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Electrochemical Molecularly Imprinted Polymer Based Sensors for Pharmaceutical and Biomedical Applications (Review)

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Abstract

Recent challenges in the pharmaceutical and biomedical fields require the development of new analytical methods. Therefore, the development of new sensors is a very important task. In this paper, we are outlining the development of molecularly imprinted polymer (MIP) based sensors, which belongs to important branch of affinity sensors. In this review, recent advances in the design of MIP-based sensors are overviewed. MIPs-based sensing structures can replace expensive natural affinity compounds such as receptors or antibodies. Among many different polymers, conducting polymers show the most versatile properties, which are suitable for sensor application. Therefore, significant attention is paid towards MIPs based on conducting polymers, namely polypyrrole, polythiophene, poly(3,4-ethylenedioxythiophene), polyaniline and ortho-phenylenediamine. Moreover, many other materials, which could be imprinted analyte molecules, are overviewed. Among many conducting polymers, polypyrrole is highlighted as one of the most suitable for molecular imprinting. Some attention is dedicated to overview polymerization methods applied for the design of sensing structures used in various affinity sensors. The transduction of analytical signal is an important issue, therefore, physicochemical methods suitable for analytical signal transduction are also outlined. Advances, trends and perspectives in MIP application are discussed.

Keywords: Molecularly imprinted polymers (MIPs); Affinity sensors; Immunosensors; Conducting polymers (CPs); Electrochemical deposition; Electrochemical sensors.

Table of Contents

List of abbreviations.....	2
1. Introduction	3
2. Formation of conducting polymers for MIPs by chemical or electrochemical methods.....	4
2.1. Chemical formation of conducting polymers based on redox processes.....	4
2.2. Electrochemical methods applied for the formation of conducting polymer based structures	6
3. The applications of MIPs based sensors for pharmaceutical and biomedical applications	8
3.1. Polymers imprinted by proteins and large bio-compounds	8
3.2. Signal transducers applied in sensors based on molecularly imprinted polymers	11
4. Compatibility of conducting polymers with various biological compounds and immune system of mammals as of prediction of the wearable sensors	13
5. Conclusions	13
References	14

List of abbreviations

Conducting polymers	CPs
Density-Functional-Theory	DFT
Electrochemical QCM	EQCM
Glucose oxidase	GOx
Gold nanoparticles	AuNPs
Human hemoglobin	HbA
Molecularly imprinted polymer	MIP
Poly(3,4-ethylenedioxythiophene)	PEDOT
Poly(styrenesulfonate)	PSS
Polyaniline	PANI
Polypyrrole	Ppy
Polythiophene	PTH
Quartz crystal microbalance	QCM
Quartz crystal microbalance with dissipation	QCM-D
Surface plasmon resonance	SPR

1. Introduction

Among various types of systems, the pharmaceutical formulations and biomedical matrixes are the most complex. Consequently, the design of sensitive and selective analytical system is still rather challenging task. Various affinity sensors are a good choice in the purpose of simplifying the analysis and reducing expenses [1]. The combination of the different sensor types with different analytical signal registration methods leads to the sufficient sensitivity [2, 3]. The most common sample types in biomedical applications are: saliva, urine, blood serum, and some other biological liquids. Such samples contain biomarkers, which are marking some diseases. These biomarkers can be detected by sensors and biosensors, but the most of these biomarkers are determined or detected by affinity sensors [4, 5].

