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REVIEWS

Food Analyses Using Molecularly Imprinted Polymers

Olof Ramström,*,† Kristina Skudar,† John Haines,‡ Pradip Patel,‡ and Oliver Brüggemann*,§

Pure and Applied Biochemistry, Center for Chemistry and Chemical Engineering, Lund University, P.O. Box 124, SE-221 00, Lund, Sweden; Rapid Methods Section, Leatherhead Food RA, Randalls Road, Leatherhead, Surrey KT22 7RY, United Kingdom; and Institut für Technische Chemie - TC 8, Technische Universität Berlin, Strasse d. 17 Juni 124, 10623 Berlin, Germany

Molecular imprinting technology (MIT) is a technique for generating polymers bearing biomimetic receptors. It offers several advantages to the agrofood industry in areas such as analysis, sensoring, extraction, or preconcentration of components. It has the potential of becoming a tool for acquiring truly simple, rapid, and robust direct measurements. In this review, the special features of MIT that have bearing on food science and technology are highlighted.

Keywords: *Molecular imprinting; polymers; food; analysis; sensors; solid phase extraction; chromatography*

INTRODUCTION

The agricultural and food sector is in constant need of improved analytical techniques that can be used to control manufacturing processes and the safety and quality of the products (*1*, *2*). Increasing demands and regulations from authorities in Europe as well as in United States, together with an enhanced public understanding, are incentives for better controlling the food that is produced. Of special interest are cost-effective methods that are fast and reliable and can be used in rough environments, methods that can be used in monitoring food processes, and techniques that provide fast on-the-spot answers during field-work. To date, many analytical methods are based on natural specific recognition elements, such as antibodies, enzymes, and receptors. These include, for example, enzyme assays and immunoassays, biosensors, and various affinity techniques. Although of fundamental importance, these methods sometimes suffer from features such as low stability and high production costs. Other common analytical methods constitute physicochemical techniques such as high-performance liquid chromatography (HPLC), capillary electrophoresis (CE), gas chromatography (GC), nuclear magnetic resonance (NMR), and mass spectrometry (MS). For biological samples, HPLC is still the major analytical tool, especially powerful when coupled to advanced detectors such as MS or NMR. Also, with this technique, new and more specific stationary phases are ever needed. Thus, alternative techniques are therefore of great interest and value.

* Corresponding authors [(O.R.) telephone +46 46-2228259; fax +46 46−2224611; e-mail Olof.Ramstrom@tbiokem.lth.se; (O.B.) telephone +49-30-314-26006; fax +49-30-314-79552; e-mail brueggemann@chem.tu-berlin.de].
† Lund University.
‡ Leatherhead Food RA.
§ Technische Universität Berlin.

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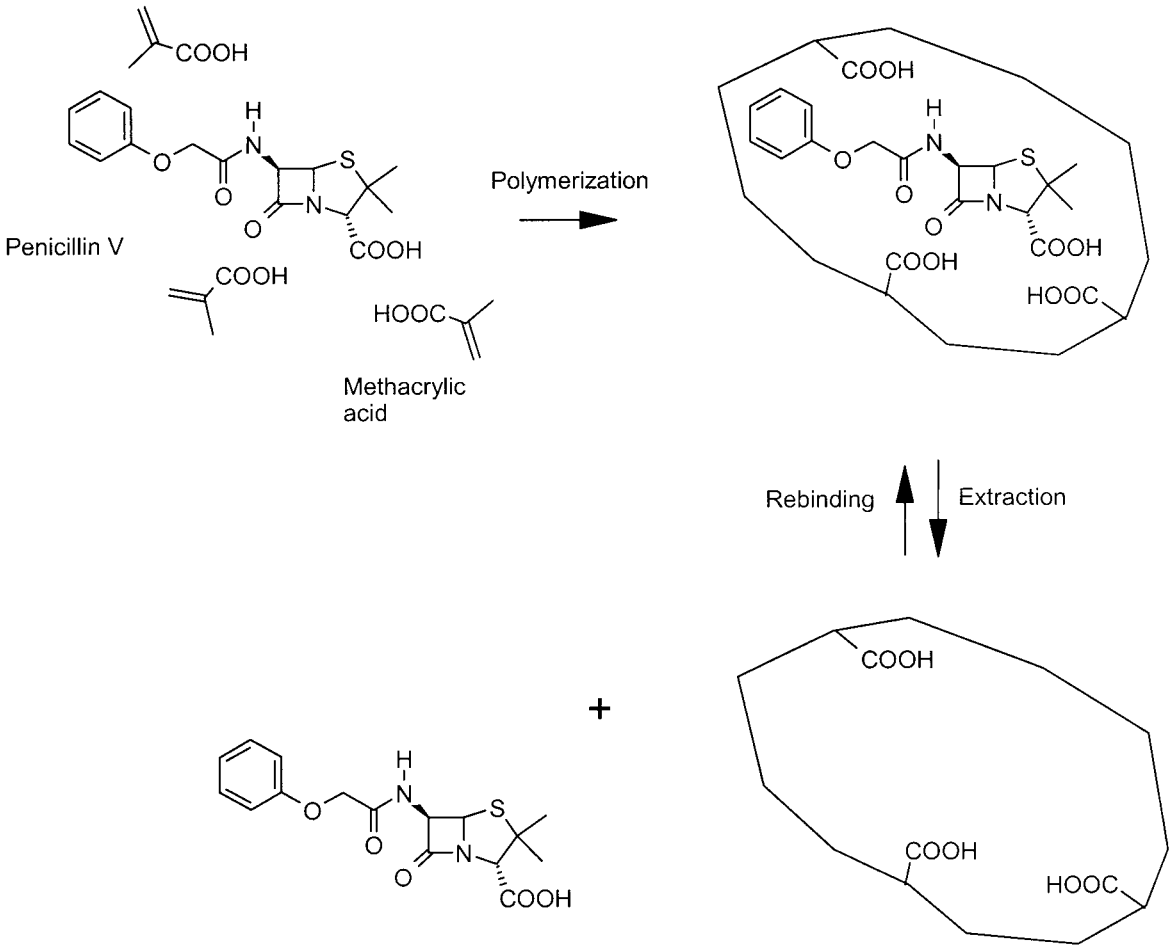


