

分子印迹聚合物在食品添加剂检测中的应用进展

范冬妮 何洪源

(中国人民公安大学侦查学院, 北京 100038)

摘要:食品添加剂的不规范使用会威胁食品安全和人类健康,建立灵敏、快速的食品添加剂检测方法至关重要。分子印迹技术作为一种特异性、选择性识别真实样品中模板分子的技术,被广泛应用于制造分子印迹聚合物。该技术的出现为食品添加剂的检测提供了新视角。文章概述了分子印迹聚合物的新型制备方法和材料,综述了近5年分子印迹聚合物在食品添加剂样品前处理及构建检测传感器等方面的研究进展,并对分子印迹聚合物的制备、检测范围以及构建便携化检测传感器等的未来发展进行了展望。

关键词:分子印迹聚合物;食品添加剂;检测;传感器

Progress in the application of molecularly imprinted polymers in the detection of food additives

FAN Dongni HE Hongyuan

(School of Criminal Investigation, People's Public Security University of China, Beijing 100038, China)

Abstract: The improper use of food additives poses a threat to food safety and human health, making it essential to establish sensitive and rapid detection methods for food additives. Molecular imprinting technology, which enables the specific and selective recognition of template molecules in real samples, has been widely applied in the fabrication of molecularly imprinted polymers. The emergence of this technology provides a new perspective for the detection of food additives. This paper outlines novel preparation methods and materials for molecularly imprinted polymers, reviews research progress over the past five years on their application in food additive sample pretreatment and the construction of detection sensors, and prospects future developments in molecularly imprinted polymer preparation, detection scope, and the development of portable detection sensors.

Keywords: molecularly imprinted polymers; food additives; detection; sensor

食品添加剂是为改善食品的色、香、味等品质,以及为防腐和加工工艺的需要而加入到食品中的人工合成或天然物质。根据《食品安全国家标准 食品添加剂使用标准》(GB 2760—2024)规定,中国允许使用的食品添加剂共23类,数量达2 000多种,但个别食品生产加工企业为牟取利益,存在超剂量、超范围使用添加剂的行为,这对人们身体健康和食品安全产生极大危害。因此,建立精准、快捷、高效的食品添加剂检测方法,是保障食品安全的重要途径。

目前,食品添加剂的检测方法主要有高效液相色谱

法^[1]、气相色谱—质谱联用法^[2]、液相色谱—质谱联用法^[3]、傅里叶变换红外光谱法^[4]和近红外光谱法^[5]等,这些方法虽然准确性高、重现性好,但存在设备昂贵、检测时间长、操作复杂等局限性。随着科学技术发展,分子印迹技术的出现为食品添加剂检测提供了新思路。

分子印迹技术(molecular imprinting technology, MIT)是一种模拟酶—底物或抗原—抗体特异性结合原理,以实现特异性分离与检测为目标的多学科技术^[6]。由该技术制备的分子印迹聚合物(molecularly imprinted polymers, MIPs)制备方法简单、选择性好、抗应力强、稳定

基金项目:中国人民公安大学刑事科学技术双一流创新研究专项(编号:2023SYL06)

通信作者:何洪源(1965—),女,中国人民公安大学教授,博士。E-mail: 13311296819@189.cn

收稿日期:2025-02-19 **改回日期:**2025-11-29

引用格式:范冬妮,何洪源. 分子印迹聚合物在食品添加剂检测中的应用进展[J]. 食品与机械, 2026, 42(4): 229-240.

Citation: FAN Dongni, HE Hongyuan. Progress in the application of molecularly imprinted polymers in the detection of food additives[J]. Food & Machinery, 2026, 42(4): 229-240.

性高,与传统液质检测方法相比,MIPs的核心优势在于特异性识别能力和成本效益,MIPs的印迹空腔能够选择性识别目标物,且MIPs可以重复使用,特别适合快速、低成本和现场检测的场景,传统液质检测适用于实验室中对目标物的高分辨定性定量和复杂组分的分离分析。因此,MIPs被广泛应用于生物医药、环境监测、食品安全等领域。

文章拟介绍MIPs的新型制备方法和材料,综述近年MIPs在食品添加剂检测中的应用情况,以期在食品添加剂检测方面的相关研究提供参考。

1 MIPs概述

MIPs的制备过程如图1所示,模板分子是目标分子或结构模拟物,相当于“钥匙”,MIPs相当于“锁”,用于设计和适应“钥匙”。制备MIPs主要分为3步:①模板分子和功能单体经过预聚合形成模板分子—功能单体复合物

物。模板分子是制备聚合物的关键分子,其引导了功能单体的官能团进入印迹过程,功能单体含有识别位点,可以增加识别的选择性。理想的模板分子需具备以下条件:包含能够与功能单体容易结合官能团,不包含参与或阻止聚合的基团,在聚合过程中具有优异的化学稳定性。②在交联剂、致孔剂、引发剂等物质的作用下,通过聚合反应形成高度交联的三维多孔网状聚合物。③经反应脱去模板分子,留下与模板分子空间和化学功能互补的印迹空腔MIPs^[7]。应用于样品时,这些印迹空腔只能识别和捕捉与它们匹配的目标分子,由此实现对目标物选择性、特异性识别。但由于现有表征技术的局限性,目前分子印迹技术的理论研究还不够完善,对印迹整体过程的研究比较成熟,但对印迹过程的微观认识还不够深入,高度交联的三维MIPs内部结构并不十分清楚,需进一步探索MIPs内部空腔和通道的分布、特点。

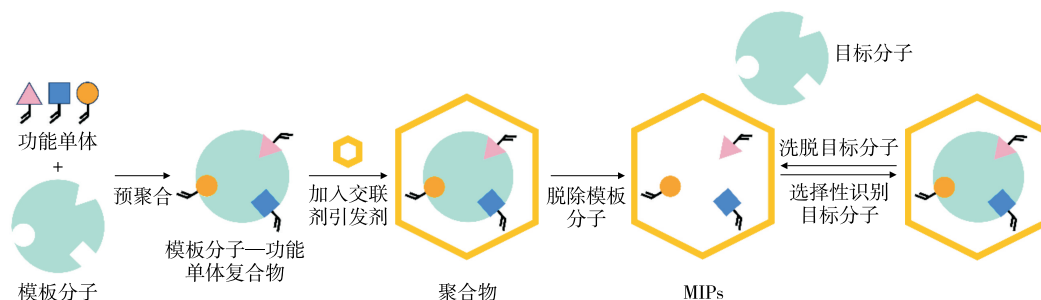


图1 MIPs的制备示意图

Figure 1 Schematic diagram of the preparation of MIPs

目前,MIPs的常见形态有单片式MIPs、表面印迹MIP微珠、单分散MIP球、纳米级MIPs、MIP膜^[8]等。制备MIPs主要基于共价键、非共价键、半共价键和金属离子配位的相互作用^[9]。MIPs的制备方法通常包括本体聚合、悬浮聚合、乳液聚合、沉淀聚合、溶液—凝胶法等。然而,传统MIPs制备方法在不断发展中遇到一些瓶颈,如识别位点可达性差、模板去除不彻底、传质缓慢、亲水性差等,许多学者已致力于开发新的制备技术和策略。通过梳理与对比,新型制备技术和策略特点见表1。关于面向刺激响应的印迹策略,除了表中梳理出的,还包括热、电、力、pH、离子强度和生物分子等各类外界刺激,此方面的应用需要进一步研究探索。

随着材料科学的发展,各种新型材料不断应用于样品前处理和构建高性能的传感器,如碳基材料、磁性纳米颗粒、金属和金属氧化物、量子点、金属有机骨架等。其中,由碳纳米材料与金属有机骨架(metal-organic frameworks, MOFs)构建的MIPs在食品添加剂检测领域应用广泛。应用于MIPs的常见碳纳米材料有碳纳米管

(CNTs)、MXenes、碳点(CDs)/石墨烯点(GDs)、石墨烯/氧化石墨烯和3D碳纳米材料等。MOFs具有高比表面积、可控的孔隙结构和显著的热稳定性等特性,但缺乏特异性识别能力,将MOFs与MIPs结合,可进一步扩大MIPs应用范围。