Various semiconductors-based structures are developed to increase the selectivity and sensitivity of chemical sensors and biosensors [6, 7], but conducting polymers (CPs) are used for this purpose the most frequently. The research articles describe many different approaches to deposit the conducting polymers on the electrode surface. Recently the conducting polymers are used for the development of sensing-structures useful for electrochemical applications, which increases the selectivity of the analytical system toward selected analytes [2]. Some polymers have several features that make them especially interesting for the design of sensors. These features are electrical conductivity [8], high electrical capacitance [9–11], good adherence on the surface of the electrodes, and the ability to form physically and chemically stable coatings [12, 13]. Ability to transfer electrical charges is characteristic for some CPs, therefore, they are used for charge transfer from some redox enzymes and some other biomolecules [14]. Due to aforementioned properties, CPs are used in the development of sensing structures in combination with various signal transducers. Polyaniline (PANI), polypyrrole (Ppy), poly(3,4-ethylenedioxythiophene) (PEDOT) and polythiophene (PTH) are CPs, which are the mostly applied in sensor and biosensor design [15–19]. These polymerization methods, which are the most commonly used for the formation of CPs, can be divided into four main types: chemical synthesis [20], enzymatic formation [21], electrochemical deposition [9] and/or microorganism assisted polymerization [22–25]. It is notable that only electrochemical deposition is the most preferred method when thin polymer film deposited on an electrode is needed. Meanwhile some other methods (chemical polymerization induced with hydrogen peroxide, FeCl₃, etc., enzymatic polymerization or microorganism assisted polymerization) have advantages for the production of polymer based particles. Moreover, CPs can be used as immobilization matrixes for biomolecules that can selectively bind selected analytical-targets including DNA [26], receptors [27], antibodies [2], antigens [28], antibodies [21] and enzymes [29–31]. However, some of these

immobilized biomolecules are very expensive and are unstable, therefore, some alternatives are required. One of the most promising alternatives to native biomolecules is the design and exploitation of various ‘artificial receptors’ and/or molecularly imprinted polymers (MIPs) [32, 33]. It should be noted that conducting polymers can be used for the design of these structures [32–35]. In some investigations, it was shown that MIPs can be used for the design of biosensors for the detection of infection agents [36].

In this paper methods used for the development of CP-based sensors and the formation of molecularly imprinted sites within these polymers are overviewed. It is very usual to classify MIPs according to the detection principle in the review articles of MIPs applications. Principally, MIPs are formed in such steps: (i) chemical or electrochemical polymerization, (ii) deposition on the electrode of the MIP structure, (iii) extraction of the template molecule. In the case of electrochemical polymerization of conducting polymer with imprints of template molecule, the deposition of polymer on the electrode is obtained simultaneously. After the last step of template molecule extraction, the MIP has the shape and structure, which is ready for interaction with target molecules. Such MIPs can be used in the design of optical, electrochemical, electrochromic, magnetic and other sensors. On the basis of the here-mentioned attitude, this review confines the description and considerations about MIPs in the polymerization conditions, template molecule, and signal transduction in sensors. The first part of the review is dedicated to the description of polymerization conditions with an overview of chemical and electrochemical methods. Next part of the review is dedicated for the description of application of MIPs template with high and low molecular weight molecules. In the same part of the review, we found reasonable to summarize the findings about signal transducers applied in sensors based on molecularly imprinted polymers. The last part of the review is dedicated for the aspects of compatibility. We find particularly interesting the compatibility aspects regarding potentially growing interest of scientific community to the potential application of MIPs in the field of wearable sensors.

2. Formation of conducting polymers for MIPs by chemical or electrochemical methods

2.1. Chemical formation of conducting polymers based on redox processes

Chemical synthesis is one the most suitable polymerization method for the formation of CP-based nano- or/and micro-particles. Such nano-or/and micro-particles of conducting polymer with molecular imprints further are used in the design of chemical sensors, chromatographic systems and some other technological purposes [37, 38]. The application field of electro-active polymers is not limited with sensor design [39, 40] but also are applied for various biomedical purposes including tissue regeneration [41].

In order to fulfill recent technological demands, various conducting polymer synthesis methods have been elaborated. Chemical methods can be used for the formation of large amounts of CPs. Chemical polymerization is initiated using oxidants such as FeCl_3 , H_2O_2 etc. [42–44]. The application of H_2O_2 enables the synthesis of rather clean conducting polymers, while all excess of H_2O_2 turns into water and oxygen. Many types of monomers were polymerized in presence of H_2O_2 including polypyrrole [20, 44, 45], (Fig. 1), polythiophene [44, 46], poly-phenanthrenequinone [47], poly(pyrrole-2-carboxylic acid) [48], polyphenanthroline [14], azobenzene [49] and carbazole [50].

