Molecularly Imprinted Polymer-Based Luminescent Chemosensors

Subjects: Chemistry, Inorganic & Nuclear
Contributor: Ruoyang Liu, Chi-Chiu Ko

Molecularly imprinted polymer (MIP)-based luminescent chemosensors combine the advantages of the highly specific molecular recognition of the imprinting sites and the high sensitivity with the luminescence detection. Luminescent molecularly imprinted polymers (luminescent MIPs) towards different targeted analytes are constructed with different strategies, such as the incorporation of luminescent functional monomers, physical entrapment, covalent attachment of luminescent signaling elements on the MIPs, and surface-imprinting polymerization on the luminescent nanomaterials.

Keywords: luminescent ; molecularly imprinted polymer ; chemosensor ; transition metal complex ; quantum dots ; organic dye

1. Introduction

Chemosensors are composed of a receptor functional moiety and a reporter, which can produce a detectable signal response, such as absorption, luminescent or electrical, to reflect the binding of an analyte with the receptor via non-covalent host-guest interactions. For an ideal chemosensor, the host-guest interaction must be highly specific to the targeted analyte and preferably with high binding affinity to achieve high selectivity and sensitivity [1][2][3][4]. As a result, receptor design is crucial for the successful development of chemosensors but is usually the most challenging task. On the other hand, the high sensitivity and non-destructive nature of luminescence, both fluorescence and phosphorescence, are attractive features for a chemosensor's reporter. In this context, the development of luminescent molecular devices, such as switches, sensors, and molecular machines, has been an active area of research in supramolecular photochemistry. To design luminescent chemosensors, a luminophore is connected to the receptor so that the binding event between the receptor (host) and the targeted analyte (guest) induce a change of its emission properties, which serve as the read-out signals for the qualitative and quantitative determination of the analyte [4][5][6][7][8].

The extensive developments of molecularly imprinted polymers (MIPs) have provided an effective way for preparing materials with receptor sites, which are highly specific to the molecular template used in the preparation of the MIPs or molecules with high structural similarity, including the distributions of the functional group moieties, hydrophobicity, and polarity. In addition to the highly selective binding receptors, MIPs are also well-known for their inherent mechanical and chemical stability, strong binding affinity, short development time, and low cost with well-developed preparation strategies [9][10][11]. Generally, the in-situ polymerization of the monomer, functional monomer, and crosslinker in the presence of a target template molecule is employed to synthesize MIPs. The functional monomers are designed with substituents or groups to interact with template molecules. Due to the interactions, such as hydrogen bonds or non-covalent interactions, between the functional monomer and the template, the reaction mixtures are pre-organized such that the template molecules are surrounded by functional monomers. Upon cross-linking polymerization, the template molecules are encapsulated in the polymer matrices. After the removal of the template molecules, template-shaped cavities with complementary functional groups, sizes, and shapes best-fitting the template molecules become the highly selective receptor site for the template molecules. These molecular imprinting technologies have been well-established to develop materials with highly selective receptors and thus widely exploited in many significant applications in different fields, including biosensors, solid-phase extraction, chromatographic separation, catalysis, drug-controlled release, chemical analysis, and hybrid with organic polymers (such as MOFs) to make composite materials [12][13][14][15][16]. The merits of the imprinting effect of MIP are characterized by the imprinting factor, binding capacity, and selectivity. Amongst, the imprinting factor is determined by comparing the amount of bound analyte by MIP and its corresponding nonimprinted polymer (NIP), the selectivity is determined by the outcome of rebinding assay compared between the target analyte and structural analog, and the equilibrium binding capacity is normally measured by HPLC, GS-MS, and UV-vis. The details of measurement have been described in a recent review [17].

The use of MIPs in the development of chemosensors offers another advantage, as the polymeric systems are well-known to provide collective responses to enhance their sensitivity by “amplifying” the signals compared to single molecular systems [18]. The amplifying effect enables the detection of the binding event by gravimetric methods using a highly sensitive quartz microbalance [19]. However, the use of an expensive and sophisticated microbalance has limited their applications in the research laboratory. To extend their applications as portable or real-time monitoring sensors for on-site utilization, a signal-transducing component has been introduced to the receptor-containing polymer. Optical signaling, including absorption and luminescence, is one of the preferable means as it is easily detected with portable devices or even the naked eye. For example, chemosensors for aromatic explosives such as 2,4,6-trinitrotoluene (TNT) and 2,4-dinitrotoluene (DNT) can be developed by conjugation of a suitable fluorophore into a polymer main chain [20]. Polymer-based luminescent chemosensors for metal cations such as lead(II), palladium(II), and iron(II) ions have also been developed [21][22][23]. In these chemosensors, the binding of the target molecules/ions onto the polymer can be reflected by the quenching of fluorescence of the fluorophore. Apart from “turn-off” fluorescent chemosensors, the more sensitive “turn-on” polymer-based chemosensors have also been developed [24][25].