2 MIPs在食品添加剂样品前处理中的应用

食品基质成分复杂,食品添加剂种类繁多,部分添加剂在食品中的含量甚至处于微量、痕量级别。因此,选择合适的样品前处理技术对于食品添加剂的分析与检测工作十分重要。

由于MIPs具有易于制备、稳定性好、高度选择性和可重复利用等优点^[21],Sellergren^[22]于1994年将MIPs作为吸附剂用于固相萃取(solid phase extraction, SPE),开启了分子印迹固相萃取(molecularly imprinted solid-phase extraction, MISPE)研究的序幕。目前,MIPs作为吸附剂,已经以多种形式被广泛应用于食品添加剂的分离、富集、预处理等领域,具体应用见表2。

表1 MIPs的新型制备方法和策略

Table 1 New preparation methods and strategies for MIPs

技术与策略	名称	特点	参考文献
印迹技术	表面印迹技术	产生更多有效的识别位点,去除模板彻底,传质性能好;制备过程复杂,MIPs层的厚度和密度对传质速率有显著影响	[10]
	纳米印迹技术	纳米材料的高比表面积提高了MIPs的结合能力,一般适用于制备直径<200 nm的球形MIPs颗粒;多应用于固相载体表面,在溶液中富集MIPs颗粒效果不理想	[11]
印迹策略	点击化学技术	选择性功能化,可组合多种功能基序,反应条件温和;兼容性有限,操作复杂成本高	[12]
	虚拟模板/片段印迹	适用于高成本、不稳定或会造成污染的目标物;特异性不足,选择合适的虚拟模板和片段模板具有挑战性	[13-14]
	多模板/多功能单体	前者可同时检测多种目标物,后者可增加有效印迹位点的数量,特异性高;前者吸附能力低,结合位点存在异质性;后者结合位点不均一,需要选择合适的功能单体	[15-16]
	染料置换	目前主要针对小分子,对蛋白质、多肽等大分子的印迹效果有待提高;多适用于MIPs传感器;目前可用染料种类有限,需选择性能合适的染料	[17]
	基于树状大分子的单分子印迹	印迹效率高、结合位点均匀;需进行多步合成和严格的纯化,适用于少数分子结构对称的目标物	[18]
面向刺激响应的印迹策略	磁刺激响应法	检测效率高,对环境友好,常与其他刺激响应组合,合成多重刺激响应性的MIPs;在高通量和多路检测方面具有发展潜力	[19]
	光响应法	利用光能调节MIPs的聚合反应,制备过程更为智能;目前常用的光响应功能单体为偶氮苯及其类似物,极大限制MIPs应用;如何提高光响应速度和稳定性、优化聚合过程,需进一步探索	[20]

MISPE目前正朝着自动化、小型化方向发展,管内固相微萃取SPME可以方便地实现提取过程的自动化^[48]。为了实现MISPE小型化,Sun等^[49]提出了一种使用注射器作为过滤支架、可重复使用的小型化MIPs吸附剂萃取装置,用MIPs作填充吸附剂对水和生物样本中的二苯甲酮进行SPME。

在DSPE方法中,吸附剂MIPs通常与样品混合后装

入柱中,与MISPE相比,DSPE简化了前处理步骤、减少样品损失、消耗MIPs少,但此方法中的吸附剂难以从样品中分离,影响其重复使用。MEPS方法仅需要少量样品和洗脱溶剂,但在处理黏性或高浓度的食品样品时可能会导致吸附剂堵塞,需要额外的预处理步骤。SBSE方法需注意提高MIPs与搅拌棒结合时的化学和机械稳定性,防止在使用过程中降解和失去结合位点。

表2 MIPs在食品添加剂样品前处理中的应用[†]

Table 2 Application of MIPs in the pretreatment of food additive samples

种类	目标物	功能单体	模式	检测方法	样本	检出限	线性范围	回收率/%	参考文献
抗氧化剂	槲皮素	3-氨基丙基三乙氧基硅烷	SPME	HPLC-UV	茶叶、咖啡	0.009 94 μg/mL	0.05~100 μg/mL	94.20~98.50	[23]
	槲皮素	甲基丙烯酸	MSPE	FT-IR	橙汁、茶提取物	0.001 1 μg/mL	0.005~1.25 μg/mL	92.20~104.70	[24]
	槲皮素	甲基丙烯酸	MSPE	FT-IR	洋葱	0.2 μg/mL	0.32~25.0 μg/mL	96.00~98.60	[25]
	山柰酚	丙烯酰胺	MSPE	FT-IR	苹果	0.006 8 μg/mL	0.05~20.0 μg/mL	90.50~95.40	[26]
	矢车菊素-3-O-葡萄糖苷	1,5-二氨基-4,8v二羟基蒽醌	SPME	HPLC	野樱梅	0.15 μg/mL	1~500 μg/mL	84.72	[27]
	芦丁	二甲氨基丙基甲基丙烯酸酰胺	MSPE	FT-IR	葡萄汁	0.27 μg/mL	1~80 μg/mL	90.40~94.00	[28]
	咖啡酸	4-乙烯基吡啶	SPE	HPLC	猕猴桃、苹果、木瓜、杨梅	0.2 μg/mL	1~100 μg/mL	87.10~101.30	[29]
	甜菜碱	4-乙烯基吡啶	SPE	FT-IR	石榴汁	0.69 μg/mL	—	—	[30]

续表 2

种类	目标物	功能单体	模式	检测方法	样本	检出限	线性范围	回收率/ %	参考 文献
	咖啡因	甲基丙烯酸	MEPS	HPLC-UV	软饮料、能量 饮料	1.0 μg/mL	1.0~50.0 μg/mL	约 100	[31]
色素	姜黄素	甲基丙烯酸	SPE	FT-IR	功能食品	0.051 μg/mL	1~25 μg/mL	95.87~118.18	[32]
	美他尼黄	甲基丙烯酸	SPE	UV	姜黄	—	—	88.10~92.76	[33]
	刚果红	甲基丙烯酸	SPE	FT-IR	蒸馏水	—	—	97.12	[34]
					自来水			94.60	
					河水			90.12	
防腐剂	肉桂酸	4-乙烯基吡啶	MSPE	HPLC-UV	苹果汁	0.006 μg/mL	0.02~10.0 μg/mL	92.70~101.40	[35]
	香豆酸	(3-氨基丙基)	MSPME	HPLC-UV	石榴、葡萄和	8×10^{-5} μg/mL	5×10^{-4} ~ $3 \times$	85.12~94.96	[36]
	阿魏酸	三乙氧基硅烷			橙子	7×10^{-5} μg/mL	10^{-1} μg/mL		
	氯丙醇	4-乙烯基苯基 硼酸	SPE	GC-MS	植物油	7.2×10^{-5} μg/mL	1.0×10^{-3} ~ 1.2 μg/mL	75.60~101.00	[37]
	香豆素	甲基丙烯酸	SPE	HPLC	决明子肉桂、 甘菊茶和托卡 伊特色葡萄酒	0.03 μg/mL	0.10~100 μg/mL	78.70~112.20	[38]
香精	苯甲酸	间苯二酚、三聚 氰胺	MSPE	HPLC-UV	河水、果汁和 人体血清	0.02~1.0 μg/mL	4.0~100 μg/mL	81.80~108.70	[10]
	香兰素	氯化胆碱和甲 基丙烯酸组成 的低共融溶剂	MSPE	HPLC- UVD	婴儿辅食	0.07 μg/mL	0.20~50.0 μg/mL	91.20~100.20	[39]
	香草醛	甲基丙烯酸	SBSE	HPLC-UV	婴儿奶粉	2.5×10^{-3} ~ $1.0 \times$ 10^{-2} μg/mL	0.01~100 μg/mL	94.70~98.90	[40]
	乙基麦芽酚						0.02~100 μg/mL	82.10~96.70	
	甲基香草醛						0.03~100 μg/mL	84.50~93.20	
	香兰素、乙基香 兰素、麦芽酚和 乙基麦芽酚	3-氨基丙基三 乙氧基硅烷	MSPE	HPLC	饮料	4.40×10^{-5} ~ 2.01×10^{-4} μg/mL	2.07×10^{-3} ~ $4.63 \times$ 10^{-1} μg/mL	91.20~107.10	[41]
	甜味剂 绿原酸	丙烯酰胺	MSPE	HPLC	苹果汁	0.03 μg/mL	0.1~100 μg/mL	93.50~101.60	[42]
	营养增补剂 L-苯丙氨酸 补剂	甲基丙烯酸	SPE	HPLC-UV	营养补充剂	1 000 μg/mL	1×10^3 ~ $1 \times$ 10^4 μg/mL	—	[43]
	亚硝胺(具体为 NDEA、NPIP、 NDPA、NDBA 和NDPHA)	甲基丙烯酸	SPE	LC-MS/MS	饮料	2×10^{-7} ~ $7 \times$ 10^{-7} μg/mL	—	93.00~107.00	[44]
	谷胱甘肽	丙烯酰胺	MSPE	HPLC	野生可食用 牛肝菌	0.024 828 μg/mL	0.1~3.0 μg/mL	93.28~103.03	[45]
	叶酸	乙烯基苯基三 甲基氯化铵	DSPE	LC-MS	生菜和饼干	0.003 μg/mL	0.01~1.0 μg/mL	≥79.50	[46]
	增白剂 苯并恶唑	1, 3, 5-三甲基 间苯三酚	SPE	HPLC/DAD	蘑菇 面粉 面条	0.23~0.28 μg/kg	1~100 μg/kg	93.90~100.50 89.40~102.30 92.10~106.50	[47]

