the pores in the network. The template molecule is then extracted, leaving a polymer with functional sites capable of molecular recognition.

The first step is the contact between the functionalized monomers and the template molecule, which leads to the formation of a complex. Its structure and stability will then determine the behavior of the future MIP. The interactions involved must be sufficiently strong to remain intact during the polymerization stage but sufficiently labile to enable template extraction and reinsertion of guest molecules in the later stages. These interactions must therefore occur rapidly and be reversible. It is crucial to optimize the choice of the different components of the system at this point.

Different types of strategies can be distinguished depending on whether the bonding between template and host is covalent or not: (i) covalent interactions, (ii) noncovalent interactions, and (iii) double approach: covalent plus noncovalent.

The second step is the polymerization step of the monomers around the complex formed in the first step (Piletsky et al., 2002). Owing to its ease of use, radical polymerization is the most frequent. The crucial question is to determine how to carry out this polymerization/cross-linking step with minimum disturbance of the complex already in place. Choices must be made; for instance, in radical polymerization, the radicals can be generated at 60°C (a,a'-azobutyronitrile as initiator; denoted as AIBN) or 45°C (azobis valeronitrile as initiator; denoted as ABDV), which could cause heat destabilization of the complex or at 4°C with low-temperature photochemical radical production (AIBN, 360 nm). Comparative studies on recognition specificity have shown that the photochemical approach gives the most specific materials (O'Shannessy et al., 1989).

Another crucial point of the preparation of MIPs is the extraction step. The proportion of extraction of the template molecules interacting with the MIP via easily hydrolyzable covalent bonds or

noncovalent linkages is estimated to be about 90%. The remaining molecules are trapped in highly cross-linked zones. This problem is exacerbated with macromolecules where steric hindrance lowers the efficiency of extraction. In addition, the synthesis of MIPs requires large quantities of guest molecule (50–500 μmol per gram of polymer). Therefore, when pure template molecule is difficult or expensive to obtain, reaching quantitative template extraction yields can be primordial. Extraction conditions must then be optimized to obtain yields of over 99%. The extraction step uses an appropriate solvent. It often proves to be long and the actual process involved is dependent on the system in question. Thus, automation of the washing steps for industrial applications still remains problematic. Extraction of the template leaves a three-dimensional material in which the cavity shapes and functional group locations are complementary to the guest molecule.

Solvent plays an important role in the formation of the porous structure of MIPs, which are a subset of a larger class known as macroporous polymers. The morphological properties of porosity and surface area are determined by the type of solvent, referred to as 'porogen,' used in the polymerization. Many solvents were tested in literature for the preparation of MIPs, presenting their main differentiation in the phase. The main organic solvents used are dimethyl sulfoxide, dimethylformamide, acetonitrile, toluene, and chloroform, while deionized water is also used as solvent (Spivak et al., 1997). Moreover, it is notable to report that 70–98% of the final mass of a prepared MIP is composed typically of its cross-linker. Numerous cross-linkers have been tested for the preparation of a rigid MIP such as divinyl benzene (DVB), ethylene glycol dimethacrylate, ethylenebis-acrylamide, and trimethylolpropane trimethacrylate (TRIM). Wulff et al. (1987) and Sibrian-Vazquez and Spivak (2004) have systematically studied the effect of cross-linkers on the recognition properties of MIPs.

Another important point is that the synthesis is related to the template used. For example, the synthesis of MIP and the binding forces between template and polymeric matrix can be strongly influenced from the valence of the template. Therefore, other reagents are selected in order to form a polymeric matrix for monovalent metal as templates and other for others.

After the preparation of MIPs, a full characterization is necessary to examine the morphological and functionalized properties of the prepared materials. The common techniques of MIP characterization are spectroscopy (nuclear magnetic resonance, Fourier transform infrared spectroscopy), swelling tests, and Brunauer–Emmett–Teller analysis (Sellergren, 1994a, 1994b).

In summary, two strategies for molecular imprinting have been established based on whether the template is associated with interactive monomers using covalent bonds or noncovalent interactions. Of the two strategies, the noncovalent approach has been used more extensively for three reasons: (i) noncovalent methodology is easier because it does not require synthetic steps toward the pre-polymer complex and interactions between monomers and template are easily obtained when all components are mixed in solution; (ii) removal of the template is generally much easier, and usually, it is accomplished by continuous extraction; and (iii) a greater variety of functionality can be introduced into the MIP binding site using noncovalent methods. An example for MIP preparation with noncovalent bonding for dye removal is given (Figure 7.2).

Prior to its use in experiments, an MIP is usually evaluated to check its recognition properties for a target. Chromatographic evaluation and equilibrium batch rebinding experiments are the methods most commonly used to investigate the selectivity of the imprinted materials. Chromatographic evaluation allows measurement of capacity factors (k') and imprinting factors of MIPs. These values are obtained from the retention time of the template molecule on a chromatographic column packed with the MIP and a second column packed with the nonimprinted polymer (NIP, which is synthesized just the same as an MIP but without the target compound). If the MIP is imprinted, then the analyte should be retained more strongly on the MIP than on the NIP because of the selective interactions. In some studies (Caro et al., 2003), the selectivity of the MIP was also probed using compounds structurally related to the template. If the MIP retains these compounds almost as well or better than the template, this indicates that the MIP shows cross-reactivity (Caro et al., 2003).