2. Molecular Imprinting Strategy

As mentioned above, MIPs, as selective sorbents, are prepared from a mixture containing at least two essential components, namely functional monomers for interacting with the template or structurally-related molecule that acts as a template. The design concept of MIP was first reported and demonstrated using silica matrices by Polyakov’s seminal work ninety years ago. Different strategies for preparing MIP have been rapidly developed over the past few decades due to the exponential growth and development of organic polymers [26].

In the syntheses of MIPs, the template-monomer(s) adduct was formed in the reaction mixture via one or more intermolecular interactions, such as reversible covalent bond formation, semi-covalent or non-covalent interactions (electrostatic affinity, van der Waals interactions, hydrophobic forces, and coordination with a metal center). The subsequent polymerization is performed in the presence of an initiator and crosslinker in the solvent. With crosslinking polymerization, the orientation of monomers and the functional sites that bound with the template molecule are fixed and rigidified by crosslinking units in a three-dimensional network to avoid their random movement. Subsequent removal of the template molecules from the MIP matrix leaves robust binding sites that are highly selective to the template molecule and structurally similar molecules having the same functional groups. These highly selective receptors are usually referred to as the “imprinted” sites of MIP [27].

In general, MIPs can be prepared by copolymerization reactions of a combination of the most commonly used building blocks (monomer and crosslinker) in the presence of template molecules, initiators, and solvents, as summarized in **Table 1**. Although different types of MIPs are designed based on the same principle, their imprinting performance is strongly dependent on the building blocks, types of target molecules as well as the polymerization conditions, including temperature, initiator, and solvents [28][29]. The molecular design of the monomer, crosslinker, template, and polymerization conditions to enhance the imprinting factors have been extensively reviewed [28][29][30][31][32][33][34]. In these reviews, the development of functional monomers with complementary functional moieties to form donor-acceptor interactions with the template molecules [30][31][32] and the effects of crosslinkers and solvents on controlling the recognition site as well as polymer morphology are discussed in detail [33][34].

Table 1. Commonly used reagents in the preparation of MIPs.

Components	Examples
Monomer	**Acrylic acid**
	Methacrylic acid
	2-Vinylpyridine
	Styrene
	4-Vinylaniline
	Methyl methacrylate
	1-Vinylimidazole
	Acrylamide

Components	Examples
Crosslinker	Ethylene glycol dimethacrylate
	Divinylbenzene
	1,1,1-Trimethylolpropane trimethacrylate
	1,3-Diisopropenyl benzene
	Pentaerythritol triacrylate
Solvent	Acetonitrile
	2-Methoxyethanol
	Methanol
	Chloroform
	Tetrahydrofuran
	N,N-Dimethylformamide
Initiator	Benzoyl peroxide
	Azobisisobutyronitrile
	Ammonium persulfate
	Ethyl 2-chloro-propionate

With the highly selective binding sites, MIPs have found a wide range of applications such as solid-phase extraction (SPE), sensors, membranes, catalysis, synthesis, and drug delivery [35][36]. Moreover, the high thermal stability and structural rigidity of MIPs enable their use under harsh conditions. Owing to the unique features of structure predictability and recognition specificity, molecularly imprinted polymers are universally applied in sample pretreatment, chromatographic separation, and chemical/biological sensing [37][38]. With the recent advance in surface imprinting technology together with the hollow porous polymer synthesis, MIPs with high adsorption capacity and high imprinting efficiency, good morphology, uniform size, and ideal surface properties can be obtained [39]. The surface MIPs on hollow porous polymers are ideal to be used as sorbents and stationary phases for sample pretreatment and chromatography [40]. Further enhancements of the surface areas, interfacial properties, and binding capacity have also been achieved by incorporating the composite imprinting strategy into sol-gel processes for nanomaterials and nanoimprinting [41][42].

3. Design Strategies of Luminescent MIPs for Chemosensing Applications

Luminescence detection has been providing a significant and attractive approach for numerous chemical, biological, and environmental species because of its high sensitivity, non-destructive nature, and stability [4][5][6][7][8]. As demonstrated in recent decades, many luminescent MIP-based sensors possess high sensitivity of luminescence detection and high selectivity of MIP recognition [43][44][45][46].

For emissive analytes, their MIP-based chemosensors can be non-emissive and thus are generally prepared using the standard method for MIPs using the analyte as the template. As the luminescent properties of the analytes would change upon binding with the imprinted sites of the MIP due to the changes in the micro-environment and the electronic properties resulting from the binding interactions, such changes can be used for the qualitative and quantitative determination of the analyte. Selected examples include MIP-based sensors for enrofloxacin and fluoroquinolone analogs [47] and rhodamine derivatives [48]. As most of the target analytes are non-emissive, there are only a few reports on this type of MIP-based luminescent chemosensors.

For non-emissive analytes, luminescent chemosensing can be achieved by displacement or competitive assay using a non-emissive MIP with a luminescent-labeled analyte as the template [49][50]. However, this design cannot be widely applied as luminescent labeling of the target analyte can be extremely challenging or even impossible. The introduction of luminophore into the MIP to report the binding event of the imprinted site represents a more versatile design strategy for developing luminescent MIP-based chemosensors [51]. With this strategy, different types of luminophores, including fluorescent organic compounds, luminescent transition metal complexes, nanoparticles, and quantum dots with different emission characteristics, can be rationally chosen to successfully develop the luminescent MIP-based chemosensors [43][44][45][46][52][53].