Figure 1. Schematic representation of a molecular imprinting process. Complexes, formed in solution by interactions between the print molecule (here penicillin V) and one or more functional monomer(s) (e.g., methacrylic acid), become fixed during polymerization with a cross-linker. Polymeric recognition sites are formed, complementary in shape and functionality to the print species.

Molecular imprinting technology (MIT) is a burgeoning field that offers several advantages to the analytical food chemist. With this method it is possible to design and produce tailor-made, stable recognition matrices for a wide range of analytes. These matrices subsequently can be employed in a multitude of analytical formats. In this paper, we review the efforts that have been made of the use of molecularly imprinted materials for agrofood analyses to date and highlight some trends and possible future developments of the technology in this area.

MOLECULAR IMPRINTING TECHNOLOGY

General Description of MIT. MIT has over the past few years developed to become a capable alternative to common analytical methods based on natural recognition elements (*3*−*7*). Originally introduced as a means to create binding sites in synthetic polymers, the technique has now matured and is established for several applications. The technology offers an effective means to produce materials that are able to mimic natural binding entities such as antibodies and receptors.

Molecular imprinting is, briefly described, a technology in which macromolecular structures are prepared by a polymerization process in which sites are introduced by use of a ligand as a template in a casting procedure. The selected ligand or *print molecule* is first allowed to establish bond formations with polymerizable functionalities, and the resulting complexes or adducts are subsequently copolymerized with cross-linkers into a rigid polymer. Following extraction of the print molecule, specific recognition sites are left in the polymer, where the spatial arrangement of the complementary functional entities of the polymer network together with the shape image correspond to the imprinted molecule (*4*). The technique is outlined in Figure 1, where penicillin V has been employed as the print molecule.

Molecularly imprinted materials can be prepared in different ways, and two basic approaches to molecularly imprinted materials may be distinguished: on the one hand is the self-assembly approach, where the prearrangement between the print molecule and the functional monomers is formed by noncovalent or metal coordination interactions; and on the other hand the preorganized approach, where the aggregates in solution prior to polymerization are maintained by (reversible) covalent bonds. By use of a high percentage of cross-linker, polymers of substantial rigidity and complete insolubility are obtained.

The physical and chemical characteristics of molecularly imprinted materials are highly appealing. These materials exhibit high physical and chemical resistance against external degrading factors. Thus, molecularly imprinted polymers (MIPs) are remarkably stable against

mechanical stress and high temperatures and pressures, resistant against treatment with acid, base, or metal ions, and stable in a wide range of solvents (*8*, *9*). However, it has to be noted that because MIPs are typically made in organic solvents, their optimal binding conditions usually require an organic-based medium. The storage endurance of the polymers is also very high: Storage for several years at ambient temperature leads to no apparent reduction in performance (*10*). Furthermore, the polymers can be used repeatedly, well in excess of 100 times during periods of years without loss of the "memory effect". In comparison with natural, biological recognition sites, which are often proteins, these properties would in a number of cases certainly be advantageous.