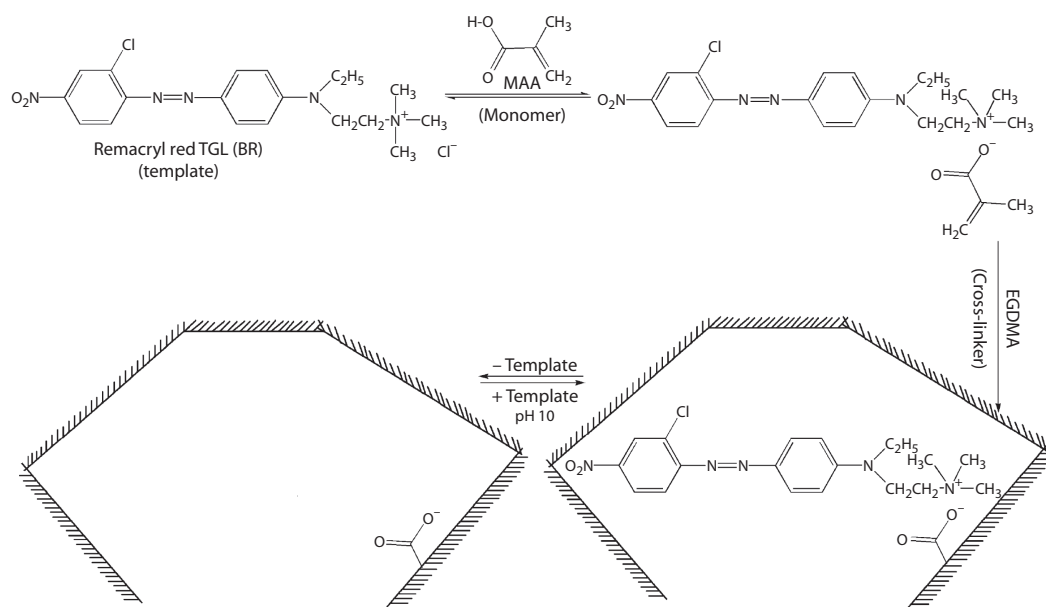


FIGURE 7.2 Schematic representation of the imprinting process for basic dye. (Reprinted from Kyzas, G. Z., and D. N. Bikiaris, *Advances in Materials Science and Engineering*, 2014, 93263, 2014. With permission.)

For equilibrium batch rebinding experiments, a known mass of template in solution is added to a vial containing a fixed mass of polymer. Once the system has come to equilibrium, the concentration of free template in the solution is measured and the mass of template adsorbed to the MIP calculated (Brüggemann et al., 2004). Some of these experiments are based on radioligand binding, which is a very highly sensitive method to study the population of binding sites with the strongest binding characteristics (Shea and Sasaki, 1991). Typically, the sample is incubated with the radioligand for several hours and a centrifugation step is used to sediment the polymer particles. The radioactivity in the supernatant is then measured.

7.3 SAMPLE PREPARATION FOR MOLECULARLY IMPRINTED POLYMERS

Many works for MIPs were published in literature with the topic ‘sample preparation’ (Figure 7.3). The impressive increase of the related published works in the last 5 years is noteworthy (2011–2015). This implies the need for further consideration of sample preparation.

7.3.1 SOLID-PHASE EXTRACTION FOR MOLECULARLY IMPRINTED POLYMERS (MOLECULARLY IMPRINTED SOLID-PHASE EXTRACTION)

SPE is one of the most promising and important techniques for MIPs. This is confirmed by the fact that many industries and companies attempt (and some have achieved this) to make commercially available cartridges packed with MIPs, which are appropriate for the target analyte determination in different samples. Many papers were also published regarding the applicability of MIPs for SPE. A drawback in literature is that the studies published only suggest (or describe) the need for using different templates for different applications. A little number of works suggests new trends for limiting the inherent drawbacks in preparing and using MIPs (template bleeding, tedious synthesis procedure, and slow mass transfer).

As it was described in Section 7.2, the bulk polymerization was the first designing plan/strategy for synthesis of MIPs. After extraction and sieving, the MIP particles obtained invariably possessed

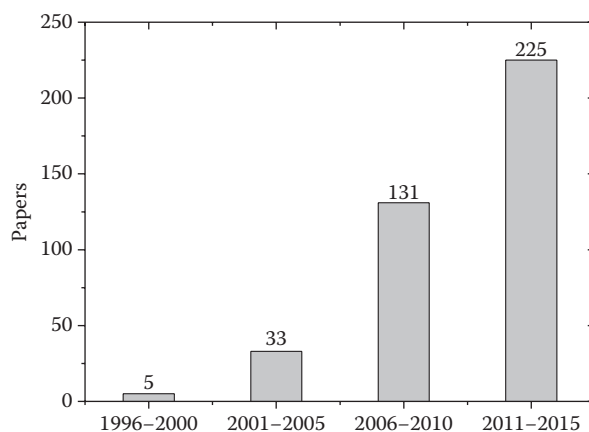


FIGURE 7.3 Works published using the terms *sample preparation* and *molecular imprinted polymers* (data after search in Scopus).

a heterogeneous particle size distribution with poor binding site accessibility for the target analyte. Many attempts have been done in this path developing novel synthesis routes in order to have MIP microspheres with suitable properties (physical characteristics, size, porosity, pore volume, and surface area). Only multistep swelling and polymerization (Hosoya et al., 1996) and precipitation polymerization (Wang et al., 2003) have been used for the preparation of MIPs for SPE of a wide variety of analytes in biological samples (Haginaka et al., 1999; Haginaka and Sanbe, 2000; Sanbe and Haginaka, 2003) and environmental samples (Cacho et al., 2003; Tamayo et al., 2003, 2005).

Various MISPE modes have been assayed such as (i) batch SPE technique, where MIPs are incubated with the sample; (ii) conventional off-line SPE technique, where MIPs are packed into cartridges; and (iii) several modes of online SPE technique. The former has been changed and displaced by the conventional off-line SPE format. Andersson et al. (1997) revealed for first time that the use of a close structural analogue of analyte as imprint species prevented the problems associated with template bleeding, which, until now, is one of the most serious and common problems of using MIPs.

Off-line protocols: Off-line MISPE protocols do not have any difference from other SPE procedures. In a typical procedure, a small amount (15–500 mg) of MIPs is packed into polyethylene (PET) cartridges. Then, after conditioning, loading, and washing, analytes are eluted, ideally free of co-extractives, and the elution extract is further analyzed by LC, GC, or capillary electrophoresis.