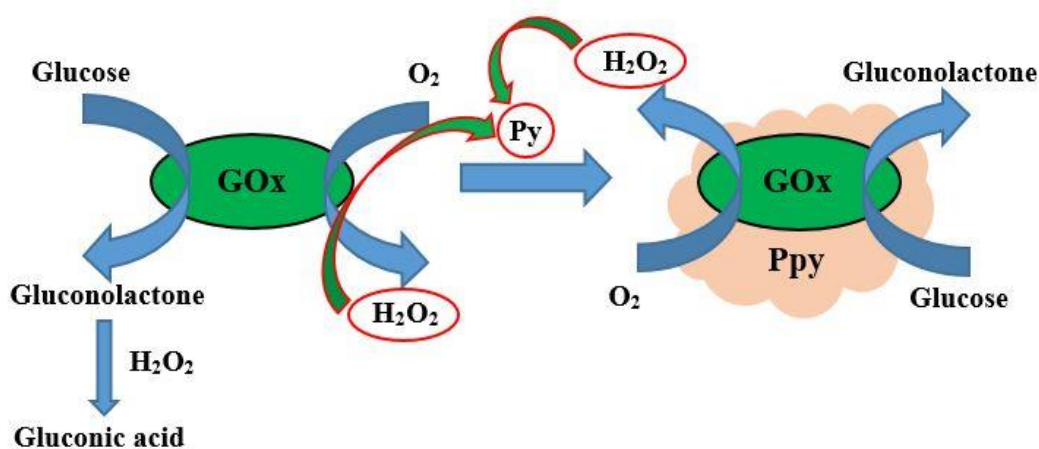


Figure 1. Glucose oxidase (GOx) assisted formation of polypyrrole H_2O_2 formed during enzymatic reaction initiated this polymerization reaction. Adapted from reference [51].

Chemical polymerization enables to form large amounts of CPs. During chemical polymerization, different nanostructures, biomolecules, organic and inorganic molecules and even various ions can be entrapped formed polymeric structure [31, 48, 55–57].

Some redox enzymes (e.g. glucose oxidase (GOx)) can be used for the synthesis of conducting polymers [21, 31, 48, 55–57]. Such enzyme assisted formation of CPs can be performed in an aqueous media at ambient conditions [58]. Dissolved [55, 57] and immobilized [29, 31, 48, 56] enzymes can be applied for the synthesis of CPs and after encapsulation of enzyme within formed CP-based structure enzyme often retain some enzymatic activity. Such method can be applied for the adjustment of enzymatic characteristics (e.g. Michaelis constant (K_M)) that is dependent on diffusion of reacting materials towards active site of enzyme embedded within CP. CP/enzyme-based structures are used in biosensor and biofuel cell design [2, 5, 59, 60].

Some conducting polymers (e.g. polypyrrole) can be formed by oxidizing chemicals (e.g. Fe^{3+} or $[\text{Fe}(\text{CN})_6]^{3-}$ ions) [61], which can be generated by metabolic processes that are occurring in living cells, therefore, some cell-induced redox processes can be used for the synthesis of CPs [22–25]. Structures based on PANI, Ppy with entrapped GOx and gold nanoparticles (AuNPs) PANI/AuNPs&GOx can be formed [62], which is suitable for the mass production of MIPs [63, 64]. Transducer surface can be covered by such conducting polymer based MIPs by solvent casting or some other reliable method [65]. It should be noted, that CPs can be not dissolved in conventional solvents, therefore, the deposition of CP-based structures on analytical signal transducer is rather challenging. Electrochemical deposition of conducting polymers can be applied in order to overcome this obstacle.

2.2. Electrochemical methods applied for the formation of conducting polymer based structures

Many different approaches are applied for the electrodeposition of CP-based layers [66]. Parameters used for the electrodeposition are significantly affecting the most important characteristics of deposited conducting polymer based structures. The electrodeposition is mostly controlled by: (i) the application of particular potential or current control techniques (e.g. potentiodynamic methods such as potential pulses, linear or cyclic potential sweeping can be applied), (ii) potential variation rate and critical voltages, [67, 68], (iii) the composition of polymerization- solution [69–71], and (iv) additional treatment by other conditions (e.g. application of ultrasound) [72]. Here mentioned factors are affecting the density, thickness, permeability and some other characteristics of electrodeposited CP-layers [28, 73, 74]. The analytical characteristics of CP-based layer is affected by the porosity of formed conducting polymer that can be tailored by the variation of above mentioned electrochemical setups [75–77]. It is remarkable that, the electrodeposition of CPs can be well tailored by the assessment of electrical current applied to electrode [28]. Polypyrrole [1, 9, 12, 15, 16, 28, 32, 45, 78], polyaniline [62], poly-9,10-phenanthrenequinone [47] and polythiophene derivatives [42, 79], are these conducting polymers, which are mostly used for the electrodeposition.