Early design of luminescent MIPs is mainly based on the physical entrapment or chemical modification of the MIPs through the addition of luminescent dye or polymerizable organic fluorescent-dye-containing monomers in the preparation of MIPs, respectively [54][55]. However, most of the fluorescent moieties in the MIPs do not show any emission responses to the binding event of the imprinted receptors because they are randomly embedded in MIP, and most of them do not have any electronic communication with the receptor moieties. To increase the luminescent responses to the binding event of the imprinted receptors, monomers with both fluorescent and binding moieties have been used [56]. However, the syntheses of the highly functionalized monomer are usually complicated, and the fluorescent responses of the MIPs are still not as strong as the receptor-containing fluorescent monomer in the solution state. To further enhance the emission changes of the MIPs upon binding with the target guest molecules at the receptors, a new design of luminescent MIPs by chemical modification of the imprinted receptor sites of the non-emissive MIPs with the emissive dyes has been reported [57]. With the recent development of luminescent nano-particles and nano-clusters, which show intense emission with narrow emission band, large Stokes shift, and readily tunable emission characteristics [58], new designs of luminescent MIPs with core-shell structures have been prepared by surface imprinting polymerization on these luminescent nano-particles. However, the successful signal transduction of the binding event of the surface-imprinted polymer to perturb the emission of the nano-particles remains challenging.

3.1. Using Luminescent Monomer as a Building Block of MIPs

Through the copolymerization of luminescent monomer in the preparation of MIPs, emissive MIPs with the emission properties derived from the luminophore of the monomer can be obtained. This method has been extensively explored in the past decade for the development of luminescent chemosensors. For example, Rurack and coworkers [56] designed a fluorescent monomer containing both urea-receptor and nitrobenzoxadiazole fluorophore to prepare a fluorescent MIP. Based on the binding of the urea group with the carboxylate, fluorescent MIP with imprinting sites specific for N-carbobenzyloxy-l-phenylalanine (Z-L-Phe) can be prepared by reversible addition-fragmentation chain-transfer (RAFT) polymerization of the fluorescent monomer, ethylene glycol dimethacrylate (EDGA) and benzyl methacrylate. With the hydrogen-bonding interactions between Z-L-Phe and the urea functional group in the binding site, a strongly bonded complex adduct is formed to avoid the formation of the non-emissive deprotonated species. As a result, the presence of Z-L-Phe leads to a pronounced enhancement of fluorescence, which can be used for qualitative and quantitative analysis of Z-L-Phe. It is worth noting that the solvent used for the RAFT polymerization also plays an important role in the binding affinity and sensing responses of the resulting MIP.

Another example is illustrated in fluorescent tetracycline-imprinted polymers reported by Zhang and coworkers [59]. By copolymerization of a fluorescent monomer (2-hydroxyethyl anthrancene-9-carboxylate) methacrylate (AnHEMA), methacrylic acid monomer, and EDGA crosslinker in the presence of tetracycline as a template, fluorescent MIP for tetracycline (Tc-MIP) can be obtained. However, the tetracycline-binding of such MIP is limited in organic solvents due to its hydrophobicity, and thus the fluorescent response for the chemosensory application cannot function in aqueous and biological media. To introduce the hydrophilicity of the fluorescent Tc-MIP so that it can function in an aqueous medium and undiluted bovine serum, poly(2-hydroxyethyl methacrylate) (PHEMA) as hydrophilic polymer brushes grafted on the surface of fluorescent Tc-MIP nanoparticles were prepared. The hydrophilic polymer brushes were introduced by the addition of a well-defined PHEMA with a dithioester end group in the RAFT precipitation copolymerization reaction. With the PHEMA-grafted fluorescent Tc-MIP, significant fluorescence quenching resulting from the binding of tetracycline could be observed in the biological milieu. Apart from organic fluorescent MIPs, silica-based fluorescent MIPs designed using a similar synthetic strategy with a fluorescent monomer have also been reported [60]. By one-pot copolymerization of a fluorescent monomer containing fluorescein fluorophore (FITC) and amino-receptor containing monomer, 3-aminopropyltriethoxysilane, and the tetraethoxysilane in the presence of naproxen as the template under a catalyst-free condition, fluorescent silica-based MIP nanoparticles showing fast and specific sensing luminescent response towards naproxen can be obtained.

Although wide varieties of organic fluorescent functional monomers are observed to have good compatibility with polymeric materials and relatively high fluorescent intensities, their universal applications are hindered by the broad and tailing emission peaks. These limitations are more pronounced in MIPs with fluorophores and receptors derived from two separated monomers, in which the emission of some of the fluorophores is unaffected by the binding event. Moreover, poor photostability and photobleaching of these MIPs have also been reported [46].