A huge development of off-line MISPE methods has been observed recently for the determination of many analytes in environmental samples (river water, groundwater, wastewater, tap water, seawater, and soil extracts), biofluids (urine, plasma, serum, and blood), and food samples. In general, the sample is loaded onto the MIP cartridge in a low-polarity solvent, since in such media, specific interactions are maximized, and after multiple washings for the removal of compounds, which have been nonspecifically bound to the polymeric matrix, analytes are eluted with a solvent able to disrupt the typical noncovalent interactions between the analyte and the imprinted polymer. Aqueous samples can also be directly loaded onto MIP cartridges. However, in this case, MIPs behave like a reversed-phase sorbent, and thus, both target analytes and matrix components are retained through nonspecific interactions. Then, a washing solvent able to remove matrix components and to redistribute nonspecifically bound analytes to the selective imprints is introduced.

Online protocols: In a typical procedure, a small precolumn packed with MIPs (typically about 50 mg) is placed in the loop of a six-port injection valve. After loading the sample and washing out interfering compounds, the analytes are eluted by the mobile phase and then separated in the analytical column.

In-line protocols: Extraction, enrichment, separation, and determination of target analytes can be achieved in one single step by the direct coupling of an MIP column in-line with the detection system thanks to the high selectivity provided by MIPs.

Advanced batch protocols: The batch MISPE technique has been displaced by other SPE techniques/modes. However, batch MISPE has reemerged using magnetic MIPs (Chen et al., 2009; Ji et al., 2009; Zhang et al., 2009), which, after extraction, can be separated from the media by a simple magnet, avoiding filtration and/or centrifugation. Based on literature, this procedure has been successfully used for the extraction of triazines from soil, soybean, lettuce, and millet (Zhang et al., 2009); tetracycline antibiotics from egg and tissue (Chen et al., 2009); and bisphenol A in environmental water and milk (Ji et al., 2009). Another approach is the molecularly imprinted microsolid phase extraction (MIMSPE) (Feng et al., 2009). The MIMSPE device consists of MIPs enclosed within a polypropylene flat-sheet membrane envelope. The membrane presents a porous structure that is ideal for holding submicrosphere MIP particles not suitable for MISPE since they cannot be held back by the typical frits used in SPE cartridges. A successful example of the application of MIMSPE is the selective extraction of phenolic compounds from tap, river, and sewage waters (Feng et al., 2009) and ochratoxin A from coffee, grape juice, and urine (Lee et al., 2012).

7.3.1.1 Molecularly Imprinted Solid-Phase Extraction for Environmental Applications

The first MISPE approach for MIPs was done by Sellergren (1994a), who determined pentamidine in urine samples. The number of works published with MISPE environmental applications is large and can be divided into subtopics. One of the most important applications is the selective extraction of analytes from environmental samples (Andersson, 2001; Caro et al., 2006; Baggiani et al., 2007; Pichon and Chapuis-Hugon, 2008; Lok and Son, 2009).

Environmental samples (mainly environmental waters, sediments, and soils) have been applied to MISPE for the extraction of pesticides, pharmaceuticals, and phenolic compounds (Table 7.1). An initial off-line MISPE work describes an environmental application dealt with the extraction and enrichment of six chlorotriazines from groundwater and sediment samples using a terbuthylazine-imprinted polymer (Ferrer et al., 2000). An aliquot of 100 mL of water sample was percolated, and after a cleanup step with dichloromethane, the matrix components were removed, whereas target analytes were selectively retained with recoveries higher than 80% (except for propazine, with a recovery of 53%) after percolating 100 mL of water sample.

Despite these results, subsequent works have concluded that small amounts of water on the MIP have a negative effect on the retention of analytes, making it necessary to include an exhaustive drying step before the cleanup. Besides, matrix effects due to the presence of divalent cations in real water (such as calcium ions) have been observed. An ion-exchange interaction between these cations and the hydrogen of the carboxyl groups of the MIP occurs, thus preventing subsequent interactions (by H-bonding) between the triazines and the MIP (Chapuis et al., 2003). However, this matrix effect can be easily avoided by introducing an acidic washing step after the percolation of the water sample. Alternatively, as mentioned previously, it is possible to perform a two-step SPE procedure by firstly loading water samples onto conventional sorbents (i.e., C18, DVD) and then retained analytes eluted with an organic solvent suitable for further loading on the MIP (Turiel et al., 2001; Pap et al., 2002).

MISPE has been successfully applied, although in a lesser extent, to the cleanup of soil sample extracts for the determination of triazines (Turiel et al., 2001; Chapuis et al., 2004), monosulfuron (Dong et al., 2004), and fluoroquinolones (Turiel et al., 2007a).

Especially for pharmaceutical application, the MISPE examples are numerous. Table 7.2 summarizes pharmaceutical applications of MISPE, which are divided into two categories: one is to extract a target compound(s) in pharmaceutical preparations and herbal medicines or herbs selectively (Hu et al., 2003; Mena et al., 2003; Hu et al., 2005; Karasová et al., 2005; Nakamura et al., 2005; Karasová et al., 2006; Lin et al., 2006; Liu et al., 2006; Djozan and Baheri, 2007; Farrington and Regan, 2007; Rezaei et al., 2008). The other is to extract a compound(s) structurally related to