Different materials can be incorporated within electrodeposited layer of CP (Fig. 2) [51]. In order to design MIPs these materials can be removed from polymeric matrix by various solvents. Various polymerization methods are applied for the design of MIPs, but among them electrodeposition is the most beneficial [80, 81], because it enables to vary the thickness, morphology and doping/de-doping of formed CP-based structures. In addition, the overoxidation at electrode potentials, which are more positive than that required for electrochemical polymerization of corresponding monomers [51], is useful for the development of MIPs, due to formation of oxygen containing groups such as carboxyl,

carbonyl and hydroxyl, which all are able to form hydrogen bonds and to attend in various electrostatic interactions with imprinted molecules. After the removal of these molecules, formed carboxyl, carbonyl and hydroxyl groups are creating a complementary site, which selectively ‘recognizes’ imprinted molecule. Sometimes, overoxidation can be applied to facilitate the extraction of imprinted materials and/or regeneration of sensing structures after the measurement [82]. Overoxidized polypyrrole deposited on glassy carbon electrode was used for the design of sensors sensitive to Adefovir [83] and Pemetrexed [84].

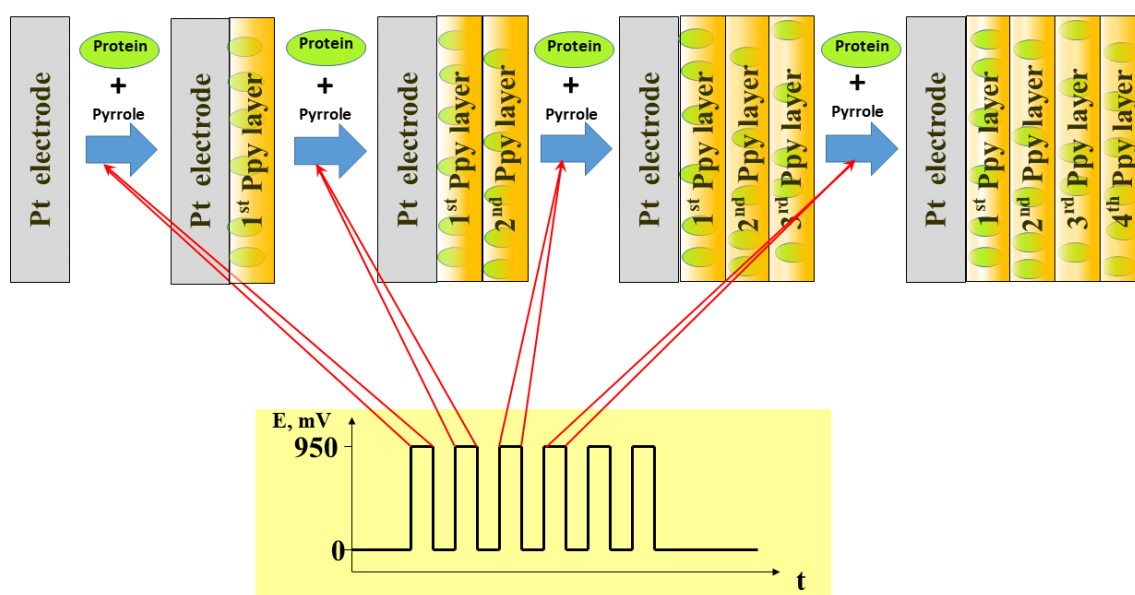


Figure 2. Electrochemical deposition of polypyrrole with simultaneously entrapped proteins using potential pulse-based technique, figure adapted from [51].