3.2. Chemical Surface Functionalization with a Luminophore

MIPs can be made luminescent through immobilization strategies by attaching luminescent signaling elements. Chemical surface functionalization methods are applied to provide covalent binding sites for exterior luminescent moieties. The

commonly used functional groups for covalent immobilization include thiol, amino, carboxyl, hydroxyl, vinyl, and azide groups [61][62][63]. With these functional groups on the MIPs, luminophores can be covalently immobilized on the surface, including the molecular recognition cavities, or directed to the designed sites through click reactions and post-imprinting modification. This strategy has been extensively explored since 2010 [57]. Upon grafting luminescent labels, the luminescent signals can be detected by emission spectroscopy based on the intrinsic properties of luminescent signaling elements [57][64][65].

Wang and coworkers [66] developed a fluorescent protein-imprinted polymer sensor for the fast detection of glycoproteins. In this study, the thiol groups are used for linkage with 4-vinyl phenylboronic acid through click reaction to serve as recognition and luminescent signaling moiety. The 4-vinyl phenylboronic acid forms the imprinted recognition cavity as well as extends π-conjugation to enhance the luminescence properties. Takeuchi and coworkers [67] reported a fluorescent sensing platform for exosome detection. Using antibody-conjugated exosomes with polymerizable methyacryloyl group as templates, MIPs with imprinted cavities can be prepared. Subsequent removal of the exosomes would leave the imprinted sites with thiol groups. Fluorophores can then be directed to the thiol groups on the cavity to form an immobilization linkage and to serve as a reporter for the binding event between the cavity and the exosomes.

With luminophores attached through covalent bonding, a chemical surface functionalization is a promising tool for translating recognition events into luminescent signals. However, maintaining the integrity of the binding cavities after chemical surface functionalization so as not to weaken the selectivity remains a challenging issue.

3.3. Physical Entrapment

Since the first report of luminescent lanthanide-based copolymer sensors by Murray and coworkers [54][68], lanthanide metal ions/complexes, especially those of terbium(III) and europium(III), have been extensively used as luminophores for developing luminescent MIP-based sensors. The popularity of lanthanides can be attributed to their unique luminescent properties, such as narrow emission bandwidths and extremely long emission lifetimes. Lanthanide ions can be incorporated into the polymer matrix through physical entrapment. After physical entrapment, the lanthanide ions are surrounded by the rigid polymeric matrix, and thus they are highly stable. Moreover, they also exhibit similar photophysical properties as in the solution state [69].

For example, Pan and coworkers [70] incorporated [Eu(TTA)$_3$phen] into poly(amidoamine) dendrimer to serve as a luminescent additive dispersing on the surface of the molecularly imprinted membrane for the selective recognition of salicylic acid. Moreno-Bondi and coworkers [71] developed a molecularly imprinted nanofilament polymer with physically entrapped Eu(III) ions for fluorescent sensing of enrofloxacin. In their report, the entrapped Eu(III) ions can be derivatized by enrofloxacin in the solution state to form a europium-enrofloxacin complex. By the detection of the change in the emission intensity, in-situ monitoring of the enrofloxacin can be achieved. As the luminescent lifetimes of lanthanides are significantly longer than the polymer backbone, time-resolved emission spectroscopy can be used to discriminate the background emission from the polymer backbone.

3.4. Encapsulation

Luminescent MIPs can also be fabricated by encapsulation with luminescent micro- or nano-particles, which are produced by emissive nanomaterials or immobilization of luminophores on the solid-supported micro- or nano-particles. These types of emissive MIPs are commonly prepared by surface molecularly imprinting techniques on solid luminescent substrates. For example, Yan and coworkers [72] fabricated a fluorescent core-shell MIP sensor for selective detection of λ-cyhalothrin. The imprinting sites are formed on the surface of the modified SiO_2 beads with a fluorescent dye FITC as the fluorescent reporter. To prepare SiO_2 spheres with FITC, FITC is first conjugated with 3-aminopropyltriethoxysilane and then coated on SiO_2 spheres. The resulting core-shell fluorescent MIP sensor can quantify λ-cyhalothrin with a wide range of 10–60 nM and a detection limit of 9.17 nM, according to the Stern–Volmer quenching study.

For emissive nanomaterials, different strategies were used to incorporate these materials in the preparation of luminescent MIPs. These include the addition of nanoparticle emitters in the conventional preparation of MIPs to give nanocomposite through chemical bonding or physical effects [73]; surface imprinting polymerization as a coating layer with imprinted cavities on the surface of emissive nanomaterials or on the surface of encapsulated luminescent inorganic nanomaterials [74]. The last strategy is exemplified in a recently reported molecularly imprinted silica polymer on the perovskite quantum dots (QDs) encapsulated mesoporous silica [75]. In this study, the emission properties of the QDs can be used for the detection of 2,2-dichlorovinyl dimethyl phosphate.