† 分散固相萃取(dispersive solid phase extraction,DSPE)、固相微萃取(solid phase microextraction,SPME)、搅拌棒吸附萃取(stir bar sorptive extraction,SBSE)、搅拌饼吸附萃取(stir cake sorptive extraction,SCSE)、填充吸附剂微萃取(microextraction by packed sorbent,MEPS)、磁性固相萃取(magnetic solid phase extraction,MSPE)、磁分散固相萃取(magnetic dispersive solid phase extraction,MDSPE)、磁性固相微萃取(magnetic solid phase microextraction,MSPME)。

MSPE方法是在SPE的基础上引入外磁场,无需过滤和离心,简化了样品预处理过程,而且大多数磁性吸附剂可以回收再利用,绿色环保。其面临的挑战是需开发更多磁性材料有效合成方法,提高磁性复合材料的吸附选择性,减少非特异性结合引起的背景干扰。

MOFs由于高孔隙率和大比表面积,已成为MIPs常用支撑材料。到目前为止,已经有MOFs中的多种系列与MIPs结合^[50],如网状金属有机骨架(isoreticular metal-organic frameworks, IRMOFs)、类沸石咪唑骨架(zeolitic imidazolate frameworks, ZIFs)、拉瓦希尔骨架(material of institute lavoisier frameworks, MILs)、锆基金属有机骨架(zirconium-based metal-organic frameworks, Zr-MOFs)、铜基金属有机框架(copper-based metal-organic frameworks, Cu-MOFs)等。但是,由于大部分MOFs系列在水溶液和有机溶剂中缺乏足够的稳定性,目前,水稳定性好的ZIFs、MILs和锆基金属有机骨架中的UIOs(university of oslo, UIOs)系列在前处理方面应用广泛。

牛浩宇等^[51]将MOFs系列中的UIO-66-NH₂作为载体和荧光团,制备了表面分子荧光传感器用于检测干辣椒中的罗丹明6G。Kardani等^[52]利用GO@ZIF-8 MOF纤维结合MIPs,对饮料和零食中非法添加的安非他明衍生物进行SPME。Chen等^[53]合成了一种由MOF包覆、通过多虚拟模板制备MIPs的(MIL-101(Fe)@DMIPs),对盐渍蔬菜中N-亚硝胺进行SPE。随着技术不断进步,期待更多种类的MOFs与MIPs结合应用于食品检测。

将基于MIPs吸附剂的设备与便携设备联用,近年来已有显著发展。一方面,MIPs可与智能手机联用,如Elfadil等^[54]合成了涂覆磁性纳米粒子的聚多巴胺基MIPs复合材料(Fe₃O₄@PDA@MIP),对食品样品中赤藓红B进行MDSPE萃取,然后结合手机上比色分析程序进行测定;另一方面,MIPs与纸质分析设备联用,已开始应用于对食品中的药物进行现场便携式检测,并与各种平台集成。Lamaoui等^[55]将基于MIPs的吸附剂集成到一个基于纸张的分析设备中,创建了一个便携式和可折叠的平台,用于选择性地分析环境样品中的磺胺甲氧唑。Vodova等^[56]使用一种基于MIPs的紫外诱导荧光光谱便携式纸质分析设备检测食品中的农药。这对基于MIPs的食品添加剂检测如何更加便携化是一种启示。

3 MIPs传感器在食品添加剂检测中的应用

3.1 MIPs电化学传感器

MIPs电化学传感器是将MIPs制成具有特异性识别功能的分析物,使其沉积在电极表面,通过识别分析物产生的不同电信号进行检测。与其他类型的MIPs传感器相比,MIPs电化学传感器具有低检出限、操作简单、低成本

本、易于实现小型化和自动化等诸多优点。

MIPs电化学传感器常见的检测方法有伏安法、安培法、电位法、电化学阻抗谱检测法等^[57],具体应用见表3。

基于MIPs的伏安法、安培法检测的传感器应用广泛,但是,伏安法和安培法也有一定的弊端,如果目标分析物不能被电化学反应氧化或还原,则只能通过与印迹空腔结合以引起电流变化进行检测。因此,对于仅由聚合物组成的传统MIPs,其检测到的变化的电流信号范围有限,构成的传感器灵敏度较低。近年来,通过探究发现,一方面可通过添加其他导电材料解决,如添加金属纳米颗粒和金属有机框架,提高MIPs材料的导电性^[83];另一方面,可直接在导电材料如石墨烯、碳纳米管表面制作MIPs层,将其作为印迹层。此外,未来随着相应控制仪器小型化和低成本生产,此类MIPs传感器有望作为现场便携式检测设备被推广。

电化学阻抗谱检测法(electrochemical impedance spectroscopy, EIS)与MIPs技术结合是在电极表面构建MIPs层,通过测量阻抗信号的变化来检测生物识别事件。但是由于基质中的干扰物质与印迹腔会发生非特异性结合,产生的阻抗变化会影响检测准确度,该不足在其他MIPs电化学传感器也会出现。此时可以通过添加各种形式的功能单体来提高印迹空腔的特异性。如段定定^[84]将金属有机骨架NH₂-Fe-MIL-88B与石墨烯复合,制备了多巴胺和邻苯二胺为双功能单体,用于构建电化学传感器对牛磺酸进行检测,该传感器的检测范围为10⁻¹⁴~10⁻⁸ mol/L。

MXenes作为一类新型的过渡金属碳化物或氮化物二维材料,比表面积大、导电性优异、表面基团丰富,是构建电化学传感器的理想材料。Zhang等^[65]建立了一种基于MXenes的MIPs电化学传感器用于检测食品中的三氯生,通过MXenes中的碳化钛(Ti₃C₂T_x)材料对电极进行修饰,经试验三氯生在10 nmol/L~50 μmol/L浓度范围内线性关系良好,检出限低至1.18 nmol/L,对桃汁、洋葱和鱼样品中三氯生的回收率为86.38%~95.52%,该传感器具有良好的灵敏度和选择性。

3.2 MIPs光化学传感器

MIPs光化学传感器是将MIPs作为传感器的识别元件对目标物进行特异性识别,将材料的光学性质变化转化为分析信号,通过读取信号数据实现对目标物的检测。

根据光信号的来源,MIPs光化学传感器可以分为MIPs亲和传感器和MIPs光电传感器^[57]。

MIPs亲和传感器主要包括荧光传感器、表面等离子共振传感器、比色传感器和基于SERS的传感器等^[85],其中,前两者应用比较广泛。

根据荧光信号来源的不同,分子印迹荧光传感器(molecular imprinted fluorescence sensor, MIFs)主要分为

表 3 MIPs 电化学传感器在食品添加剂检测中的应用[†]