In previous studies, the polypyrrole was electrochemically deposited from pyrrole-based aqueous solutions for different electrochemical approaches [85]. The numerous researches on electrochemically formed polypyrrole based MIPs confirms significant advantages of the Ppy-based MIPs in sensor design. Moreover, the electrochemical polymerization is strictly controllable, and the predictability of the final structure provides opportunity for the modification with dopants or ‘decoration’ with various types of nanoparticles and/or other nanostructures. This process can be performed by computerized potentiostats [28]. Polypyrrole-based MIPs were applied in the design of sensors for the determination of dopamine [86, 87], theophylline [32, 88], caffeine [15, 16, 89], histamine [90], quercetin [91], gallic acid [92], bilirubin [93], sarcosine [94], tetracycline [85], microcystin-LR [95], sulfanilamide [96], adrenaline [97], ganciclovir [98], uric acid [99], serotonin [100], L-aspartic acid [101], cysteine enantiomers [102], kanamycin [103], dibutyl phthalate [104],

epinephrine [105, 106], tryptamine [107], testosterone [108], fenvalerate [109] and NO^3 - ions [110].

Phenylenediamine-derivatives [111–113] are frequently applied in the formation of MIPs that are used for the determination of anticancer-drugs, e.g. ortho-phenylenediamine was molecularly imprinted by pemetrexed [114] and butyrylcholinesterase [115]. Electrodeposited MIP based on poly-meta-phenylenediamine molecularly imprinted by erythromycin was applied for the determination of erythromycin in water-based samples [111]. Poly-nicotinamide based electrochemical sensors for the determination of dopamine were developed [116]. Moreover, polyresorcinol molecularly imprinted by sulphanilamide [117], triphenylamine molecularly imprinted by poly(1-naphthylamine) [118] and azorubine imprinted 1-naphthylamine [119] have been developed. It was reported that, MIPs can be used for the determination of various medications [120].

Structures, which are based on CPs, which can be further modified in many different ways [29], e.g. by organics [121], some inorganic compounds [31, 48, 55–57], ions [125] and various biomolecules [44, 55, 57, 122, 123]. Such modified structures can be used in the design of sensors and biosensors [124].

3. The applications of MIPs based sensors for pharmaceutical and biomedical applications

3.1. Polymers imprinted by proteins and large biological compounds

The health system has improved significantly due to innovative solutions and inventions in the field of pharmaceuticals and their monitoring by biomedical devices. However, the benefits of pharmaceuticals are effective if they are free of impurities and used in the right way. The biocompatibility is one of the most important aspect of pharmaceuticals before their application. Various chemical and instrumental methods, which are used for the evaluation of pharmaceuticals before assess their intended application, are regularly developed. Impurities in pharmaceuticals can appear during development, transportation, and storage stages. Therefore, pharmaceuticals and their components need to be detected and quantified during all these stages. Some of these goals can be achieved using MIP-based sensors. High number of immunosensors have been developed by immobilizing proteins within polymeric layers. The performance of immunosensors depends on the orientation of immobilized proteins, which recognizes the analyte, which in most cases is also a protein that is binding with immobilized one by forming corresponding immune-complex, and in such way it induces analytical signal [126]. Therefore, proper orientation of immobilized protein molecules is among key issues during the design of affinity-based immunosensors [27, 127,