Applications of Imprinted Polymers. A number of applications of MIT have been foreseen and developed, especially over the past few years. In essence, all of these are based on the use of the imprinted materials as recognition elements for a certain analyte or group of analytes. Thus, molecularly imprinted materials have been successfully applied in affinity chromatography, binding assays, and sensor development. The materials have also been used for synthetic applications in controlling or inducing a certain chemical reaction. In this way, the MIPs can be used as equilibrium shifters in reversible reactions, as guides for site-specific assembly, and directly as catalysts.

Affinity-based separation is the most developed area for molecularly imprinted materials. Numerous studies have concentrated on chiral resolutions, in part due to the ease of validating and assessing the materials (*11*). Liquid chromatography (LC), and in particular HPLC, has been a general tool in these studies, although some efforts in the CE area have been made (*12*−*15*). Inherent to these LC methodologies is the weak affinity properties of such systems, depending to some extent on the flow rate, and estimated binding affinities generally lie within the millimolar range (*16*). However, the affinities can be advantageous for many applications because strong elution conditions can be avoided (*17*).

Another area, which has realized intense research efforts more recently, is the use of molecularly imprinted materials in *solid phase extraction* (SPE) (*18*−*23*). Here, a sample of low concentration can be dramatically enriched by passing a large volume over a molecularly imprinted material. The bound analyte is then extracted into a small volume, which improves its further analysis. In comparison to other materials on the market, such as reversed-phase columns, the imprinted materials add an element of selectivity to the separation process. Thus, the bulk matrix can be washed away without affecting the bound analyte.

The extraordinary binding properties of molecularly imprinted materials is best shown in *binding assays*, using compounds that can be detected in very low concentrations (radioligands, fluorescently labeled ligands, etc.). In this case, the equilibrium conditions, in conjunction with the low concentration of analyte, reveal the best binding sites of the materials. In several cases, apparent binding strengths have been monitored in the nanomolar range (*24*).

Furthermore, there has been high interest in using molecularly imprinted materials for *sensor development* (*25*, *26*). Given the attractive properties of the materials with respect to chemical and physical stabilities, in combination with high configurational versatility, many researchers have tried to exchange natural recognition elements, such as enzymes, antibodies, and receptors, for MIPs.

Table 1. Food Analytes

food analyte class	example
pharmaceuticals	antibiotics, steroids
additives	preservatives, sweeteners, colorants, flavors
components	sugars, peptides, proteins, vitamins, fats, oils
contaminants	pathogenic bacteriae, microbial toxins
herbicides, pesticides	triazines
minerals, trace metals	heavy-metal ions

Imprinted materials can also be applied to *synthetic systems*. In these cases, catalytic groups can be built into the recognition sites of the MIPs (*27*, *28*), leading to polymers with enzyme-like properties. The materials can also be used to guide a reaction (*29*), for example, to push a reaction toward an otherwise unfavorable equilibrium.

In addition to the above-mentioned usages, several less advanced applications have been developed. These include the use of MIPs as *controlled release* matrices (*30*) and in the *screening of combinatorial libraries* (*31*, *32*).

FOOD ANALYSES

Introduction. The modern food industry is a complex and highly organized business, manufacturing a wide range of food types, including minimally processed products, modified atmosphere-packaged foods, specialist dietary formulas, and products with few or no additives. The industry is increasingly aware of the demands from the consumer for wholesome manufactured foods and, indeed, must now ensure compliance with national and international legislation on ensuring food safety and quality for the consumer. With requirements such as these, the industry is aware of the risks posed by improper control of the product quality and the resulting financial consequences. The food industry is rapidly changing its practices of end product testing (quality control) to wider quality assurance (e.g., HACCP) and management systems (e.g., BS5750 and TQM). Analytical testing for microbiological and non-microbiological analytes must be considered in the context of a properly evaluated and implemented quality assurance system, which can be specific, rapid, and on- or near-line to cope with modern just-in-time manufacturing. From the food safety perspective, the majority of testing carried out by the agrofood industry is for microorganisms (e.g., pathogens and spoilage organisms), microbial toxins (e.g., mycotoxins and bacterial toxins), antibiotic residues, pesticides, and artificial hormones (cf. Table 1).