Table 3 Application of MIPs electrochemical sensor in the detection of food additives

种类	目标物	功能单体	电化学技术	样本	检出限	线性范围	参考文献
调味剂	辣椒素	β -环糊精	CV	青辣椒提取物	7 nmol/L	100~1 000 nmol/L	[58]
甜味剂	果糖	苯基硼酸	CV、EIS	橙汁、苹果汁和葡萄汁	3.2×10^{-6} nmol/L	$1 \times 10^{-5} \sim 1 \times 10^{-2}$ nmol/L	[59]
	阿斯巴甜	丙烯酸	DPV	运动饮料	22 nmol/L	8~6 000 nmol/L	[60]
	阿斯巴甜	低共熔溶剂(DES)	CV、DPV	碳酸饮料	—	0.1~50.0 mg/mL	[61]
	橙皮苷	阿魏酸	CV	橙汁	7 nmol/L	25~1 000 nmol/L	[62]
	安赛蜜	邻苯二胺	CV、DPV	饮料	350 nmol/L	100~17 000 nmol/L	[63]
防腐剂	硝酸盐	苯胺	CV、LSV、EIS	矿泉水和井水	100 nmol/L	$1 \times 10^3 \sim 1 \times 10^8$ nmol/L	[64]
抗菌剂	三氯生	对氨基苯甲酸	CV	桃汁、洋葱和鱼样品	1.18 nmol/L	$10 \sim 5 \times 10^4$ nmol/L	[65]
香料	香草醛	丙烯酰胺	CV、DPV	冰淇淋、酸奶、蛋奶冻、奶昔	1.43 nmol/L	0.1~1 000 nmol/L	[66]
	香兰素	甲基丙烯酸	CV、EIS、DPV	蛋奶糊、奶茶、蛋糕	5×10^{-3} nmol/L	$1 \times 10^{-2} \sim 1 \times 10^5$ nmol/L	[67]
色素	姜黄素	4-戊烯基丙氨酸壳寡糖	CV、EIS、DPV	姜黄粉	5 nmol/L	10~2 000 nmol/L	[68]
	姜黄素	玉米醇溶蛋白	CV	薯片	10 nmol/L	$100 \sim 1 \times 10^5$ nmol/L	[69]
	日落黄	3-氨基丙基三乙氧基硅烷	CV	美年达橙汁和芬达橙汁	1.6 nmol/L	$10 \sim 1 \times 10^5$ nmol/L	[70]
	柠檬黄	L-蛋氨酸	CV	藏红花粉和果汁	0.027 nmol/L	0.6~160 nmol/L	[71]
	柠檬黄	多巴胺	CV	橙汁、黄酒、冰淇淋、果冻、速溶果汁粉、糖果、饼干	1.1 nmol/L	3~180 nmol/L	[72]
	柠檬黄	L-精氨酸	DPV	果冻粉、软饮料	2.7 nmol/L	8~112 nmol/L	[73]
	胭脂红	甲基丙烯酸甲酯	CV、DPV、EIS	饮料	6.05 nmol/L	$9.0 \sim 3.9 \times 10^3$ nmol/L	[74]
抗氧化剂	木犀草素	咪唑	CV	胡萝卜、菊花茶	9 nmol/L	40~2 000 nmol/L	[75]
	丁基羟基甲苯醚	水合肼和吡咯	CV、DPV	薯片、燕麦片和方便面	7.9 nmol/L	$1 \sim 1 \times 10^5$ nmol/L	[76]
	丁基羟基甲苯醚	邻苯二胺	CV、DPV、EIS	蛋黄酱、黑孜然油、大豆油	6 nmol/L	$10 \sim 1 \times 10^6$ nmol/L	[77]
	维生素 B ₆	3-氨基苯甲酸	CV、DPV	片剂、能量饮料、菠萝汁	10 nmol/L	$600 \sim 7 \times 10^5$ nmol/L	[78]
	叔丁基对苯二酚	邻苯二胺	CV	食用油	0.046 μ g/mL	0.5~60.0 μ g/mL	[79]
	反式白藜芦醇	丙烯酰胺	CV	红酒、葡萄	4.4 nmol/L	$10 \sim 1 \times 10^4$ nmol/L	[80]
	4-己基间苯二酚	2-氨基噻唑	CV	虾	6.03 nmol/L	30~300 nmol/L	[81]

[†] 伏安法主要包括微分脉冲伏安法(differential pulse voltammetry, DPV)、循环伏安法(cyclic voltammetry, CV)、方波伏安法(square wave voltammetry, SWV)和线性扫描伏安法(linear sweep voltammetry, LSV)^[82]等。

有机荧光染料型、量子点型、稀土材料型和荧光比值型 4 种类型^[86]。量子点(quantum dots, QDs)^[87-88]和碳点(carbon dots, CDs)^[89]是 MIFs 常用的荧光团。在食品基质中检测,可以通过构建 MIPs 膜^[90]和用二氧化硅涂层的核-壳结构^[91],保证荧光团性能稳定。

表面等离子共振(surface plasmon resonance, SPR)是一种由光激振金属表面自由电子而引发电子集体振荡的光学现象^[92]。将 SPR 传感器与 MIPs 结合,可以表现出高灵敏度、高选择性特点。如 Ozgur 等^[85]以丙烯酰胺和甲基丙烯酸为双功能单体,采用甲基丙烯酸羟乙酯和乙二醇

二甲基丙烯酸酯两相微乳液聚合法,建立 MIPs-SPR 传感器用于检测果汁中的苋菜红。

光电传感器应用 MIPs 与分析物结合时产生的电化学发光进行检测。如 Jin 等^[93]建立了基于还原氧化石墨烯和上转换纳米粒子的 MIPs 光电传感器对猪肉和肝脏制品中的瘦肉精进行检测。并且,有研究也将此类传感器与智能手机结合,进行便携式检测^[94]。

MOFs 的高孔隙率不仅可以提高 MIPs 的传质效率,而

且可以负载量子点构建 MOFs-MIPs 复合材料的光学传感器。Xu 等^[95]将 CDs 嵌入 MOFs,采用本体聚合法制备 MIPs,获得 CDs@MOFs@MIPs 复合材料,进而用其构建 MIFs 对保健食品银杏叶提取物胶囊中的槲皮素进行检测,该传感器的荧光强度随槲皮素浓度增加呈良好的线性下降关系,线性范围为 0~50 μmol/L,检测限为 2.9 nmol/L,精密度的 1.9%。

MIPs 光化学传感器在食品添加剂检测中的应用见表 4。

表 4 MIPs 光化学传感器在食品添加剂检测中的应用

Table 4 Application of MIPs photochemical sensor in the detection of food additives

种类	目标物	功能单体	检测方法	样本	检出限	线性范围	参考文献
色素	苋菜红	丙烯酰胺和甲基丙烯酸	SPR	果汁	18 μg/mL	100~1.5×10 ⁴ μg/mL	[85]
	柠檬黄	3-氨丙基三乙氧基硅烷	MIF	假藏红花、藏红花茶、藏红花冰淇淋	1.3 nmol/L	3.3~20.0 nmol/L	[96]
	柠檬黄	3-氨丙基三乙氧基硅烷	MIF	自来水、湖水、鱼、番红花、橙汁	23.7 nmol/L	50~8×10 ⁴ nmol/L	[97]
	亮蓝	3-氨丙基三乙氧基硅烷	MIF	碳酸饮料、白兰地鸡尾酒、跳跳糖、巧克力糖、绿豆糕和蓝莓干	8.8 nmol/L	0~1 000 nmol/L	[98]
增香剂	酪胺	甲基丙烯酸	MIF	奶酪	1.457×10 ⁴ nmol/L	1×10 ⁴ ~1×10 ⁷ nmol/L	[99]
营养添加剂	叶酸	3-氨丙基三乙氧基硅烷	MIF	孕妇奶粉、叶酸片、菠菜、西兰花、番茄和橙子	48 nmol/L	230~1.13×10 ⁵ nmol/L	[100]
	抗坏血酸	3-氨丙基三乙氧基硅烷	MIF	维生素 C 片	1 560 nmol/L	4×10 ³ ~2×10 ⁵ nmol/L	[101]
抗氧化剂	阿魏酸	3-氨丙基三乙氧基硅烷	MIF	菠萝汁和苹果汁	8.5×10 ⁻⁴ μg/mL	2×10 ⁻³ ~0.1 μg/mL	[102]
抑菌剂	咖啡酸	4-乙烯基吡啶	MIF	海水、湖水	150 nmol/L	1 000~1.5×10 ⁵ nmol/L	[103]