References

1. Potyrailo, R.A. Toward High Value Sensing: Monolayer-Protected Metal Nanoparticles in Multivariable Gas and Vapor S ensors. Chem. Soc. Rev. 2017, 46, 5311–5346.
2. Mansha, M.; Akram Khan, S.; Aziz, M.A.; Zeeshan Khan, A.; Ali, S.; Khan, M. Optical Chemical Sensing of Iodide Ions: A Comprehensive Review for the Synthetic Strategies of Iodide Sensing Probes, Challenges, and Future Aspects. Che m. Rec. 2022, 7, e202200059.
3. Huang, L.; Wang, Z.; Zhu, X.; Chi, L. Electrical Gas Sensors Based on Structured Organic Ultra-Thin Films and Nanocr ystals on Solid State Substrates. Nanoscale Horizons 2016, 1, 383–393.
4. Kumar, V.; Kim, H.; Pandey, B.; James, T.D.; Yoon, J.; Anslyn, E.V. Recent advances in fluorescent and colorimetric che mosensors for the detection of chemical warfare agents: A legacy of the 21st century. Chem. Soc. Rev. 2023, 52, 663–704.
5. Li, D.; Yu, J. AIEgens-Functionalized Inorganic-Organic Hybrid Materials: Fabrications and Applications. Small 2016, 1 2, 6478–6494.
6. He, L.; Dong, B.; Liu, Y.; Lin, W. Fluorescent Chemosensors Manipulated by Dual/Triple Interplaying Sensing Mechanis ms. Chem. Soc. Rev. 2016, 45, 6449–6461.
7. Xu, X.; Li, H.; Xu, Z. Multifunctional luminescent switch based on a porous PL-MOF for sensitivity recognition of HCl, tr ace water and lead ion. Chem. Eng. J. 2022, 436, 135028.
8. Jaiswal, S.; Das, S.; Kundu, S.; Rawal, I.; Anand, P.; Patra, A. Progress and perspective: Fluorescent to long-lived emis sive multifunctional probes for intracellular sensing and imaging. J. Mat. Chem. C 2022, 10, 6141–6195.
9. Sharma, P.S.; D'Souza, F.; Kutner, W. Molecular Imprinting for Selective Chemical Sensing of Hazardous Compounds and Drugs of Abuse. TrAC—Trends Anal. Chem. 2012, 34, 59–77.
10. Chen, L.; Wang, X.; Lu, W.; Wu, X.; Li, J. Molecular Imprinting: Perspectives and Applications. Chem. Soc. Rev. 2016, 45, 2137–2211.
11. Akgönüllü, S.; Kılıç, S.; Esen, C.; Denizli, A. Molecularly Imprinted Polymer-Based Sensors for Protein Detection. Poly mers 2023, 15, 629.
12. Fuchs, Y.; Soppera, O.; Haupt, K. Photopolymerization and Photostructuring of Molecularly Imprinted Polymers for Sen sor Applications—A Review. Anal. Chim. Acta 2012, 717, 7–20.
13. Wu, X.; Tang, S.; Zhao, P.; Tang, K.; Chen, Y.; Fu, J.; Zhou, S.; Yang, Z.; Zhang, Z. One-pot synthesis of ternary-emissi on molecularly imprinted fluorescence sensor based on metal–organic framework for visual detection of chloramphenic ol. Food Chem. 2023, 402, 134256.
14. Gui, R.; Jin, H.; Guo, H.; Wang, Z. Recent Advances and Future Prospects in Molecularly Imprinted Polymers-Based El ectrochemical Biosensors. Biosens. Bioelectron. 2018, 100, 56–70.
15. Gao, D.; Zhang, Z.; Wu, M.; Xie, C.; Guan, G.; Wang, D. A Surface Functional Monomer-Directing Strategy for Highly D ense Imprinting of TNT at Surface of Silica Nanoparticles. J. Am. Chem. Soc. 2007, 129, 7859–7866.
16. Wu, S.; Tan, L.; Wang, G.; Peng, G.; Kang, C.; Tang, Y. Binding Characteristics of Homogeneous Molecularly Imprinted Polymers for Acyclovir Using an (Acceptor-Donor-Donor)-(Donor-Acceptor-Acceptor) Hydrogen-Bond Strategy, and An alytical Applications for Serum Samples. J. Chromatogr. A 2013, 1285, 124–131.
17. Ndunda, E.N. Molecularly Imprinted Polymers—A Closer Look at the Control Polymer Used in Determining the Imprinti ng Effect: A Mini Review. J. Mol. Recognit. 2020, 33, e2855.
18. Swager, T.M. The Molecular Wire Approach to Sensory Signal Amplification. Acc. Chem. Res. 1998, 31, 201–207.
19. Kartal, F.; Çimen, D.; Bereli, N.; Denizli, A. Molecularly imprinted polymer based quartz crystal microbalance sensor for the clinical detection of insulin. Mater. Sci. Eng. C 2019, 97, 730–737.
20. Mako, T.L.; Racicot, J.M.; Levine, M. Supramolecular Luminescent Sensors. Chem. Rev. 2019, 119, 322–477.
21. Toal, S.J.; Trogler, W.C. Polymer Sensors for Nitroaromatic Explosives Detection. J. Mater. Chem. 2006, 16, 2871–288 3.
22. Na Kim, H.; Xiu Ren, W.; Seung Kim, J.; Yoon, J. Fluorescent and Colorimetric Sensors for Detection of Lead, Cadmiu m, and Mercury Ions. Chem. Soc. Rev. 2012, 41, 3210–3244.
23. Zhou, L.; Zhao, K.; Hu, Y.J.; Feng, X.C.; Shi, P.D.; Zheng, H.G. A Bifunctional Photoluminescent Metal–organic Framew ork for Detection of Fe3+ Ion and Nitroaromatics. Inorg. Chem. Commun. 2018, 89, 68–72.