128], because it is critical to achieve efficient target-protein binding [127]. Hence, analytical performance of immunosensors and some other affinity sensors depends on the orientation of immobilized antibodies [129], fragments of antibodies, which are generated by the reduction of disulfide bounds holding together polypeptides that are forming antibodies [127] or receptors [27]. Proper entrapment of the proteins in the assembled polymer layer matrix can be achieved by the electrochemical methods, which can be used to form the conducting polymer based layers [28]. Molecular imprinting technology enables to design MIPs that have properly oriented binding sites [99, 130, 131]. Therefore, the application of polymers imprinted by proteins is very promising [132, 133] (Fig. 3), because it enables to replace very expensive antibodies [28] and receptors [27], which are used in affinity sensors, therefore, protein imprinted MIPs are frequently applied for the bioanalytical purposes [134–137]. During the entrapment and extraction procedures, proteins can undergo some conformational changes [138], and/or proper orientation of formed cavity within polymer can be achieved [139]. Therefore, MIPs often are called as ‘synthetic receptors’ or ‘artificial receptors’ [135] and ‘plastic antibodies’ [140, 141]. Various conducting polymers prepared by electrochemical deposition can form a polymeric backbone suitable for MIP formation, e.g. polypyrrole imprinted bovine leukemia virus glycoprotein was designed [135]; Electrochemically formed poly-o-phenylenediamine/hydroquinone imprinted by human serum albumin (HSA) was applied for the determination of HSA in urine [142]; the surface of polydopamine layer was imprinted by immunoglobulin G [143]; molecularly imprinted hetero-structure based on PEDOT/PSS was also used for the detection of proteins [139]; synthetic receptor based on electrochemically formed polydopamine was applied for the determination of a prostate specific antigen in human blood plasma [144]; electrodeposited composite based on polypyrrole/(carbon nanotube) was imprinted by S-ovalbumin and was used for the detection of this protein in egg’s white [145]; electrochemically formed poly(o-phenylenediamine) was imprinted by myoglobin [146]; electrodeposited MIPs based on polyscopoletin were exploited for the detection of HSA [147]; poly-scopoletin imprinted by cytochrome c (Cyt-c) was applied for the determination of Cyt-c [148]; copolymer based on hydroxyethyl acrylate and ethylene glycol dimethacrylate imprinted by lysozyme was developed [149]; poly(2-hydroxyethyl methacrylate-N-methacryloyl-(L)-histidin-Cu(II)) imprinted by ceruloplasmin was synthesized by radical polymerization [150]; the SARS-CoV-2 protein imprinted poly-m-phenylenediamine based electrochemical sensor was used for the determination of infection by SARS-CoV-2 [113]; MIP-based sensor for detection of follicle-stimulating hormone was designed [151]; electrodeposited ortho-polydopamine imprinted by alpha-fetoprotein, which was temporarily covalently immobilized on gold nanoparticle covered substrate, was applied in sensor design [152]; acrylamide/N,N₀-methylenebisacrylamide copolymers imprinted by both prostate-specific antigen and

myoglobin were applied for the determination of both these proteins [153]; sensor based on polyacrylamide imprinted by hemoglobin was developed [154]; and o-phenylenediamine was used for the determination of imprinted troponin T [155].

Conducting polymer – polyaniline (PANI) is also rather often used in sensor design [Erreur ! Signet non défini.]. However, in the research based on molecularly imprinted polymers only a few reports related to PANI-based MIPs can be found: PANI-based MIP was applied for the determination of antibiotic azithromycin [156] and for some hydroxy acids and saccharides [157]. It should be noted that even inorganic compounds such as titanium dioxide (TiO₂) can be molecularly imprinted by proteins, e.g.: TiO₂ was imprinted by urease [158]. In some researches it was shown that peptides, which are serving as epitopes of some proteins, can be imprinted and such MIPs can be used for the determination of the ‘parent proteins’ and this technology was applied for the design of electrochemical sensor based on MIP imprinted by N-terminal pentapeptide VHLTP-amide, which is an epitope of human hemoglobin (HbA) [159].

MIP-formation needs knowledge in organic and polymer chemistry [160, 161]. It was demonstrated that DNA [29] can be entrapped [26] and molecularly imprinted [162–164] within CP-based layers. Therefore, some investigations are dedicated to replace direct application of DNA-based sequences in analytical systems [165]. It should be noted that even relatively large objects such as whole bacteria [166, 167] (e.g.: *Escherichia coli* [168]) or spores (e.g.: *Bacillus cereus*) [169] were imprinted within electrodeposited polypyrrole. Some polymers were imprinted by viruses [170] and bacteria [168, 171–174] and other living cells [175]. Such MIPs can be used for the determination of bacteria in various environments [36, 176].