4 展望

食品添加剂检测对于保障食品安全具有重要意义。随着分析技术和新型材料的发展,分子印迹聚合物在食品添加剂检测中的研究将会更广泛、更深入,但该技术目前也面临一些挑战。

(1) 分子印迹聚合物多应用于单目标的传感器检测,较少用于多目标检测。开发多目标检测,可以同时测定多个目标物,大幅提升检测效率。目前分子印迹聚合物多目标检测主要依据多模板分子印迹聚合物,合成多模板分子印迹聚合物可采用原位多重印迹和顺序印迹 2 种策略。使用原位多重印迹制备分子印迹聚合物,以电聚合方式为主,在顺序印迹中,各制备方法均有其优缺点,需综合考虑模板分子的兼容性和工艺复杂性等因素进行选择。

(2) 分子印迹聚合物研究的目标分子大多是有机小分子,如除草剂、农药、色素、药物等,这些物质大多易溶于有机溶剂而难溶于水,限制了分子印迹聚合物的应用,开发出与水兼容的分子印迹聚合物,将来可以拓宽分子

印迹聚合物在食品添加剂检测领域中的应用。制备与水兼容的分子印迹聚合物,可从以下思路予以探索:① 在缓冲液和水体系中制备分子印迹聚合物;② 使用亲水性的分子印迹聚合物前体,特别是功能单体和功能共聚物;③ 印迹后,使用亲水性聚合物层或官能团修饰分子印迹聚合物表面;④ 通过油包水 Pickering 乳液制备分子印迹聚合物;⑤ 采用多刺激响应策略制备分子印迹聚合物等。目前开发与水兼容分子印迹聚合物的相关研究也存在一定的局限性,如结合位点存在异质性,干扰物与模板分子在水介质中存在非特性结合等。

(3) 分子印迹聚合物为了减少制备分子印迹聚合物过程中产生的污染物,可以基于计算机辅助设计,寻找制备分子印迹聚合物的最佳单体和条件。

(4) 在基于新型材料构建分子印迹聚合物的过程中,如何精确控制碳纳米材料和金属有机骨架材料的形态与尺寸仍然存在挑战。

(5) 目前,在分子印迹聚合物传感器应用方面,已实现携带电化学工作站、荧光分光光度计等小型仪器进行现场检测,但仍需较大人力、物力等成本,微控流技术和

智能手机等分析平台为分子印迹聚合物传感器便携化应用提供新方向。微控流技术具有低能耗、高通量等特点,可以构建纸基微控流分子印迹聚合物传感器,作为一次性功能化电极,也可以集合传感单元、信号处理、微控流芯片,设计为可穿戴微控流设备。智能手机主要依靠其计算能力和数字成像功能,记录目标物光学图像的 RGB 值,通过蓝牙与电化学传感平台集成,进行实时分析和检测。

在未来的研究中,如何将分子印迹聚合物传感器与 3D 打印、智能手机、可穿戴传感器等其他便携技术结合,在各种环境中进行快速测试,如食品生产领域、餐馆、家庭等,并将数据传输到云平台,并与物联网、大数据融合,实现即时、准确、快捷地存储与分析目标,还需要进一步深入研究。

参考文献

- [1] 马康, 蒋孝雄, 赵敏, 等. 高效液相色谱法同时测定软饮料中 20 种食品添加剂[J]. 分析化学, 2012, 40(11): 1 661-1 667.
MA K, JIANG X X, ZHAO M, et al. Simultaneous determination of 20 food additives in drinks by high performance liquid chromatography coupled with photo-diode array detector[J]. Chinese Journal of Analytical Chemistry, 2012, 40(11): 1 661-1 667.
- [2] 鞠福龙, 李春娟, 李东刚. 气相色谱-质谱联用法同时检测调味品中 7 种防腐剂[J]. 中国调味品, 2009, 34(10): 79-81, 84.
JU F L, LI C J, LI D G. Simultaneous testing 7 preservatives in condiments by GC-MS[J]. China Condiment, 2009, 34(10): 79-81, 84.
- [3] 刘丽丽, 任璐, 罗冠龙, 等. 一种高效液相色谱-质谱联用法同时检测凤香型白酒中六种甜味剂的方法[J]. 酿酒, 2020, 47(3): 101-104.
LIU L L, REN L, LUO G L, et al. Simultaneous determination of six artificial sweeteners in Fengxiang Baijiu by high performance liquid chromatography with mass spectrometry[J]. Liquor Making, 2020, 47(3): 101-104.
- [4] COPIKOVA J, BARROS A S, SMIDOVA I, et al. Influence of hydration of food additive polysaccharides on FT-IR spectra distinction[J]. Carbohydrate Polymers, 2006, 63(3): 355-359.
- [5] 田晶, 李巧玲. 近红外光谱法快速检测饮料中的食用合成色素[J]. 食品科学, 2018, 39(2): 293-297.
TIAN J, LI Q L. Rapid determination of synthetic pigments in fruit-flavored beverage by near infrared spectroscopy[J]. Food Science, 2018, 39(2): 293-297.
- [6] 丁同英, 袁航. 分子印迹传感器在真菌毒素检测中的应用研究进展[J]. 食品与机械, 2021, 37(12): 197-201.
DING T Y, YUAN H. Application and progress of molecularly imprinted sensors in mycotoxins detection[J]. Food & Machinery, 2021, 37(12): 197-201.
- [7] 韩颜蓉, 陈彦荣, 王晨宇, 等. 分子印迹电化学传感器在兽药残留检测中的应用进展[J]. 食品与机械, 2025, 41(7): 207-218.
HAN Y R, CHEN Y R, WANG C Y, et al. Progress in the application of molecularly imprinted electrochemical sensors in the detection of veterinary drug residues[J]. Food & Machinery, 2025, 41(7): 207-218.
- [8] CHEONG W J, YANG S H, ALI F. Molecular imprinted polymers for separation science: a review of reviews[J]. Journal of Separation Science, 2013, 36(3): 609-628.
- [9] MALIK M I, SHAIKH H, MUSTAFA G, et al. Recent applications of molecularly imprinted polymers in analytical chemistry[J]. Separation & Purification Reviews, 2019, 48(3): 179-219.
- [10] LI H, LONG R Q, TONG C Y, et al. Shell thickness controlled hydrophilic magnetic molecularly imprinted resins for high-efficient extraction of benzoic acids in aqueous samples[J]. Talanta, 2019, 194: 969-976.
- [11] ZHANG M X, LI Z H, ZHANG Z Y, et al. Dual improvement in sensitivity and selectivity of SnO₂ nanospheres for formaldehyde sensing based on molecular imprinting and Ag doping[J]. Materials Chemistry and Physics, 2024, 313: 128708.
- [12] AWINO J K, GUNASEKARA R W, ZHAO Y. Selective recognition of D-aldoheoses in water by boronic acid-functionalized molecularly imprinted cross-linked micelles[J]. Journal of the American Chemical Society, 2016, 138(31): 9 759-9 762.
- [13] GUO L H, MA X G, XIE X W, et al. Preparation of dual-dummy-template molecularly imprinted polymers coated magnetic graphene oxide for separation and enrichment of phthalate esters in water[J]. Chemical Engineering Journal, 2019, 361: 245-255.
- [14] DAN L, WANG H F. Mn-doped ZnS quantum dot imbedded two-fragment imprinting silica for enhanced room temperature phosphorescence probing of domoic acid[J]. Analytical Chemistry, 2013, 85(10): 4 844-4 848.
- [15] OSTOVAN A, GHAEDI M, ARABI M, et al. Hydrophilic multi-template molecularly imprinted biopolymers based on a green synthesis strategy for determination of B-family vitamins [J]. Acs Applied Materials & Interfaces, 2018, 10(4): 4 140-4 150.
- [16] XU Y, TANG Y H, ZHAO Y Y, et al. Bifunctional monomer magnetic imprinted nanomaterials for selective separation of tetracyclines directly from milk samples[J]. Journal of Colloid and Interface Science, 2018, 515: 18-26.
- [17] LOWDON J W, EERSELS, K, ROGOSIC R, et al. Substrate displacement colorimetry for the detection of diarylethylamines [J]. Sensors and Actuators B: Chemical, 2019, 282: 137-144.
- [18] DAI Y, JIANG W, ZHENG Y N, et al. Recyclable molecularly imprinted polymers based on Fe₃O₄@SiO₂ and PAMAM