Numerous rapid detection kits and instruments [e.g., kits based on enzyme-linked immunosorbent assays (ELISAs), DNA probes, and PCR; and electrical impedance-based instruments] are available for pathogens. Techniques such as direct epifluorescent filter test (DEFT), ATP bioluminescence, flow cytometry, and electrical impedance techniques have been reported for food spoilage flora, including spoilage bacteria and yeasts (*33*). However, these techniques are generally not robust due to interference from the background food components and the turbidity of food homogenates. The availability of efficient and robust techniques that can simply and rapidly isolate and concentrate the target

microbial flora from the background interference would allow both an increase in the speed of analysis and the reliable detection of target organisms in a wide range of food matrices.

The most commonly tested chemical analytes include antibiotics (e.g., β-lactams and sulfonamides), mycotoxins (e.g., aflatoxins and ochratoxins), and pesticides (e.g., organophosphates and atrazine). There is also concern over the presence of degraded carrageenans (polysaccharide) in infant foods and bioavailability of vitamins. The current techniques for the analysis of polysaccharides (*34*), antibiotics (*35*), and vitamins (*36*) include GC, HPLC, electrophoresis, microbial assays, radioligand assays, and immunological tests. Each technique has its advantages and limitations (*37*). The major limitations of the chromatographic techniques include the requirement for high technical skills, expensive equipment, and lengthy and cumbersome sample preparation, whereas microbiological assays are not always reliable, require technical expertise, and are time-consuming. ELISAs are technically simple, but the antibody reagents can show batch-to-batch variation; the assays are not wholly robust, and the commercial kits generally have limited shelf life.

Overall, real-time analytical techniques are required to address the changes in food production testing practices and to monitor compliance with international and European food safety legislation. Considerable cost savings can occur through proactive measures such as effective intervention during food processing if problems arise and minimum holding time for the manufactured products. The control of certain analyte concentrations (e.g., vitamins in fortified products) can also avoid unnecessary wastage, thus further reducing costs. In addition, any new technique must be capable of monitoring the target analytes in a wide range of foodstuffs, including raw milk and meat products, infant foods, and beverages.

Present Applications of MIPs in Food Chemistry. Intense ongoing research in the food and agricultural area has proven that MIPs can be efficiently used in this area (cf. Table 2.). The majority of interest has been focused upon the analysis of herbicides and pesticides, but other analytes have been the object for research as well. Thus, MIPs have been developed for all food analyte classes indicated in Table 1.

Pharmaceuticals. Over the past few years, strong emphasis has been put upon the development of MIPs against drugs. Generally, these attempts have been made toward drugs acting within humans, but some efforts have been invested in targeting animal drugs as well. Of special interest in this area are the antibiotic drugs, the treatment of farm animals with antibiotics consuming half of the world antibiotic output (*89*).

The first study in this area concerned macrolide antibiotics (*39*), a drug class that is commonly used in the treatment of a variety of diseases. In this case, MIPs were prepared against erythromycin A, oleandomycin, and tylosin and tested for their recognition properties in the HPLC mode in comparison to other macrolides having similar structures. The resultant polymers displayed efficient selectivity of their respective template species.

Recently, MIPs have also been developed for β-lactam antibiotics (*43*, *44*). Here, penicillin V, penicillin G, and oxacillin were used as templates and the properties monitored using the MIPs as stationary phases in HPLC. The results showed that imprinted materials could be developed, which proved to be selective for the respective template. Furthermore, MIP protocols were also developed, resulting in selectivities for the β-lactam group in general. A further benefit of these MIPs was that they proved to be efficient also in aqueous phase.

A β-lactam antibiotic was also chosen as a template molecule by other researchers (*38*), namely, ampicillin. The generated MIP was applied in assays for binding ampicillin in aqueous media, showing two different populations of binding sites within the polymer. A Scatchard graph was generated resulting in binding constants (K_D) of 0.03 and 0.96 mmol/L and site densities of 5.8 and 42 μmol/g, respectively.

A fourth study concerning antibiotics was aimed toward chloramphenicol (*42*). This bacteriostatic anti-