TABLE 7.1
Relevant MISPE Applications in Environmental Analysis

Analytes	Template/Monomer/ Cross-Linker	Porogen	Sample	MISPE Mode
Triazines	Terbutylazine/MAA/EDMA	Dichloromethane	Groundwater and sediments	Off-line
Triazines	Terbutylazine/MAA/EDMA	Dichloromethane	Waters (industrial effluent)	Off-line
Triazines	Terbutylazine/MAA/EDMA	Toluene	Waters	Online (SPE + MIP)
Triazines	Propazine/MAA/EDMA	Toluene	Tap, groundwater soil	Off-line (SPE + MIP)
Triazines	Terbutylazine/MAA/EDMA Ametryn/MAA/EDMA	Dichloromethane	Soil and grape juice	Off-line
Monosulfuron	Monosulfuron/MAA/EDMA	Dimethylformamide	Soil	Off-line
Fluoroquinolones	Ciprofloxacin/MAA/EDMA	Methanol	Soil	Off-line and in-line
4-Nitrophenol	4-Nitrophenol/4-VP/EDMA	Acetonitrile	River water	Online
Triazines	Terbutylazine/MAA/EDMA	Toluene	River water	Online (RAM + MIP)
Chlorinated phenoxy acids	2,4,5-Trichlorophenoxyacetic acid/4-VP/EDMA	Methanol/water	River water	Off-line
Bisphenol A	Bisphenol A/4-VP/EDMA	Toluene	River water	Online
Bisphenol A	Bisphenol A-d16/4-VP/EDMA	Toluene/poly(vinyl alcohol)	River water	Off-line
Bisphenol A	Bisphenol A/4-VP/TRIM	Acetonitrile	Tap and lake water	In-line
Methylthiotriazines	Irgarol/TFMAA/EDMA	Toluene	River water	Online
Penicillin G	Penicillin G procaine salt/1-(4-vinylphenyl)-3-(3,5-bis(trifluoromethyl)phenyl)urea + methacrylamide/EDMA	Acetonitrile	Tap and river water	Off-line
Nonylphenol and its ethoxylated derivatives	Nonylphenol/MAA/EDMA	Toluene/acetonitrile	Environmental solids	Off-line
Diclofenac	Diclofenac (2-VP/EDMA)	Toluene	Surface and wastewater	Off-line
Acidic pharmaceuticals	Not available (commercial MIP)		Wastewater	Off-line
Atrazine and metabolites	Terbutylazine/MAA/EDMA	Dichloromethane	Soils	Off-line
Fluoroquinolones	Enrofloxacin/1-(4-vinylphenyl)-3-(3,5-bis(trifluoromethyl)phenyl)urea + methacrylamide/EDMA	Acetonitrile	Environmental waters	Off-line
Ethynyl estradiol	Ethynyl estradiol/MAA/EDMA	Acetonitrile	River water	Online
Benzimidazole fungicides	Thiabendazole/MAA/DVB	Toluene/acetonitrile	Environmental waters	Online

(Continued)

TABLE 7.1 (CONTINUED)
Relevant MISPE Applications in Environmental Analysis

Analytes	Template/Monomer/ Cross-Linker	Porogen	Sample	MISPE Mode
Polycyclic aromatic hydrocarbons	PAH solution/MAA/EDMA	Acetonitrile	Coastal sediments, atmospheric particulates, and industrial effluents	Off-line
Benzimidazole compounds	Thiabendazole/MAA/DVB	Toluene/acetonitrile	Waters	Off-line and online
Antiepileptics	Cyclobarbitol/4-VP/EDMA	Toluene	River water	Online (RAM-MIP)
Phenolic compounds	2,4,6-Trichlorophenol/MAA/EDMA	Acetonitrile	Tap, river, and sewage waters	Off-line

Source: *Analytica Chimica Acta*, 668, Turiel, E., and A. Martín-Esteban, Molecularly imprinted polymers for sample preparation: A review, 87–99, Copyright (2010), with permission from Elsevier.

Note: 2-VP, 2-vinylpyridine; 4-VP, 4-vinylpyridine; DVB, divinylbenzene; EDMA, ethylene glycol dimethacrylate; HEMA, 2-hydroxyethyl methacrylate; MAA, methacrylic acid; TFMAA, 2-(trifluoromethyl)-acrylic acid; TRIM, trimethylol-propane trimethacrylate.

TABLE 7.2
Relevant MISPE Applications in Pharmaceutical Applications

Template	Target Molecules	Preparation Method	MISPE Method
Amobarbital	Phenobarbital	Suspension	On-column, LC
Atropine	Atropine, scopolamine	Multistep swelling	Online, LC
Chloramphenicol	Chloramphenicol	Bulk	Offline, voltammetry
Diacetylmorphine	Diacetylmorphine	Monolith	SPME, GC, GC-MS
(<i>E</i>)-piceatannol	(<i>E</i>)-piceatannol, butein, quercetin	Bulk	Offline, LC-MS
Esculetin	Esculetin and analogues	Bulk	Offline, LC
Harman	Harmaline and harmine	Bulk	Offline, LC-MS
Ibuprofen	Ibuprofen	Bulk	Offline, LC
Piroxicam	Piroxicam	Bulk	Off-line, UV
Protocatechuic acid	Phenolic acids	Bulk	Offline, LC
Quercetin	Quercetin, kaempferol	Bulk	Offline, LC
Quercetin	(<i>E</i>)-piceatannol, butein	Bulk	Offline, LC
<i>trans</i> -Resveratrol	<i>trans</i> -Resveratrol, emodin	Bulk	Offline, LC
Sinomenine	Sinomenine	Bulk	Offline, LC
Sulfamethoxazole	Sulfamethoxazole	Monolith	On-column, LC
Trimethoprim	Trimethoprim	Bulk, suspension	Offline, LC

Source: Haginaka, J.: Molecularly imprinted polymers as affinity-based separation media for sample preparation. *Journal of Separation Science*. 2009. 32. 1548–1565. Copyright Wiley-VCH Verlag GmbH & Co. KGaA. Reproduced with permission.

a template molecule from crude extracts of herbal medicines or herbs (Xie et al., 2001, 2002; Xie et al., 2003, 2003; Zhu and Xu, 2003; Zhuang et al., 2008).

An MIP for atropine was prepared using a multistep swelling and polymerization method. The MIP produced was applied for the determination of tropane alkaloids (atropine and scopolamine) in a commercial gastrointestinal drug by a column-switching LC system, consisting of the MIP as a precolumn and a cation-exchange column as an analytical column. Since the amount of atropine included in the commercial gastrointestinal drug was high, the leaked template molecule, atropine, did not interfere the assay of atropine. When injecting the sample solution directly to the analytical column, large amounts of interfering components are eluted at the peak of scopolamine. However, by online MISPE, tropane alkaloids (atropine and scopolamine) could be determined accurately.