- dendrimers for the determination of myosmine in cigarettes [J]. *Microchim Acta*, 2022, 189(12): 467.
- [19] HUANG S Y, XU J Q, ZHENG J T, et al. Synthesis and application of magnetic molecularly imprinted polymers in sample preparation[J]. *Analytical and Bioanalytical Chemistry*, 2018, 410(17): 3 991-4 041.
- [20] CHEN W, MA Y, PAN J M, et al. Molecularly imprinted polymers with stimuli-responsive affinity: progress and perspectives[J]. *Polymers*, 2015, 7(9): 1 689-1 715.
- [21] 乔雪勇, 赵晓磊, 孙国冉, 等. 基于中空结构材料的分子印迹技术在食品安全检测中的研究进展[J]. *食品与机械*, 2025, 41(10): 194-202.
- QIAO X Y, ZHAO X L, SUN G R, et al. Research progress of molecular imprinting technique based on hollow structural materials in food safety detection[J]. *Food & Machinery*, 2025, 41(10): 194-202.
- [22] SELLERGREN B. Direct drug determination by selective sample enrichment on an imprinted polymer[J]. *Analytical Chemistry*, 1994, 66(9): 1 578-1 582.
- [23] RAHIMI M, BAHAR S, HEYDARI R, et al. Determination of quercetin using a molecularly imprinted polymer as solid-phase microextraction sorbent and high-performance liquid chromatography[J]. *Microchemical Journal*, 2019, 148: 433-441.
- [24] KARRAT A, PALACIOS-SANTANDER J M, AMINE A, et al. A novel magnetic molecularly imprinted polymer for selective extraction and determination of quercetin in plant samples[J]. *Analytica Chimica Acta*, 2022, 1 203: 339709.
- [25] ABDULLAH, ALVEROGLU E, BALOUCH A, et al. Evaluation of the performance of a selective magnetite molecularly imprinted polymer for extraction of quercetin from onion samples[J]. *Microchemical Journal*, 2021, 162: 105849.
- [26] CHENG Y, NIE J Y, LIU H D, et al. Synthesis and characterization of magnetic molecularly imprinted polymers for effective extraction and determination of kaempferol from apple samples[J]. *Journal of Chromatography A*, 2020, 1 630: 461531.
- [27] ZHAO Q Y, MA C, LIU J Y, et al. Synthesis of magnetic covalent organic framework molecularly imprinted polymers at room temperature: a novel imprinted strategy for thermo-sensitive substance[J]. *Talanta*, 2021, 225: 121958.
- [28] WANG F Q, NI X, ZHANG J J, et al. Novel composite nanomaterials based on magnetic molecularly imprinted polymers for selective extraction and determination of rutin in fruit juice[J]. *Food Chemistry*, 2022, 381: 132275.
- [29] TRIADHI U, ALIZADEH ZULFIKAR M, SETIYANTO H, et al. Effects of (monomer-crosslinker-initiator) composition during non imprinted polymers synthesis for catechin retention [J]. *Journal of Physics: Conference Series*, 2018, 1 013(1): 012192.
- [30] GHASEMPOUR Z, AIIZADEH KHALED-ABAD M, VARDAST M R, et al. Fabrication of betanin imprinted polymer for rapid detection of red beet adulteration in pomegranate juice[J]. *Polymer bulletin*, 2019, 76(4): 1 793-1 805.
- [31] TEIXEIRA L S, SILVA C F, DE OLIVEIRA H L, et al. Microextraction by packed molecularly imprinted polymer to selectively determine caffeine in soft and energy drinks[J]. *Microchemical Journal*, 2020, 158: 105252.
- [32] NGUYEN V T, GIANG H H, NHA TRAN T T N, et al. Synthesis and characteristics of polymer-mediated curcumin molecular imprinting for quantitative determination of curcumin in food samples[J]. *Journal of Chromatography A*, 2024, 1 713: 464567.
- [33] ARABKHANI S, POURMOSLEMI S, LARKI HACHEGANI A. Rapid determination of metanil yellow in turmeric using a molecularly imprinted polymer dispersive solid-phase extraction and visible light spectrophotometry[J]. *Food Chemistry*, 2022, 380: 132120.
- [34] SHAFQAT S R, AHMAD BHAWANI S, BAKHTIAR S, et al. Synthesis of molecularly imprinted polymer for removal of Congo red[J]. *BMC Chemistry*, 2020, 14(1): 27.
- [35] SHI S Y, FAN D X, XIANG H Y, et al. Effective synthesis of magnetic porous molecularly imprinted polymers for efficient and selective extraction of cinnamic acid from apple juices[J]. *Food Chemistry*, 2017, 237: 198-204.
- [36] ALIPANAHPOUR DIL E, GHAEDI M, ASFARAM A, et al. Magnetic dual-template molecularly imprinted polymer based on syringe-to-syringe magnetic solid-phase microextraction for selective enrichment of p-Coumaric acid and ferulic acid from pomegranate, grape, and orange samples[J]. *Food Chemistry*, 2020, 325: 126902.
- [37] QIU X Z, XU X Y, LIANG Y, et al. The molecularly imprinted polymer supported by anodic alumina oxide nanotubes membrane for efficient recognition of chloropropanols in vegetable oils[J]. *Food Chemistry*, 2018, 258: 295-300.
- [38] MACHYNAKOVA A, LHOTSKA I, HROBONOVA K, et al. On-line coupling of molecularly imprinted solid phase extraction with liquid chromatography for the fast determination of coumarins from complex samples[J]. *Journal of Pharmaceutical and Biomedical Analysis*, 2017, 145: 144-150.
- [39] JI Y H, ZHAO J, ZHAO L S. Fabrication and characterization of magnetic molecularly imprinted polymer based on deep eutectic solvent for specific recognition and quantification of vanillin in infant complementary food[J]. *Food Chemistry*, 2022, 374: 131720.
- [40] WU J H, YANG Z Y, CHEN N, et al. Vanillin-molecularly targeted extraction of stir bar based on magnetic field induced self-assembly of multifunctional Fe₃O₄@polyaniline