Table 2. Food Analytes Used in MIT

print species	application	reference
Pharmaceuticals		
ampicillin	assay	*38*
erythromycin A	LC	*39*
oleandomycin	LC	*39*
tylosin	LC	*39*
clenbuterol	SPE	*40*
epinephrine	assay	*41*
chloramphenicol	LC	*42*
penicillin V	LC	*43*
penicillin G	LC	*43*
oxacillin	LC	*43*, *44*
hexestrol	LC	*45*
cortisol	LC	*46*
estradiol	LC	*47*
estradiol	assay	*48*
ethynylestradiol	assay	*49*
nicotine	SPE	*50*
Food Additives		
Cbz-aspartame	synthesis	*29*
caffeine	sensor	*51*
caffeine	assay	*52*
menthol	assay	*53*, *54*
Food Components		
amino acids/peptides	LC, assay	*55*
carbohydrates	LC, assay	*4*, *56*
cholesterol	LC	*57*
cholesterol	assay	*58*−*60*
cholesterol	sensor	*61*
flavonol	sensor	*62*
methyl-β-glucose	sensor	*63*
phenylalanine	LC	*64*
proteins	LC	*65*−*67*
Food Contaminants		
Listeria monocytogenes *Staphylococcus aureus*	assay	*68*
Herbicides, Pesticides		
atrazine	assay	*69*−*71*
atrazine	SPE	*20*, *21*
atrazine	LC	*70*−*73*
atrazine	sensor	*74*
bentazone	SPE, LC	*75*
terbuthylazine	SPE	*76*
2,4-D-phenoxyacetic acid	assay	*77*
prometryn	LC	*78*
s-triazine	assay, LC	*70*
triazine	SPE, LC	*79*
triazine	sensor	*80*
Trace Metals		
Co^{2+}	recognition	*81*
Cu^{2+}	recognition	*81*, *82*
Eu^{3+}	recognition	*83*
Hg^{2+}	recognition	*83*
Ni^{2+}	recognition	*81*, *82*
Pb^{2+}	recognition	*84*
Zn^{2+}	recognition	*82*, *85*−*88*

biotic is effective for a wide range of infectious diseases and distributes uniformly throughout the body. In part because of production of aplastic anemia and other blood dyscrasias in a small percentage of patients treated, governmental bodies specifically disallow its use in food-producing animals. Here, fluorescent detection and displacement chromatography were employed in the analyses, which yielded a detection range of 10−3000 μM.

In another very recent study, clenbuterol was targeted (*40*). Clenbuterol is a growth-promoting drug in the β-adrenergic-agonist class of compounds. Its illegal use, particularly in show animals, is linked to its ability to induce weight gain and a greater proportion of muscle to fat, and it has also been at the center of livestock show and horseracing scandals. Clenbuterol has been associated with the acute poisoning of humans who consumed meat from clenbuterol-fed animals. In the cited study, experiments were performed using the MIPs in SPE with recovery rates of clenbuterol of 75% from urine samples.

Piletsky et al. have demonstrated that MIPs can be applied as recognition elements in enzyme-linked assays for β-agonist analyses (*41*). They coated microplates with a polymer layer imprinted with epinephrine. The increased affinity of the polymer toward the template was determined when using a conjugate of horseradish peroxidase and norephedrine for the assay.

In another publication, the determination of nicotine and its oxidation products in nicotine chewing gum was performed after a nicotine-imprinted polymer had been applied as phase for SPE (*50*). Without such a cleanup step, none of the investigated analytes could be determined when using a coupled reversed-phase HPLC column for separation.

Stilbene estrogenic substances are banned from application in the European Union (EU). However, their use as growth promoters is allowed in other countries. Consequently, it is necessary to determine their content in animal tissues imported into the EU. A polymer molecularly imprinted with hexestrol as an example for this group of artificial estrogenic compounds was investigated in HPLC, showing obvious imprinting factors of up to 6.39 (*45*).

Furthermore, several other steroids have been chosen as templates for molecular imprinting. Baggiani et al. focused on the steroid cortisol, which could be separated from structurally related steroids with HPLC applying a polymer imprinted with cortisol. They observed an imprinting factor of 9.71 compared with a blank polymer (*46*). A polymer imprinted with β-estradiol was used for the determination of β-estradiol in HPLC based on a fluorescence sensing system (*47*). When imprinted and non-imprinted polymers were compared, an imprinting factor of 8.83 was calculated, and β-estradiol could be detected in the range of 0.1−4 μmol/L. An interesting approach was reported by Ye et al. They generated monodisperse microspheres imprinted with 17β-estradiol and investigated the polymers in competitive radioassays, which demonstrated the high specificity of the MIP toward the template (*48*). A structurally related compound was molecularly imprinted by Idziak et al., namely, 17α-ethynylestradiol (*49*). In immunoassays, it could be shown that the recognition properties of the MIP toward the template were comparable with those of antibodies, or even better.

Additives. Food additives is the collective name for chemicals used to improve food character. Aspects such as taste, color, texture, and food longevity can be controlled by additives. This very broad compound class includes substances such as preservatives, natural and artificial sweeteners, colorants, and flavors.