A combination of an MIP column and an MS detector afforded affinity extraction and online identification of antitumor components from the herb extracts (Xie et al., 2002). An MIP for harman, a structural analogue of antitumor components, was prepared. Two antitumor components, harmine and harmaline, were extracted and identified from the methanol extract of *Peganum nigellastum* seeds. Furthermore, an MIP for quercetin, an active inhibitor of epidermal growth factor receptor (EGFR), was prepared. The crude extract of *Caragana jubata*, a Chinese traditional Tibetan medicine, was loaded onto the MIP, and two novel active EGFR inhibitors, (*E*)-piceatannol and butein, were found to be selectively retained on the MIP (Zhu and Xu, 2003). When an MIP for (*E*)-piceatannol was used as affinity media, two different compounds besides the template itself were specifically recognized by the MIP, which were identified to be butein and quercetin (Zhu et al., 2003).

7.3.1.2 Molecularly Imprinted Solid-Phase Microextraction for Environmental Applications

Although the combination of molecular imprinting technology with SPME is still in its infancy, several papers have been published demonstrating the selectivity provided by imprinted fibers, allowing the determination of target analytes at trace levels in different kinds of samples.

The simplest way to desorb analytes after MIP-SPME is performing elution by immersing the fiber in a small volume of a solvent able to disrupt the specific interactions taking place at imprinted cavities. The first example was reported by Koster et al. (2001) for the determination of brombuterol in urine samples. Analytes were extracted from urine for 45 min using an MIP-coated fiber of ~75 μm . After a washing step, brombuterol was statically eluted for 5 min in a small volume (200 μL) of a methanol/acetic acid (90:10) mixture and further analyzed by HPLC with electrochemical detection. In a similar manner, the selective extraction of triazines from soils and vegetables was performed by immersing propazine-imprinted monolith in toluene-based sample extracts for 1 h under low stirring. Then, to remove nonspecific interactions, fibers were immersed in toluene for 15 min under stirring and subsequently air-dried for 5 min and analytes were finally desorbed with 200 μL of methanol by sonication for 5 min. The full methanolic extracts were diluted with 200 μL of water and further analyzed by HPLC with UV detection. The high selectivity provided by the propazine-imprinted fiber allows the detection of target analytes at very low concentration levels, which would be extremely difficult without performing any cleanup (Turiel et al., 2007b).

When off-line elution is performed, only a small fraction of the total volume used for the elution is injected in the chromatographic system. Thus, in order to improve detection limits, the online combination of SPME to HPLC is a useful alternative. This approach has been followed by Li et al. (2009) for the SPME-HPLC analysis of prometryn in soybean and corn (Hu et al., 2007b); triazines in soybean, corn, lettuce, and soils (Hu et al., 2007a), tetracyclines in chicken feed, chicken muscle, and milk (Hu et al., 2008); and μ -blockers in urine and plasma (Hu et al., 2009) using MIP-coated fibers. After extraction and washing steps, the fibers were immersed into the chamber of the specially designed SPME-HPLC six-way injection valve, the analytes being eluted statically for a fixed time with a suitable solvent or directly by the mobile phase used for the chromatographic separation

of target analytes. Regardless of the methodology used, clean chromatograms were obtained reaching detection limits at very low concentration levels.

As mentioned previously, most of the reported imprinted fibers are thermally stable up to temperatures ranging from 250°C to 300°C, thus making them suitable for SPME-GC, which is the simplest, cheapest, and more environmental friendly approach. This methodology has been used for the determination of diacetylmorphine and analogous compounds in street heroin (Djozan and Baheri, 2007); triazines in water, rice, onion, and maize (Djozan and Ebrahimi, 2008; Djozan et al., 2009); and polybrominated diphenyl ethers in municipal wastewaters (Li et al., 2009) with high sensitivity and selectivity. Although few are the applications reported, until now, the thermal stability of imprinted fibers will surely help to the development of MIP-based SPME and to its implementation in analytical laboratories in the near future.

ACKNOWLEDGMENTS

The support for this study was received from the Greek Ministry of Education and Religious Affairs through Operational Program 'Education and Lifelong Learning' of the National Strategic Reference Framework (NSRF)—Research Funding Program 'Excellence II (Aristeia II)' under the title 'Advanced microextraction approaches based on novel nanopolymers to measure pharmaceuticals, personal care products and their transformation products in the aquatic environment' (No. 4199), which is gratefully appreciated.

REFERENCES

- Alahmadi, S.M., Mohamad, S., Jamil Maah, M. 2013. Preparation of organic-inorganic hybrid materials based on MCM-41 and its applications. *Advances in Materials Science and Engineering* 2013: 634863.
- Andersson, L.I. 2001. Selective solid-phase extraction of bio- and environmental samples using molecularly imprinted polymers. *Bioseparation* 10: 353–364.
- Andersson, L.I., Paprica, A., Arvidsson, T. 1997. A highly selective solid phase extraction sorbent for preconcentration of sameridine made by molecular imprinting. *Chromatographia* 46: 57–66.
- Baggiani, C., Anfossi, L., Giovannoli, C. 2007. Solid phase extraction of food contaminants using molecular imprinted polymers. *Analytica Chimica Acta* 591: 29–39.
- Balogh, A.G., Baba, K., Cohen, D.D., Elliman, R.G., Ensinger, W. et al. 2012. Modification, synthesis, and analysis of advanced materials using ion beam techniques. *Advances in Materials Science and Engineering* 2012: 431297.
- Bergemann, C., Müller-Schulte, D., Oster, J., À Brassard, L., Lübke, A.S. 1999. Magnetic ion-exchange nano- and microparticles for medical, biochemical and molecular biological applications. *Journal of Magnetism and Magnetic Materials* 194: 45–52.
- Brüggemann, O., Visnjeviski, A., Burch, R., Patel, P. 2004. Selective extraction of antioxidants with molecularly imprinted polymers. *Analytica Chimica Acta* 504: 81–88.
- Cacho, C., Turiel, E., Martín-Esteban, A., Pérez-Conde, C., Cámara, C. 2003. Clean-up of triazines in vegetable extracts by molecularly-imprinted solid-phase extraction using a propazine-imprinted polymer. *Analytical and Bioanalytical Chemistry* 376: 491–496.
- Caro, E., Marcé, R.M., Cormack, P.A.G., Sherrington, D.C., Borrull, F. 2003. On-line solid-phase extraction with molecularly imprinted polymers to selectively extract substituted 4-chlorophenols and 4-nitrophenol from water. *Journal of Chromatography A* 995: 233–238.
- Caro, E., Marcé, R.M., Borrull, F., Cormack, P.A.G., Sherrington, D.C. 2006. Application of molecularly imprinted polymers to solid-phase extraction of compounds from environmental and biological samples. *TrAC Trends in Analytical Chemistry* 25: 143–154.
- Chapuis, F., Pichon, V., Lanza, F., Sellergren, S., Hennion, M.C. 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. *Journal of Chromatography A* 999: 23–33.
- Chapuis, F., Pichon, V., Lanza, F., Sellergren, B., Hennion, M.C. 2004. Retention mechanism of analytes in the solid-phase extraction process using molecularly imprinted polymers: Application to the extraction of triazines from complex matrices. *Journal of Chromatography B: Analytical Technologies in the Biomedical and Life Sciences* 804: 93–101.