- nanoparticles for detection of vanilla-flavor enhancers in infant milk powders[J]. *Journal of Colloid and Interface Science*, 2015, 442: 22-29.
- [41] FU X, ZHU D L, HUANG L, et al. Superparamagnetic core-shell dummy template molecularly imprinted polymer for magnetic solid-phase extraction of food additives prior to the determination by HPLC[J]. *Microchemical Journal*, 2019, 150: 104169.
- [42] CHENG Y, LIU H D, LI J, et al. Efficient and selective extraction of chlorogenic acid in juice samples using magnetic molecularly imprinted polymers[J]. *Microchemical Journal*, 2022, 183: 108110.
- [43] HROBONOVA K, LOMENOVA A. Molecularly imprinted polymer as stationary phase for HPLC separation of phenylalanine enantiomers[J]. *Monatshefte Für Chemie-Chemical Monthly*, 2018, 149(5): 939-946.
- [44] LI Z G, WANG J J, CHEN X, et al. A novel molecularly imprinted polymer-solid phase extraction method coupled with high performance liquid chromatography tandem mass spectrometry for the determination of nitrosamines in water and beverage samples[J]. *Food Chemistry*, 2019, 292: 267-274.
- [45] XIE Z H, ZHANG L Y, CHEN Y L, et al. Magnetic molecularly imprinted polymer combined with high-performance liquid chromatography for the selective separation and determination of glutathione in various wild edible boletes[J]. *Food Analytical Methods*, 2019, 12(12): 2 908-2 919.
- [46] PETER P, ROMINA P, ADAMA M S, et al. Development of a folic acid molecularly imprinted polymer and its evaluation as a sorbent for dispersive solid-phase extraction by liquid chromatography coupled to mass spectrometry[J]. *Journal of Chromatography A*, 2018, 1 576: 26-33.
- [47] DING H, WANG R Y, WANG X, et al. Molecularly imprinted covalent organic polymers for the selective extraction of benzoxazole fluorescent whitening agents from food samples [J]. *Journal of Separation Science*, 2018, 41(16): 66-92.
- [48] WANG X M, HUANG P F, MA X M, et al. Enhanced in-out-tube solid-phase microextraction by molecularly imprinted polymers-coated capillary followed by HPLC for endocrine disrupting chemicals analysis[J]. *Talanta*, 2019, 194: 7-13.
- [49] SUN X, JIAO X Y, LI J, et al. A miniaturized sorbent phase-based extraction device in the form of syringe filter holder using molecularly imprinted polymer as sorbent and its application to extract benzophenones[J]. *J Chromatogr A*, 2018, 1 543: 1-13.
- [50] 牛灿杰, 叶素丹. 基于金属有机骨架的分子印迹聚合物在食品检测中的应用进展[J]. *食品与发酵工业*, 2025, 51(1): 390-402.
- NIU C J, YE S D. Advances in applications of metal-organic framework-based molecularly imprinted polymers for food detection[J]. *Food and Fermentation Industries*, 2025, 51(1): 390-402.
- [51] 牛浩宇, 李媛媛, 王钢, 等. 基于 UIO-66-NH₂ 的表面分子印迹荧光传感器制备及其在检测罗丹明 6G 中的应用[J]. *发光学报*, 2025, 46(1): 156-163.
- NIU H Y, LI Y Y, WANG G, et al. Preparation of surface molecularly imprinted fluorescence sensor based on UIO-66-NH₂ and its application in detection of rhodamine 6G[J]. *Chinese Journal of Luminescence*, 2025, 46(1): 156-163.
- [52] KARDANI F, KHEZELI T, RASHEDINIA M, et al. Application of GO@ZIF-8 MOF/molecularly imprinted polymer composite for multiple monolithic fiber solid phase microextraction: determination of illegally added amphetamines in snacks and beverages and quantitation by GC-MS[J]. *Journal of Food Composition and Analysis*, 2025, 137: 106977.
- [53] CHEN H Y, WANG X Y, LV M J, et al. Preparation of metal-organic framework @molecularly imprinted polymers for extracting N-nitrosamines in salted vegetables[J]. *Journal of Chromatography B*, 2023, 1 231: 123942.
- [54] ELFADIL D, DELLA PELLE F, COMPAGNONE D, et al. Green synthesis of molecularly imprinted polymers for dispersive magnetic solid-phase extraction of erythrosine B associated with smartphone detection in food samples[J]. *Materials*, 2022, 15(21): 7 653.
- [55] LAMAOU I A, KARRAT A, AMINE A. Molecularly imprinted polymer integrated into paper-based analytical device for smartphone-based detection: application for sulfamethoxazole [J]. *Sensors and Actuators B: Chemical*, 2022, 368: 132122.
- [56] VODOVA M, NEJDL L, PAVELICOVA K, et al. Detection of pesticides in food products using paper-based devices by UV-induced fluorescence spectroscopy combined with molecularly imprinted polymers[J]. *Food Chemistry*, 2022, 380: 132141.
- [57] AHMAD O S, BEDWELL T S, ESEN C, et al. Molecularly imprinted polymers in electrochemical and optical sensors[J]. *Trends in Biotechnology*, 2019, 37(3): 294-309.
- [58] NASKAR H, PRADHAN S, GHATAK B, et al. Electrochemical detection of capsaicin in chili pepper using molecular imprinted poly β -cyclodextrin embedded graphite (MIP- β -CD@G) electrode[J]. *IEEE Sensors Journal*, 2021, 21 (16): 17 657-17 664.
- [59] MOREIRA L F P P, BUFFON E, DE S A C, et al. Fructose determination in fruit juices using an electrosynthesized molecularly imprinted polymer on reduced graphene oxide modified electrode[J]. *Food Chemistry*, 2021, 352: 129430.
- [60] SU J, SU X C. A multi-walled carbon nanotubes-based molecular imprinting electrochemical sensor for the detection of aspartame in sports beverage[J]. *Journal of Food Measurement and Characterization*, 2022, 18(1): 618-624.
- [61] TAN L, LI Q Y, LI Y J, et al. Specific adsorption and