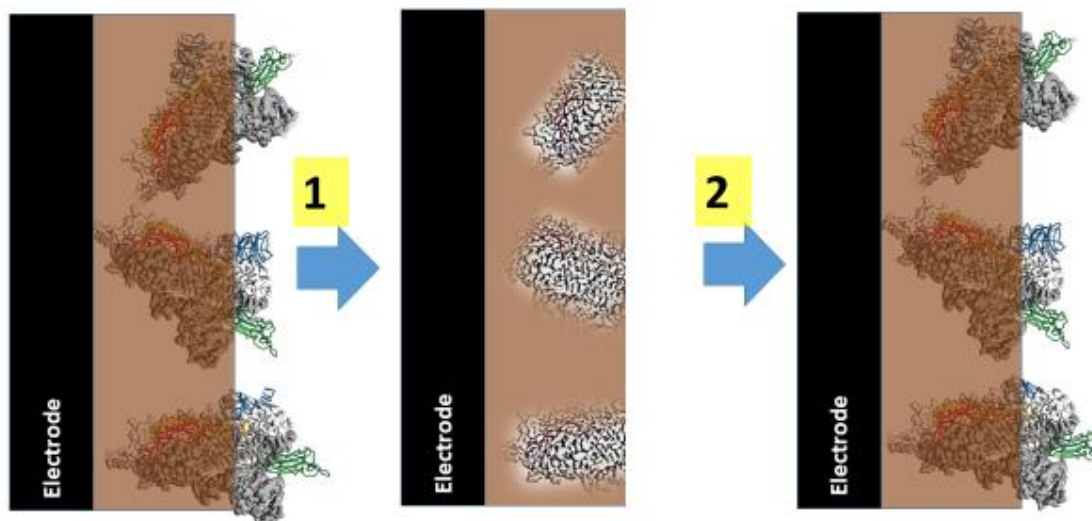


Figure 3. 1) The formation of molecularly imprinted polymer based sensor, 2) Molecularly imprinted polymer based layer in action. Figure adapted from [2].

3.2. Signal transducers applied in sensors based on molecularly imprinted polymers

Some polymeric structures can selectively recognize and bind target molecules quite selectively and have much better resistance towards harmful environmental factors in comparison to that of native biomolecules, which are commonly used in the design of biosensors. Therefore, some molecularly imprinted polymers seem very promising [177, 178] even if the application of molecularly imprinted polymers is still rather challenging [179]. The most stable at room conditions are MIPs based on acrylic acid, methacrylic acid and acrylamide [180–184].

The selection of the most suitable polymer for the design of MIP is an important technological issue [185]. Formed MIP should be able to establish hydrogen bonds, electrostatic and/or π - π interactions [186]. Moreover, all these interactions should be capable to dissociate easily [3, 183, 187], because it is important for both MIP-formation and the regeneration of sensor after the measurement. Solution theories, which were derived by Flory and Huggins [188, 189], Hansen [190, 191] and Hildebrand [192, 193], well explain the formation and action mechanism of MIPs. Shape of cavities formed within MIPs' are changing during the swelling in applied solvents [194], and it significantly affects the 'shape memory' behavior of these MIPs [195]. In order to predict the most efficient structure and composition of MIPs molecular dynamics [196] and Density-Functional-Theory (DFT) [197, 198] calculations have been applied.

The determination of analyte binding with MIPs can be performed by direct and indirect electrochemical approaches. For direct assessment of analyte binding to MIP

potentiodynamic electrochemical methods [199], which are based on the determination of restricted diffusion of some ions [200], are applied. On the other hand formation of complex between analyte and MIP can be rearrange the electronic structure of polymeric backbone and this effect induces changes of electrical conductivity of MIP-layer [199]. Due to the above-mentioned effects, MIPs can be applied for the design of organic electrochemical transistors [201]. Doping compounds can induce p- or n-type conductivity to polyaniline [202], polypyrrole [28], and poly(3,4-ethylenedioxythiophene)/poly(styrenesulfonate) (PEDOT/PSS) [203]. However, doping and/or ‘de-doping’ of CP by various ions and materials in most cases is a reversible [202], therefore, it can be also exploited for the generation of analytical signal. However, mostly direct electrochemical detection has a major drawback because in this case, various nonspecific interactions are negatively affecting registered signal. For this reason, redox-probes are used, because they can and significantly increase the sensitivity of MIP-based electro-analytical systems [204, 205]. Moreover, the enhancement of analytical signals can be achieved using enzymes, namely tyrosinase [206], glucose oxidase [207], acetylcholinesterase [208], creatine kinase [209], cytochrome P450 [210], hexameric heme protein [211], laccase [212], microperoxidase [213], horseradish peroxidase [213–215] and lactoperoxidase [213]). Some other catalytic features like catalysis by Pt/Cu-based nanoparticles [216] or the inhibition of enzymatic activity [217] can be also adapted for the amplification of registered sensor response.