Several natural sweeteners, including glucose (*56*, *63*), galactose (*56*, *90*), fructose (*90*), and mannose (*91*), have been used in various protocols using both self-assembly and preorganized imprinting approaches. These studies have clearly shown that high regio- and enantioselectivities can indeed be achieved with MIPs against carbohydrates. In addition, the application of MIPs in binding assays (*56*) and sensor development (*63*) has also been addressed.

In a recent study, the artificial sweetening agent aspartame was used as a template to prepare selective adsorbents for use as synthetic auxiliary agents (*29*). Here, MIPs selective for α-aspartame were used as thermodynamic traps to enhance the product formation in an enzymatic equilibrium reaction. In the thermolysin-catalyzed condensation of Cbz-L-aspartate with L-phenylalanine methyl ester, the yield of Cbz-α-aspartame could be dramatically increased by use of an MIP against the product. The MIP acted as a second equilibrium step, pulling the unfavorable equilibrium in the forward direction.

The flavor additive monosodium glutamate (MSG) may be one of the most slandered of additives. Nevertheless, it can, when consumed in large quantities, result in a variety of disorders such as pain and heart arrhythmia. To date, MIPs have not been applied to selectively bind MSG, but studies in this line have been presented (*64*, *92*, *93*). Other flavor additives such as menthol (*53*, *54*) and caffeine (*51*, *52*) have also been successfully applied in molecular imprinting, both for binding assays and caffeine as well for sensoring (*51*).

Components. A large number of studies have been targeted against typical food components such as amino acids, peptides, proteins, vitamins, nucleotides, sugars, and fats. Of these, amino acids and sugars have been the most attractive for use as imprint species (for reviews, see, e.g., refs *4* and *55*). Features such as high availability, structural diversity, and low cost have contributed to their extensive use, and several basic recognition studies have been developed using these compounds. Most of the studies with amino acids and peptides involve N- and/or C-protected derivatives, often necessary for dissolution. Recently, however, free amino acids were used in an imprinting protocol based on metal coordination interactions (*64*). This study opens a potential way of using MIPs in monitoring phenylalanine titers, the presence of which can be of concern to persons suffering from phenylketonuria disorder.

Imprinting protocols using proteins as target substances are generally more difficult to master, in part due to the flexibility and size of the protein structure. Nevertheless, several studies in this area have been published using proteins such as transferrin [MIP to be applied in HPLC (*65*)], RNase A [HPLC (*55*, *66*)], urease [binding assay (*67*)], and myoglobin [SPE (*94*)]. These studies point to the possibility of preparing efficient MIPs toward food proteins.

Few studies in the imprinting area have been directly targeted toward vitamins, the only ones being a preliminary ellipsometric study of vitamin K (*95*) and the use of pyridoxal (vitamin B_6) in a catalytic study (*96*)

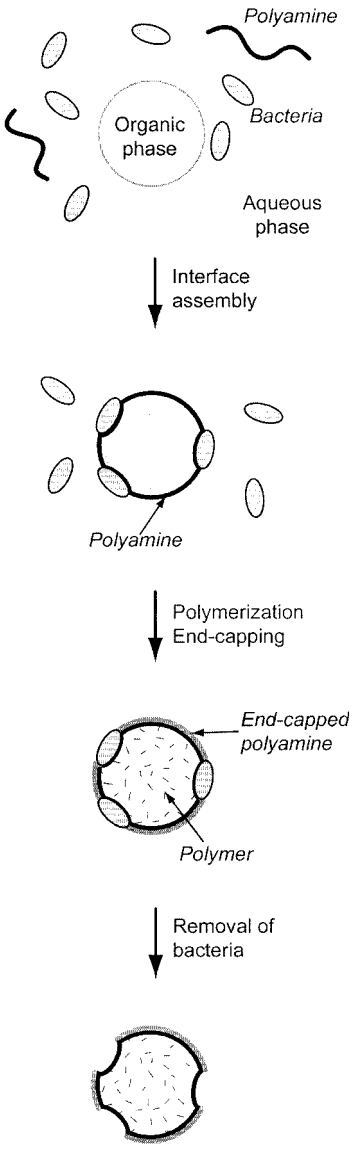


Figure 2. Surface imprinting of whole cells (*68*). Bacteria cells assemble to the interface between monomer phase droplets, covered with a polyamine, and the surrounding aqueous media. The droplets are subsequently polymerized and the exposed amino groups capped. Following removal of the bacteria, recognition sites are formed on the surface of the particles where the shape of the sites, together with the noncapped amino groups, corresponds to the form and functionality of the bacteria.