- determination of aspartame in soft drinks with a zein magnetic molecularly imprinted modified MGCE sensor[J]. RSC Advances, 2021, 11(22): 13 486-13 496.
- [62] YAKUPOVA E, MUKHARLYAMOVA A, FITSEV I, et al. Layer-by-layer combination of MWCNTs and poly (ferulic acid) as electrochemical platform for hesperidin quantification [J]. Biosensors, 2023, 13(5): 500.
- [63] SINGH R, SINGH M. Molecularly imprinted electrochemical sensor for highly selective and sensitive determination of artificial sweetener acesulfame-K[J]. Talanta Open, 2023, 7: 100194.
- [64] ESSOUSI H, BARHOUMI H, BIBANI M, et al. Ion-imprinted electrochemical sensor based on copper nanoparticles-polyaniline matrix for nitrate detection[J]. Journal of Sensors, 2019, 2 019: 1-14.
- [65] ZHANG M, YANG Y K, WANG Y W, et al. A molecularly imprinted electrochemical sensor based on cationic intercalated two-dimensional titanium carbide nanosheets for sensitive and selective detection of triclosan in food samples [J]. Food Control, 2022, 132: 108532.
- [66] NAG S, DAS D, ROY R B. Voltammetry application of molecularly imprinted polyacrylamide as vanillin receptor in desserts[J]. IEEE Sensors Journal, 2023, 23(4): 3 446-3 452.
- [67] LIU J L, DU C J, WANG S Y, et al. Preparation and electrochemical sensing properties of vanillin molecularly imprinted polymer[J]. International Journal of Electrochemical Science, 2022, 17(7): 220715.
- [68] GAO Q, ZANG Y, ZHANG Y, et al. Composite polymerized molecular imprinting membrane-based electrochemical sensor for sensitive determination of curcumin by using 4-pentenoyl-aminoacyl-chitosan oligosaccharide as functional monomer oligomer[J]. Journal of Electroanalytical Chemistry, 2020, 879: 114793.
- [69] LI W, JIANG Z F, TAN L, et al. Rapid measurements of curcumin from complex samples coupled with magnetic biocompatibility molecularly imprinted polymer using electrochemical detection[J]. Journal of Separation Science, 2020, 43(6): 1 173-1 182.
- [70] WU L, WU T, ZENG W, et al. A new ratiometric molecularly imprinted electrochemical sensor for the detection of sunset yellow based on gold nanoparticles[J]. Food Chemistry, 2023, 413: 135600.
- [71] ASHLAY G, ANILA R C, BIJU J, et al. Design optimisation and fabrication of amino acid based molecularly imprinted sensor for the selective determination of food additive tartrazine[J]. Food Chemistry, 2023, 404: 134673.
- [72] CHENG S W, TANG D Y, ZHANG Y, et al. Specific and sensitive detection of tartrazine on the electrochemical interface of a molecularly imprinted polydopamine-coated PtCo nanoalloy on graphene oxide[J]. Biosensors, 2022, 12 (5): 326.
- [73] BONYADI S, GHANBARI K. Application of molecularly imprinted polymer and ZnO nanoparticles as a novel electrochemical sensor for tartrazine determination[J]. Microchemical Journal, 2023, 187: 108398.
- [74] ZHAO X Y, DING J H, BAI W L, et al. PEDOT:PSS/AuNPs/CA modified screen-printed carbon based disposable electrochemical sensor for sensitive and selective determination of carmine[J]. Journal of Electroanalytical Chemistry, 2018, 824: 14-21.
- [75] XU B J, ZHANG B H, YANG L T, et al. Electrochemical determination of luteolin using molecularly imprinted polycarbazole on MoS/graphene-carbon nanotubes nanocomposite modified electrode[J]. Electrochimica Acta, 2017, 258: 1 413-1 420.
- [76] HAN S, DING Y X, TENG F, et al. Molecularly imprinted electrochemical sensor based on 3D-flower-like MoS decorated with silver nanoparticles for highly selective detection of butylated hydroxyanisole[J]. Food Chemistry, 2022, 387: 132899.
- [77] ALBAYATI S H M, SOYLU P. Butylated hydroxyanisole nanomolar detection using a molecularly imprinted electrochemical sensor in food samples[J]. Journal of Applied Electrochemistry, 2024, 54(4): 879-891.
- [78] CHERIAN A R, BENNY L, VARGHESE A, et al. Molecularly imprinted scaffold based on poly (3-aminobenzoic acid) for electrochemical sensing of vitamin B₆[J]. Journal of the Electrochemical Society, 2021, 168(7): 077512.
- [79] YUE X Y, LUO X Y, ZHOU Z J, et al. Selective electrochemical determination of tertiary butylhydroquinone in edible oils based on an *in-situ* assembly molecularly imprinted polymer sensor[J]. Food Chemistry, 2019, 289: 84-94.
- [80] YANG X, GUO Q J, YANG J H, et al. Synergistic effects of layer-by-layer films for highly selective and sensitive electrochemical detection of trans-resveratrol[J]. Food Chemistry, 2021, 338: 127851.
- [81] GEORGE A, CHERIAN A R, BENNY L, et al. Surface-engineering of carbon fibre paper electrode through molecular imprinting technique towards electrochemical sensing of food additive in shrimps[J]. Microchemical Journal, 2023, 184: 108155.
- [82] ELFADIL D, LAMAOU A, DELLA PELLE F, et al. Molecularly imprinted polymers combined with electrochemical sensors for food contaminants analysis[J]. Molecules, 2021, 26(15): 4 607.
- [83] HUA Y B, KUKKAR D, BROWN R J C, et al. Recent advances in the synthesis of and sensing applications for metal-organic framework-molecularly imprinted polymer (MOF-MIP) composites[J]. Critical Reviews in Environmental Science and Technology, 2023, 53(2): 258-289.

- [84] 段定定. 碳基纳米复合材料电化学传感器的构建及其在生物分析中的应用[D]. 上海: 上海大学, 2021: 103-117.
- DUAN D D. Construction of electrochemical sensor based on carbon nanocomposites and its application in biological analysis[D] Shanghai: Shanghai University, 2021: 103-117.
- [85] OZGUR F O, ÇİMEN D, DENİZLİ A, et al. Surface plasmon resonance based sensor for amaranth detection with molecularly imprinted nanoparticles[J]. Photonic Sensors, 2023, 13(2): 230201.
- [86] LIU G Y, HUANG X D, LI L Y, et al. Recent advances and perspectives of molecularly imprinted polymer-based fluorescent sensors in food and environment analysis[J]. Nanomaterials, 2019, 9(7): 1 030.
- [87] DE DIEU HABIMANA J, JI J, PI F W, et al. A class-specific artificial receptor-based on molecularly imprinted polymer-coated quantum dot centers for the detection of signaling molecules, N-acyl-homoserine lactones present in gram-negative bacteria[J]. Analytica Chimica Acta, 2018, 1 031: 134-144.
- [88] WU L, LIN Z Z, ZHONG H P, et al. Rapid detection of malachite green in fish based on CdTe quantum dots coated with molecularly imprinted silica[J]. Food Chemistry, 2017, 229: 847-853.
- [89] WU S J, ZHANG H, SHI Z, et al. Aptamer-based fluorescence biosensor for chloramphenicol determination using upconversion nanoparticles[J]. Food Control, 2015, 50: 597-604.
- [90] CIEPLAK M, KUTNER W. Artificial biosensors: how can molecular imprinting mimic biorecognition? [J]. Trends in Biotechnology, 2016, 34(11): 922-941.
- [91] WEI X, HAO T F, XU Y Q, et al. Facile polymerizable surfactant inspired synthesis of fluorescent molecularly imprinted composite sensor via aqueous CdTe quantum dots for highly selective detection of λ -cyhalothrin[J]. Sensors and Actuators B: Chemical, 2016, 224: 315-324.
- [92] HOMOLA J, YEE S S, GAUGLITZ G. Surface plasmon resonance sensors review[J]. Sensors and Actuators B: Chemical, 1999, 54(1/2): 3-5.
- [93] JIN X C, FANG G Z, PAN M F, et al. A molecularly imprinted electrochemiluminescence sensor based on upconversion nanoparticles enhanced by electrodeposited rGO for selective and ultrasensitive detection of clenbuterol[J]. Biosensors & Bioelectronics, 2018, 102: 357-364.
- [94] CAPOFERRI D, ALVAREZ-DIDUK R, DEL CARLO M, et al. Electrochromic molecular imprinting sensor for visual and smartphone-based detections[J]. Analytical Chemistry, 2018, 90(9): 5 850-5 856.
- [95] XU L H, PAN M F, FANG G Z, et al. Carbon dots embedded metal-organic framework@molecularly imprinted nanoparticles for highly sensitive and selective detection of quercetin[J]. Sensors and Actuators B: Chemical, 2019, 286: 321-327.
- [96] ZOUGHI S, FARIDBOD F, AMIRI A, et al. Detection of tartrazine in fake saffron containing products by a sensitive optical nanosensor[J]. Food Chemistry, 2021, 350: 129197.
- [97] LUO S Q, SUN X J, ZHANG L F, et al. Preparation of room-temperature phosphorescence-ratiometric fluorescence magnetic mesoporous imprinted microspheres and its application in detection of malachite green and tartrazine in multimatrix[J]. Food Chemistry, 2024, 430: 137096.
- [98] YANG Q, LI J H, WANG X Y, et al. Dual-emission color-controllable nanoparticle based molecular imprinting ratiometric fluorescence sensor for the visual detection of Brilliant Blue[J]. Sensors and Actuators B: Chemical, 2019, 284: 428-436.
- [99] LI X P, WU Z W, CAO H, et al. A molecularly imprinted fluorescence sensor for the simultaneous and rapid detection of histamine and tyramine in cheese[J]. Foods, 2025, 14(9): 1 475.
- [100] LI C Y, YANG Q, WANG X Y, et al. Facile approach to the synthesis of molecularly imprinted ratiometric fluorescence nanosensor for the visual detection of folic acid[J]. Food Chemistry, 2020, 319: 126575.
- [101] PIROT S M, OMER K M. Surface imprinted polymer on dual emitting MOF functionalized with blue copper nanoclusters and yellow carbon dots as a highly specific ratiometric fluorescence probe for ascorbic acid[J]. Microchemical Journal, 2022, 182: 107921.
- [102] WANG Z H, LONG R Q, PENG M J, et al. Molecularly imprinted polymers-coated cdte quantum dots for highly sensitive and selective fluorescent determination of ferulic acid[J]. Journal of Analytical Methods in Chemistry, 2019, 2 019: 1505878.
- [103] FU D L, CHEN T, LIU H L, et al. An ultraviolet self-initiated polymerized platform for specific recognition and elimination of caffeic acid based on the molecular imprinting technology [J]. Sensors and Actuators, B: Chemical, 2022, 361: 131659.