- Chen, B., Piletsky, S., Turner, A.P.F. 2002. Molecular recognition: Design of keys. *Combinatorial Chemistry and High Throughput Screening* 5: 409–427.
- Chen, L., Liu, J., Zeng, Q., Wang, H., Yu, A. et al. 2009. Preparation of magnetic molecularly imprinted polymer for the separation of tetracycline antibiotics from egg and tissue samples. *Journal of Chromatography A* 1216: 3710–3719.
- Chen, L., Xu, S., Li, J. 2011. Recent advances in molecular imprinting technology: Current status, challenges and highlighted applications. *Chemical Society Reviews* 40: 2922–2942.
- Djozan, D., Baheri, T. 2007. Preparation and evaluation of solid-phase microextraction fibers based on monolithic molecularly imprinted polymers for selective extraction of diacetylmorphine and analogous compounds. *Journal of Chromatography A* 1166: 16–23.
- Djozan, D., Ebrahimi, B. 2008. Preparation of new solid phase micro extraction fiber on the basis of atrazine-molecular imprinted polymer: Application for GC and GC/MS screening of triazine herbicides in water, rice and onion. *Analytica Chimica Acta* 616: 152–159.
- Djozan, D., Mahkam, M., 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. *Journal of Chromatography A* 1216: 2211–2219.
- Dong, X., Wang, N., Wang, S., Zhang, X., Fan, Z. 2004. Synthesis and application of molecularly imprinted polymer on selective solid-phase extraction for the determination of monosulfuron residue in soil. *Journal of Chromatography A* 1057: 13–19.
- Farrington, K., Regan, F. 2007. Investigation of the nature of MIP recognition: The development and characterisation of a MIP for ibuprofen. *Biosensors and Bioelectronics* 22: 1138–1146.
- Feng, Q., Zhao, L., Lin, J.M. 2009. Molecularly imprinted polymer as micro-solid phase extraction combined with high performance liquid chromatography to determine phenolic compounds in environmental water samples. *Analytica Chimica Acta* 650: 70–76.
- Ferrer, I., Lanza, F., Tolokan, A., Horvath, V.V., Sellergren, B. et al. 2000. Selective trace enrichment of chlorotriazine pesticides from natural waters and sediment samples using terbuthylazine molecularly imprinted polymers. *Analytical Chemistry* 72: 3934–3941.
- Haginaka, J. 2009. Molecularly imprinted polymers as affinity-based separation media for sample preparation. *Journal of Separation Science* 32: 1548–1565.
- Haginaka, J., Sanbe, H. 2000. Uniform-sized molecularly imprinted polymers for 2-arylpropionic acid derivatives selectively modified with hydrophilic external layer and their applications to direct serum injection analysis. *Analytical Chemistry* 72: 5206–5210.
- Haginaka, J., Takehira, H., Hosoya, K., Tanaka, N. 1999. Uniform-sized molecularly imprinted polymer for (S)-naproxen selectively modified with hydrophilic external layer. *Journal of Chromatography A* 849: 331–339.
- Hosoya, K., Yoshizako, K., Shirasu, Y., Kimata, K., Araki, T. et al. 1996. Molecularly imprinted uniform-size polymer-based stationary phase for high-performance liquid chromatography structural contribution of cross-linked polymer network on specific molecular recognition. *Journal of Chromatography A* 728: 139–147.
- Hu, S.G., Wang, S.W., He, X.W. 2003. An amobarbital molecularly imprinted microsphere for selective solid-phase extraction of phenobarbital from human urine and medicines and their determination by high-performance liquid chromatography. *Analyst* 128: 1485–1489.
- Hu, S.G., Li, L., He, X.W. 2005. Solid-phase extraction of esculetin from the ash bark of Chinese traditional medicine by using molecularly imprinted polymers. *Journal of Chromatography A* 1062: 31–37.
- Hu, X., Hu, Y., Li, G. 2007a. Development of novel molecularly imprinted solid-phase microextraction fiber and its application for the determination of triazines in complicated samples coupled with high-performance liquid chromatography. *Journal of Chromatography A* 1147: 1–9.
- Hu, X., Hu, Y., Li, G. 2007b. Preparation and characterization of prometryn molecularly imprinted solid-phase microextraction fibers. *Analytical Letters* 40: 645–660.
- Hu, X., Pan, J., Hu, Y., Huo, Y., Li, G. 2008. Preparation and evaluation of solid-phase microextraction fiber based on molecularly imprinted polymers for trace analysis of tetracyclines in complicated samples. *Journal of Chromatography A* 1188: 97–107.
- Hu, X., Pan, J., Hu, Y., Li, G. 2009. Preparation and evaluation of propranolol molecularly imprinted solid-phase microextraction fiber for trace analysis of β -blockers in urine and plasma samples. *Journal of Chromatography A* 1216: 190–197.
- Ji, Y., Yin, J., Xu, Z., Zhao, C., Huang, H. et al. 2009. Preparation of magnetic molecularly imprinted polymer for rapid determination of bisphenol A in environmental water and milk samples. *Analytical and Bioanalytical Chemistry* 395: 1125–1133.