24. Nian, S.; Pu, L. Amphiphilic Polymer-Based Fluorescent Probe for Enantioselective Recognition of Amino Acids in Immi scible Water and Organic Phases. Chem.-A Eur. J. 2017, 23, 18066–18073.

25. Rochat, S.; Swager, T.M. Conjugated Amplifying Polymers for Optical Sensing Applications. ACS Appl. Mater. Interface s 2013, 5, 4488–4502.

26. Alexander, C.; Andersson, H.S.; Andersson, L.I.; Ansell, R.J.; Kirsch, N.; Nicholls, I.A.; O'Mahony, J.; Whitcombe, M.J. Molecular Imprinting Science and Technology: A Survey of the Literature for the Years up to and Including 2003. J. Mol. Recognit. 2006, 19, 106–180.

27. Whitcombe, M.J.; Kirsch, N.; Nicholls, I.A. Molecular Imprinting Science and Technology: A Survey of the Literature for t he Years 2004–2011. J. Mol. Recognit. 2014, 27, 297–401.

28. Vasapollo, G.; Del Sole, R.; Mergola, L.; Lazzoi, M.R.; Scardino, A.; Scorrano, S.; Mele, G. Molecularly Imprinted Polym ers: Present and Future Prospective. Int. J. Mol. Sci. 2011, 12, 5908–5945.

29. Adumitrăchioaie, A.; Tertiş, M.; Cernat, A.; Săndulescu, R.; Cristea, C. Electrochemical Methods Based on Molecularly I mprinted Polymers for Drug Detection. A Review. Int. J. Electrochem. Sci. 2018, 13, 2556–2576.

30. Liu, Z.; Huang, Y.; Yang, Y. Molecularly Imprinted Polymers as Advanced Drug Delivery Systems: Synthesis, Character and Application; Springer: Singapore, 2021.

31. Mayes, A.G.; Whitcombe, M.J. Synthetic strategies for the generation of molecularly imprinted organic polymers. Adv. D rug Del. Rev. 2005, 57, 1742–1778.

32. Sajini, T.; Gigimol, M.G.; Mathew, B. A brief overview of molecularly imprinted polymers supported on titanium dioxide matrices. Mater. Today Chem. 2019, 11, 283–295.

33. Sajini, T.; Mathew, B. A Brief Overview of Molecularly Imprinted Polymers: Highlighting Computational Design, Nano an d Photo-Responsive Imprinting. Talanta Open 2021, 4, 100072.

34. Reville, E.K.; Sylvester, E.H.; Benware, S.J.; Negi, S.S.; Berda, E.B. Customizable Molecular Recognition: Advanceme nts in Design, Synthesis, and Application of Molecularly Imprinted Polymers. Polym. Chem. 2022, 13, 3387–3411.

35. Lautner, G.; Kaev, J.; Reut, J.; Öpik, A.; Rappich, J.; Syritski, V.; Gyurcsányi, R.E. Selective Artificial Receptors Based o n Micropatterned Surface-Imprinted Polymers for Label-Free Detection of Proteins by SPR Imaging. Adv. Funct. Mater. 2011, 21, 591–597.

36. Beltran, A.; Borrull, F.; Marcé, R.M.; Cormack, P.A.G. Molecularly-Imprinted Polymers: Useful Sorbents for Selective Ex tractions. TrAC—Trends Anal. Chem. 2010, 29, 1363–1375.

37. Cao, Y.; Feng, T.; Xu, J.; Xue, C. Recent Advances of Molecularly Imprinted Polymer-Based Sensors in the Detection of Food Safety Hazard Factors. Biosens. Bioelectron. 2019, 141, 111447.

38. Ashley, J.; Shahbazi, M.A.; Kant, K.; Chidambara, V.A.; Wolff, A.; Bang, D.D.; Sun, Y. Molecularly Imprinted Polymers f or Sample Preparation and Biosensing in Food Analysis: Progress and Perspectives. Biosens. Bioelectron. 2017, 91, 6 06–615.

39. Chen, L.; Xu, S.; Li, J. Recent Advances in Molecular Imprinting Technology: Current Status, Challenges and Highlighte d Applications. Chem. Soc. Rev. 2011, 40, 2922–2942.

40. Cheong, W.J.; Ali, F.; Choi, J.H.; Lee, J.O.; Yune, S.K. Recent applications of molecular imprinted polymers for enantio-selective recognition. Talanta 2013, 106, 45–59.