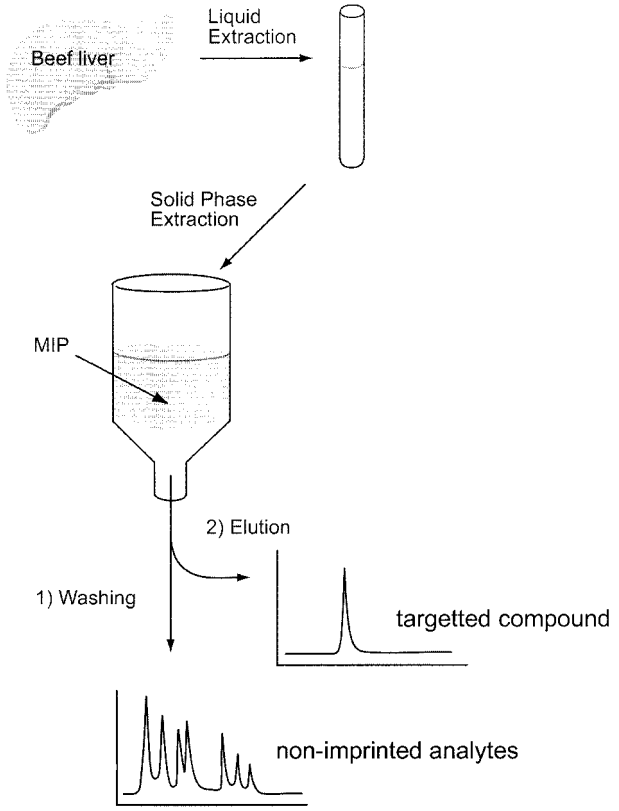


Figure 3. Sample concentration and purification by molecular imprinting SPE (*21*). The sample source, for example, beef liver, is first extracted in a suitable solvent. The crude extract, containing a multitude of compounds, is subsequently passed through an MIP, selective to one compound (or group of compounds) in the extract. After a washing step, where the bulk matrix of the extract is eliminated, the MIP is eluted and the chosen target compound(s) recovered in a purified and concentrated form.

where an *N*-pyridoxyl-L-phenylalaninanilide imprinted polymer also was investigated in HPLC mode with respect to its selectivity toward the template. The reasons for this include the difficulty of dissolution of water-soluble vitamins in organic solvent-based protocols and the low degree of functionality of the fat-soluble vitamins.

Flavonoids as a large group of secondary plant metabolites are called vitamin P and help to strengthen the capillaries and reduce the risk of lower coronary heart disease. Suarez-Rodriguez and Diaz-Garcia have applied a polymer molecularly imprinted with flavonol as a recognition element in a flow-through sensor based on fluorescence detection (*62*). A detection limit of 5×10^{-8} mol/L could be observed for flavonol.

MIPs toward nucleotides are perhaps less attractive, given the efficiency of other available binding techniques on the market, such as complementary nucleotides, nucleotide binders such as distamycin, and nucleotide analogues such as PNA. For some applications, though, when stability is a major concern, MIPs may offer an alternative. Preliminary studies in this line have been aimed at nucleotide bases [chromatographic tests and binding assays (*97*)] and mononucleotides [binding assays (*98*)], demonstrating a high degree of specificity of the prepared MIPs.

Cholesterol has been the major food lipid component subjected to molecular imprinting. This compound is of obvious high interest for various analytical applications such as serum level monitoring and in the selective removal of this steroid fat from dietary products. Studies in this area have been of a more basic nature, mainly focusing on the preparation of selective matrices. Thus, Whitcombe et al. developed a semi-covalent approach using a covalent carbonate derivative of the print species, which following polymerization could be cleaved and allowed to interact with the cholesterol analyte noncovalently (*58*). Other studies have employed a general self-assembly approach resulting in similar results (*57*, *59*). Piletsky et al. have generated self-assembled films molecularly imprinted with cholesterol (*61*). These films were used as recognition elements immobilized on gold electrode surfaces. With such an electrochemical sensor cholesterol could be determined in a range of 15−60 μmol/L within 5 min. The selective binding of cholesterol in aqueous media by assemblies of cross-linked β-cyclo-