- Jiang, G., Chen, T., Yang, Q. 2012. Photocatalytic materials. *Advances in Materials Science and Engineering* 2012: 186948.
- Karasová, G., Lehotay, J., Sádecká, J., Skačáni, I., Lachová, M. 2005. Selective extraction of derivatives of *p*-hydroxybenzoic acid from plant material by using a molecularly imprinted polymer. *Journal of Separation Science* 28: 2468–2476.
- Karasová, G., Lehotay, J., Kłodzinska, E., Gadzała-Kopciuch, R., Buszewski, B. 2006. Comparison of several extraction methods for the isolation of benzoic acid derivatives from *Melissa officinalis*. *Journal of Liquid Chromatography and Related Technologies* 29: 1633–1644.
- Koster, E.H.M., Crescenzi, C., Den Hoedt, W., Ensing, K., De Jong, G.J. 2001. Fibers coated with molecularly imprinted polymers for solid-phase microextraction. *Analytical Chemistry* 73: 3140–3145.
- Kyzas, G.Z., Bikiaris, D.N. 2014. Molecular imprinting for high-added value metals: An overview of recent environmental applications. *Advances in Materials Science and Engineering* 2014: 93263.
- Lasáková, M., Jandera, P. 2009. Molecularly imprinted polymers and their application in solid phase extraction. *Journal of Separation Science* 32: 799–812.
- Lee, T.P., Saad, B., Khayoon, W.S., Salleh, B. 2012. Molecularly imprinted polymer as sorbent in micro-solid phase extraction of ochratoxin A in coffee, grape juice and urine. *Talanta* 88: 129–135.
- Li, M.K.Y., Lei, N.Y., Gong, C., Yu, Y., Lam, K.H. et al. 2009. An organically modified silicate molecularly imprinted solid-phase microextraction device for the determination of polybrominated diphenyl ethers. *Analytica Chimica Acta* 633: 197–203.
- Liu, J.Q., Wulff, 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. *Journal of the American Chemical Society* 126: 7452–7453.
- Lin, L.Q., Zhang, J., Fu, Q., He, L.C., Li, Y.C. 2006. Concentration and extraction of sinomenine from herb and plasma using a molecularly imprinted polymer as the stationary phase. *Analytica Chimica Acta* 561: 178–182.
- Liu, X., Ouyang, C., Zhao, R., Shangguan, D., Chen, Y. et al. 2006. Monolithic molecularly imprinted polymer for sulfamethoxazole and molecular recognition properties in aqueous mobile phase. *Analytica Chimica Acta* 571: 235–241.
- Lok, C.M., Son, R. 2009. Application of molecularly imprinted polymers in food sample analysis—A perspective. *International Food Research Journal* 16: 127–140.
- Martín-Esteban, A., Fernández, P., Cámara, C. 1997. Immunosorbents: A new tool for pesticide sample handling in environmental analysis. *Fresenius' Journal of Analytical Chemistry* 357: 927–933.
- Mena, M.L., Agüí, L., Martínez-Ruiz, P., Yáñez-Sedeño, P., Reviejo, A.J. et al. 2003. Molecularly imprinted polymers for on-line clean up and preconcentration of chloramphenicol prior to its voltammetric determination. *Analytical and Bioanalytical Chemistry* 376: 18–25.
- Mobarak, Y., Bassyouni, M., Almutawa, M. 2013. Materials selection, synthesis, and dielectrical properties of PVC nanocomposites. *Advances in Materials Science and Engineering* 2013: 149672.
- Nakamura, M., Ono, M., Nakajima, T., Ito, Y., Aketo, T. et al. 2005. Uniformly sized molecularly imprinted polymer for atropine and its application to the determination of atropine and scopolamine in pharmaceutical preparations containing Scopolia extract. *Journal of Pharmaceutical and Biomedical Analysis* 37: 231–237.
- O'Shannessy, D.J., Ekberg, B., Mosbach, K. 1989. Molecular imprinting of amino acid derivatives at low temperature (0°C) using photolytic homolysis of azobisnitriles. *Analytical Biochemistry* 177: 144–149.
- Pap, T., Horváth, V., Tolokán, A., Horvai, G., Sellergren, B. 2002. Effect of solvents on the selectivity of terbutylazine imprinted polymer sorbents used in solid-phase extraction. *Journal of Chromatography A* 973: 1–12.
- Pichon, V., Chapuis-Hugon, F. 2008. Role of molecularly imprinted polymers for selective determination of environmental pollutants—A review. *Analytica Chimica Acta* 622: 48–61.
- Pichon, V., Haupt, K. 2006. Affinity separations on molecularly imprinted polymers with special emphasis on solid-phase extraction. *Journal of Liquid Chromatography and Related Technologies* 29: 989–1023.
- Pichon, V., Bouzige, M., Miège, C., Hennion, M.C. 1999. Immunosorbents: Natural molecular recognition materials for sample preparation of complex environmental matrices. *TrAC Trends in Analytical Chemistry* 18: 219–235.
- Piletsky, S.A., Piletska, E.V., Karim, K., Freebairn, K.W., Legge, C.H. et al. 2002. Polymer cookery: Influence of polymerization conditions on the performance of molecularly imprinted polymers. *Macromolecules* 35: 7499–7504.
- Radenović, A., Malina, J., Sofilić, T. 2013. Characterization of ladle furnace slag from carbon steel production as a potential adsorbent. *Advances in Materials Science and Engineering* 2013: Article ID 198240.