41. Pichon, V.; Delaunay, N.; Combes, A. Sample preparation using molecularly imprinted polymers. Anal. Chem. 2020, 92, 16–33.

42. Turiel, E.; Martín-Esteban, A. Molecularly Imprinted Polymers for Sample Preparation: A Review. Anal. Chim. Acta 201 0, 668, 87–99.

43. Kim, H.N.; Guo, Z.; Zhu, W.; Yoon, J.; Tian, H. Recent Progress on Polymer-Based Fluorescent and Colorimetric Chem osensors. Chem. Soc. Rev. 2011, 40, 79–93.

44. Liu, G.; Huang, X.; Li, L.; Xu, X.; Zhang, Y.; Lv, J.; Xu, D. Recent Advances and Perspectives of Molecularly Imprinted P olymer-Based Fluorescent Sensors in Food and Environment Analysis. Nanomaterials 2019, 9, 1030.

45. Gui, R.; Jin, H. Recent Advances in Synthetic Methods and Applications of Photo-Luminescent Molecularly Imprinted P olymers. J. Photochem. Photobiol. C Photochem. Rev. 2019, 41, 100315.

46. Yang, Q.; Li, J.; Wang, X.; Peng, H.; Xiong, H.; Chen, L. Strategies of molecular imprinting-based fluorescence sensors for chemical and biological analysis. Biosens. Bioelectron. 2018, 112, 54–71.

47. Ton, X.A.; Acha, V.; Haupt, K.; Tse Sum Bui, B. Direct Fluorimetric Sensing of UV-Excited Analytes in Biological and En vironmental Samples Using Molecularly Imprinted Polymer Nanoparticles and Fluorescence Polarization. Biosens. Bioe

lectron. 2012, 36, 22–28.

48. Carrasco, S.; Canalejas-Tejero, V.; Navarro-Villoslada, F.; Barrios, C.A.; Moreno-Bondi, M.C. Cross-Linkable Linear Co polymer with Double Functionality: Resist for Electron Beam Nanolithography and Molecular Imprinting. J. Mater. Che m. C 2014, 2, 1400–1403.
49. Piletsky, S.A.; Piletskaya, E.V.; Elskaya, A.V.; Levi, R.; Yano, K.; Karube, I. Optical detection system for triazine based o n molecularly-imprinted polymers. Anal. Lett. 1997, 30, 445–455.
50. Benito-Peña, E.; Moreno-Bondi, M.C.; Aparicio, S.; Orellana, G.; Cederfur, J.; Kempe, M. Molecular Engineering of Fluo rescent Penicillins for Molecularly Imprinted Polymer Assays. Anal. Chem. 2006, 78, 2019–2027.
51. Rouhani, S.; Nahavandifard, F. Molecular Imprinting-Based Fluorescent Optosensor Using a Polymerizable 1,8-Naphth alimide Dye as a Florescence Functional Monomer. Sensors Actuators B Chem. 2014, 197, 185–192.
52. Descalzo, A.B.; Somoza, C.; Moreno-Bondi, M.C.; Orellana, G. Luminescent Core-Shell Imprinted Nanoparticles Engin eered for Targeted Förster Resonance Energy Transfer-Based Sensing. Anal. Chem. 2013, 85, 5316–5320.
53. Zhang, W.; Liu, W.; Li, P.; Xiao, H.; Wang, H.; Tang, B. A Fluorescence Nanosensor for Glycoproteins with Activity Base d on the Molecularly Imprinted Spatial Structure of the Target and Boronate Affinity. Angew. Chemie-Int. Ed. 2014, 53, 1 2489–12493.
54. Jenkins, A.L.; Murray, G.M. Ultratrace Determination of Lanthanides by Luminescence Enhancement. Anal. Chem. 199 6, 68, 2974–2980.
55. Leung, M.K.-P.; Chow, C.-F.; Lam, M.H.-W. A sol–gel derived molecular imprinted luminescent PET sensing material for 2,4-dichlorophenoxyacetic acid. J. Mater. Chem. 2001, 11, 2985–2991.
56. Wan, W.; Biyikal, M.; Wagner, R.; Sellergren, B.; Rurack, K. Fluorescent Sensory Microparticles That “Light-up” Consist ing of a Silica Core and a Molecularly Imprinted Polymer (MIP) Shell. Angew. Chemie-Int. Ed. 2013, 52, 7023–7027.
57. Sunayama, H.; Ooya, T.; Takeuchi, T. Fluorescent Protein Recognition Polymer Thin Films Capable of Selective Signal Transduction of Target Binding Events Prepared by Molecular Imprinting with a Post-Imprinting Treatment. Biosens. Bio electron. 2010, 26, 458–462.
58. Zhou, J.; Yang, Y.; Zhang, C.-Y. Toward Biocompatible Semiconductor Quantum Dots: From Biosynthesis and Bioconju gation to Biomedical Application. Chem. Rev. 2015, 115, 11669–11717.
59. Niu, H.; Yang, Y.; Zhang, H. Efficient One-Pot Synthesis of Hydrophilic and Fluorescent Molecularly Imprinted Polymer Nanoparticles for Direct Drug Quantification in Real Biological Samples. Biosens. Bioelectron. 2015, 74, 440–446.
60. Wang, F.; Wang, D.; Wang, T.; Jin, Y.; Ling, B.; Li, Q.; Li, J. A Simple Approach to Prepare Fluorescent Molecularly Impri nted Nanoparticles. RSC Adv. 2021, 11, 7732–7737.
61. Horikawa, R.; Sunayama, H.; Kitayama, Y.; Takano, E.; Takeuchi, T. A Programmable Signaling Molecular Recognition Nanocavity Prepared by Molecular Imprinting and Post-Imprinting Modifications. Angew. Chemie-Int. Ed. 2016, 55, 130 23–13027.
62. Moczko, E.; Poma, A.; Guerreiro, A.; Perez De Vargas Sansalvador, I.; Caygill, S.; Canfarotta, F.; Whitcombe, M.J.; Pile tsky, S. Surface-Modified Multifunctional MIP Nanoparticles. Nanoscale 2013, 5, 3733–3741.
63. Sunayama, H.; Ooya, T.; Takeuchi, T. Fluorescent Protein-Imprinted Polymers Capable of Signal Transduction of Specif ic Binding Events Prepared by a Site-Directed Two-Step Post-Imprinting Modification. Chem. Commun. 2014, 50, 1347 –1349.
64. Li, Q.; Kamra, T.; Ye, L. A Modular Approach for Assembling Turn-on Fluorescence Sensors Using Molecularly Imprinte d Nanoparticles. Chem. Commun. 2016, 52, 12237–12240.
65. Wan, W.; Wagner, S.; Rurack, K. Fluorescent Monomers: “Bricks” that Make a Molecularly Imprinted Polymer “Bright”. Anal. Bioanal. Chem. 2016, 408, 1753–1771.
66. Zhao, T.; Wang, J.; He, J.; Deng, Q.; Wang, S. One-Step Post-Imprint Modification Achieve Dual-Function of Glycoprot ein Fluorescent Sensor by “Click Chemistry”. Biosens. Bioelectron. 2017, 91, 756–761.
67. Mori, K.; Hirase, M.; Morishige, T.; Takano, E.; Sunayama, H.; Kitayama, Y.; Inubushi, S.; Sasaki, R.; Yashiro, M.; Takeu chi, T. A Pretreatment-Free, Polymer-Based Platform Prepared by Molecular Imprinting and Post-Imprinting Modificatio ns for Sensing Intact Exosomes. Angew. Chem.-Int. Ed. 2019, 58, 1612–1615.
68. Jenkins, A.L.; Uy, O.M.; Murray, G.M. Polymer Based Lanthanide Luminescent Sensors for the Detection of Nerve Age nts. Anal. Commun. 1997, 34, 221–224.
69. Yosef, I.; Abu-Reziq, R.; Avnir, D. Entrapment of an Organometallic Complex within a Metal: A Concept for Heterogeneo us Catalysis. J. Am. Chem. Soc. 2008, 130, 11880–11882.