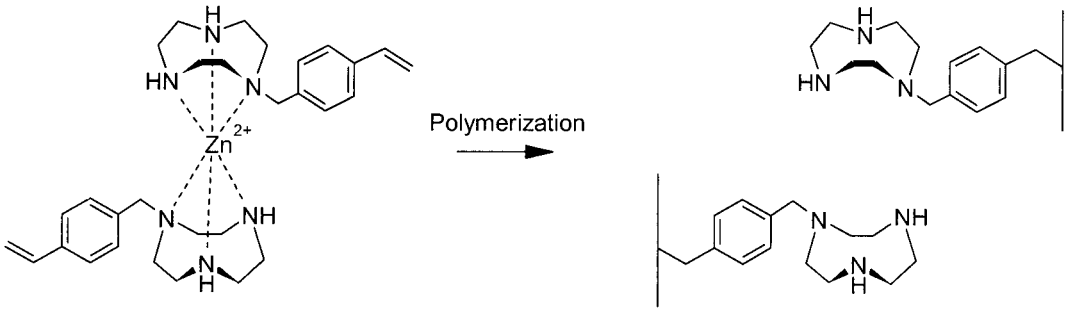


Figure 4. Formation of metal ion selective imprinted matrices (*85*). Recognition sites are built from strong coordination complexes that are established in solution between the metal ion and coordinating monomers (e.g., triazamacrocycle derivatives). The resulting materials are often very selective for the metal ion used in the process.

dextrin was described recently (*60*). When the binding activity of the imprinted polymer was compared with that of a control polymer, an "imprinting-induced promotion of binding" of 110% was observed in water/THF (5:6).

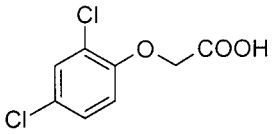
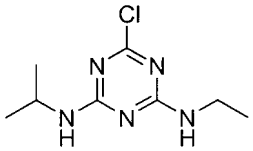
Pathogenic Organisms and Toxins. Foodborne pathogens and microbial toxins are generally recognized to be the biggest problem in the food industry. In conjunction with other methods on the market, MIPs have the potential to become an efficient recognition element in detecting food contaminants. A first study in this line has been published (*68*). Here, *Listeria monocytogenes* and *Staphylococcus aureus* were employed in a surface-imprinting protocol by which recognition sites were created on the surface of polyamide microcapsules (Figure 2) for later use in binding assays. Although somewhat preliminary in nature, inasmuch as the selectivities were rather poor, the study well supports the potential of using whole cells as target species.

As mentioned above, imprinting protocols using proteins as target substances are less easily developed. Nonetheless, the studies that have been published demonstrate the potential of preparing efficient MIPs toward bacterial toxins and other protein contaminants.

Herbicides and Pesticides. A large number of studies have dealt with herbicides and pesticides (Table 2), not only because these substances can be enriched in crops and cattle but also for environmental analyses. Thus, a number of studies have put forward the possibility of using the imprinted materials in, for example, sewage and wastewater analyses. In addition to basic recognition studies and imprinting protocol advancement (*72*, *73*, *78*), several applications have been developed. Thus, MIPs toward herbicides/pesticides have been used in radioligand binding assays (Table 3) (*69*−*71*, *77*), for SPE (Figure 3) (*20*, *21*, *75*, *76*, *79*), and in sensor devices (*74*, *80*).

Minerals and Trace Metals. A considerable number of studies have focused on metal ions as target species (for recent examples, cf. Table 2). In these cases, various metal coordination monomers have been arranged around a metal ion and subsequently been fixed during polymerization (Figure 4). By this method, highly selective matrices have been produced, capable of distinguishing closely related metal ions. In food analysis, the possibility of detection and quantitation of traces of contaminant heavy metals is of high value. Molecular imprinting offers a means of coupling robust and highly ion selective matrices to sensor devices. In this way, rapid analyses of trace metals may be performed.

Table 3. Cross-Reactivities (CR) of Some Structurally Related Compounds for Binding to Anti-2,4-D-MIPs and Anti-atrazine-MIPs, Respectively (*70*, *77*)

compound	CR (%)
	
2,4-dichlorophenoxyacetic acid (2,4-D)	
2,4-dichlorophenoxyacetic acid	100
2,4-dichlorophenoxybutyric acid	95
methyl dichlorophenoxyacetate	7
2,4-dichlorophenylacetic acid	15
4-chlorophenoxyacetic acid	24
4-chlorophenylacetic acid	10
phenoxyacetic acid	2
phenoxyethanol	<0.1
	
atrazine	
atrazine	100
terbuthylazine	44
propazine	18
simazine	12
prometryn	2
atratone	7
hydroxyatrazine	3
s-triazine	≪0.1
isoproturon	≪0.1
alachlor	≪0.1

FUTURE PROSPECTS

MIT has proven to be useful as a tool in agricultural and food technology. Highly selective and robust recognition matrices produced in this way can be employed in various applications when the analysis of diverse food analytes is an issue. Given the advantages of molecularly imprinted materials such as high stability, endurance, and low cost of production, it is plausible that products based on MIT will reach the market soon.

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