- Ramos, L., Smith, R.M. 2007a. Special issue: Advances in sample preparation—Part I. *Journal of Chromatography A* 1152: 1–286.
- Ramos, L., Smith, R.M. 2007b. Special issue: Advances in sample preparation—Part II. *Journal of Chromatography A* 1153: 1–310.
- Rezaei, B., Mallakpour, S., Rahmadian, O. 2008. A selective solid-phase extraction and preconcentration method with using molecularly imprinted polymer for piroxicam in pharmaceutical sample. *Analytical Letters* 41: 1818–1831.
- Sanbe, H., Haginaka, J. 2003. Restricted access media-molecularly imprinted polymer for propranolol and its application to direct injection analysis of β -blockers in biological fluids. *Analyst* 128: 593–597.
- Sasaki, H., Kobashi, Y., Nagai, T., Maeda, M. 2013. Application of electron beam melting to the removal of phosphorus from silicon: Toward production of solar-grade silicon by metallurgical processes. *Advances in Materials Science and Engineering* 2013: Article ID 857196.
- Sellergren, B. 1994a. Direct drug determination by selective sample enrichment on an imprinted polymer. *Analytical Chemistry* 66: 1578–1582.
- Sellergren, B. 1994b. Imprinted dispersion polymers: A new class of easily accessible affinity stationary phases. *Journal of Chromatography A* 673: 133–141.
- Shea, K.J., Sasaki, D.Y. 1991. An analysis of small-molecule binding to functionalized synthetic polymers by ^{13}C CP/MAS NMR and FT-IR spectroscopy. *Journal of the American Chemical Society* 113: 4109–4120.
- Sibrian-Vazquez, M., Spivak, D.A. 2004. Characterization of molecularly imprinted polymers employing crosslinkers with nonsymmetric polymerizable groups. *Journal of Polymer Science, Part A: Polymer Chemistry* 42: 3668–3675.
- Smith, R.M. 2003. Before the injection—Modern methods of sample preparation for separation techniques. *Journal of Chromatography A* 1000: 3–27.
- Spivak, D., Gilmore, M.A., Shea, K.J. 1997. Evaluation of binding and origins of specificity of 9-ethyladenine imprinted polymers. *Journal of the American Chemical Society* 119: 4388–4393.
- Srinivasan, R. 2011. Advances in application of natural clay and its composites in removal of biological, organic, and inorganic contaminants from drinking water. *Advances in Materials Science and Engineering* 2011: Article ID 872531.
- Tamayo, F.G., Casillas, J.L., Martín-Esteban, A. 2003. Highly selective fenuron-imprinted polymer with a homogeneous binding site distribution prepared by precipitation polymerisation and its application to the clean-up of fenuron in plant samples. *Analytica Chimica Acta* 482: 165–173.
- Tamayo, F.G., Casillas, J.L., Martín-Esteban, A. 2005. Evaluation of new selective molecularly imprinted polymers prepared by precipitation polymerisation for the extraction of phenylurea herbicides. *Journal of Chromatography A* 1069: 173–181.
- Tamayo, F.G., Turiel, E., Martín-Esteban, A. 2007. Molecularly imprinted polymers for solid-phase extraction and solid-phase microextraction: Recent developments and future trends. *Journal of Chromatography A* 1152: 32–40.
- Turiel, E., Martín-Esteban, A. 2010. Molecularly imprinted polymers for sample preparation: A review. *Analytica Chimica Acta* 668: 87–99.
- Turiel, E., Martín-Esteban, A., Fernández, P., Pérez-Cond, C., Cámara, C. 2001. Molecular recognition in a propazine-imprinted polymer and its application to the determination of triazines in environmental samples. *Analytical Chemistry* 73: 5133–5141.
- Turiel, E., Martín-Esteban, A., Tadeo, J.L. 2007a. Molecular imprinting-based separation methods for selective analysis of fluoroquinolones in soils. *Journal of Chromatography A* 1172: 97–104.
- Turiel, E., Tadeo, J.L., Martín-Esteban, A. 2007b. Molecularly imprinted polymeric fibers for solid-phase microextraction. *Analytical Chemistry* 79: 3099–3104.
- Wang, J., Cormack, P.A.G., Sherrington, D.C., Khoshdel, E. 2003. Monodisperse, molecularly imprinted polymer microspheres prepared by precipitation polymerization for affinity separation applications. *Angewandte Chemie* 115.
- Whitcombe, M.J., Rodriguez, M.E., Villar, P., Vulfson, E.N. 1995. A new method for the introduction of recognition site functionality into polymers prepared by molecular imprinting—Synthesis and characterization of polymeric receptors for cholesterol. *Journal of the American Chemical Society* 117: 7105–7111.
- Wulff, G., Heide, B., Helfmeier, G. 1987. Enzyme-analogue built polymers, 24 On the distance accuracy of functional groups in polymers and silicas introduced by a template approach. *Reactive Polymers, Ion Exchangers, Sorbents* 6: 299–310.
- Xie, J., Zhu, L., Luo, H., Zhou, L., Li, C. et al. 2001. Direct extraction of specific pharmacophoric flavonoids from ginkgo leaves using a molecularly imprinted polymer for quercetin. *Journal of Chromatography A* 934: 1–11.

- Xie, J., Zhu, L., Xu, X. 2002. Affinitive separation and on-line identification of antitumor components from *Peganum nigellastrum* by coupling a chromatographic column of target analogue imprinted polymer with mass spectrometry. *Analytical Chemistry* 74: 2352–2360.
- Xie, J., Chen, L., Li, C., Xu, X. 2003. Selective extraction of functional components derived from herb in plasma by using a molecularly imprinted polymer based on 2,2-bis(hydroxymethyl)butanol trimethacrylate. *Journal of Chromatography B: Analytical Technologies in the Biomedical and Life Sciences* 788: 233–242.
- Zhang, Y., Liu, R., Hu, Y., Li, G. 2009. Microwave heating in preparation of magnetic molecularly imprinted polymer beads for trace triazines analysis in complicated samples. *Analytical Chemistry* 81: 967–976.
- Zhu, L., Xu, X. 2003. Selective separation of active inhibitors of epidermal growth factor receptor from *Caragana jubata* by molecularly imprinted solid-phase extraction. *Journal of Chromatography A* 991: 151–158.
- Zhu, L., Chen, L., Xu, X. 2003. Application of a molecularly imprinted polymer for the effective recognition of different anti-epidermal growth factor receptor inhibitors. *Analytical Chemistry* 75: 6381–6387.
- Zhuang, X., Dong, X., Ma, S., Zhang, T. 2008. Selective on-line extraction of trans-resveratrol and emodin from *Polygonum cuspidatum* using molecularly imprinted polymer. *Journal of Chromatographic Science* 46: 739–742.