70. Meng, M.; Bai, M.; Da, Z.; Cui, Y.; Li, B.; Pan, J. Selective Recognition of Salicylic Acid Employing New Fluorescent Imprinted Membrane Functionalized with Poly(Amidoamine) (PAMAM)-Encapsulated Eu(TTA)3phen. J. Lumin. 2019, 208, 24–32.
71. Zdunek, J.; Benito-Peña, E.; Linares, A.; Falcimaigne-Cordin, A.; Orellana, G.; Haupt, K.; Moreno-Bondi, M.C. Surface-Imprinted Nanofilaments for Europium-Amplified Luminescent Detection of Fluoroquinolone Antibiotics. Chem.—A Eur. J. 2013, 19, 10209–10216.
72. Wang, J.; Gao, L.; Han, D.; Pan, J.; Qiu, H.; Li, H.; Wei, X.; Dai, J.; Yang, J.; Yao, H.; et al. Optical Detection of λ-Cyhalothrin by Core-Shell Fluorescent Molecularly Imprinted Polymers in Chinese Spirits. J. Agric. Food Chem. 2015, 63, 2392–2399.
73. Baker, S.N.; Baker, G.A. Luminescent Carbon Nanodots: Emergent Nanolights. Angew. Chemie-Int. Ed. 2010, 49, 6726–6744.
74. Huang, S.; Tan, L.; Zhang, L.; Wu, J.; Zhang, L.; Tang, Y.; Wang, H.; Liang, Y. Molecularly Imprinted Mesoporous Silica Embedded with Perovskite CsPbBr3 Quantum Dots for the Fluorescence Sensing of 2,2-Dichlorovinyl Dimethyl Phosphate. Sensors Actuators B Chem. 2020, 325, 128751.
75. Ma, Y.; Xu, S.; Wang, S.; Wang, L. Luminescent Molecularly-Imprinted Polymer Nanocomposites for Sensitive Detection. TrAC—Trends Anal. Chem. 2015, 67, 209–216.