Signal transducing systems with quartz crystal microbalance (QCM) can also be applied in MIP-based sensor design, which are capable to detect: (i) low molecular weight chemicals [218, 219], namely: naproxen [220], histamine [221], *S*-propranolol [222], ibuprofen [223]; (ii) proteins [167, 224–226], trypsin [227], ribonuclease A [228] and oxidized-low-density lipoprotein [229]; and (iii) DNA [226, 230]. QCM-based determination of mass variations of MIP-based structures can be combined with some electroanalytical techniques (EQCM) [16, 99, 231]. Recently the most advanced QCM method – QCM with dissipation (QCM-D) has been also applied in MIP-based sensors [232].

Some optical techniques such as photoluminescence [233, 234] and surface plasmon resonance (SPR) [235] have been also used in MIP-based analytical systems. Remarkable optical characteristics of CPs can be well applied in the design of sensors based on optical transducers [236, 237] and photoluminescence sensors [234, 238, 239]. Studies affirmed that conducting polymer – polypyrrole – has great photoluminescence quenching ability [234, 238], which can be well exploited in the design of sensing devices and improve sensitivity and selectivity of biosensors [128, 240].

Optical analytical registration methods are used widely: MIPs were applied for the determination of organics such as estradiol and derivatives of this compound [241–243] were exploited. MIPs-modified by quantum dot nanoparticles modified by poly(ethylene-co-vinyl

alcohol) heterocomposite was used for optical detection of some salivary proteins [244]. MIP-based on Cu^{2+} -metalorganic-framework, which was imprinted by tetrabromobisphenol A, exhibited enzyme-like catalytic activity towards the oxidation of tetrabromobisphenol A by hydrogen peroxide [245]. Microarrays based on poly-scopoletin imprinted by ferritin – have been electro-spotted on a gold-modified substrate and applied in surface plasmon resonance (SPR) based ferritin detection [246]. To improve optical capabilities MIPs can be combined with photonic crystals [247] and liquid crystals [248]. Very useful optoelectrochemical property of some conducting polymers is an electrochromic effect, which can be exploited in the development of sensing devices [202]. Electrochromism is a reversible change of optical absorbance during oxidation/reduction of electrochromic material (e.g. WO_3 [249], PEDOT/PSS, Ppy, PANI, etc.) layer by the variation of electrical potential. Such electrochromic sensors based on conducting polymers can be applied for the determination of some ions (e.g. Cu^{2+} [202] or NH_4^+ and CO_3^{2-} ions) [79, 250, 251].

4. Compatibility of conducting polymers with various biological compounds and immune system of mammals as of forecasting application in the wearable sensors based on MIPs

Implantable sensors and other biomedical tools are demanded for rapidly evolving field of biomedicine. Therefore, good compatibility of sensing elements is important for the development of implantable bioanalytical devices. However, since now, in almost all researches in this area, the biocompatibility of these structures is investigated rarely. In some researches, the biocompatibility of conducting polymers, which are forming sensing structures, only towards rather basic biological molecules (enzymes, DNA, etc.) is evaluated [29, 31, 48, 55–57]. It should be noted that such evaluation does not provide an estimation of the complex biocompatibility of these polymers, which is required for safe biomedical application [252]. Therefore, cell line and/or laboratory animal-based experiments are necessary for the evaluation of advanced biocompatibility. In several researches, it was shown that conducting polymers have a good biocompatibility with entrapped proteins [28, 29, 31, 48, 55–57]. Research have demonstrated the biocompatibility of polypyrrole with stem cells derived from bone marrow [52], primary mouse embryonic fibroblast (MEF) and human T lymphocyte Jurkat cells [53], and differentiated neuronal cell [253]. It was also acknowledged that polypyrrole is not affecting the immune system of mammals and their hematological parameters [54]. Among many composite structures hydrogels, which are based on conducting polymers, show a good biocompatibility due to the significant amount of water confined within the structure of these polymers [254]. It was demonstrated that, the biocompatibility of conducting polymer based structures can be advanced by incorporation of chitosan [255] and/or some other biocompatible polymers [256–258]. Moreover, some of

these additionally used polymers (e.g. chitosan) are suitable for the design of MIPs [259]. Outstanding biocompatibility of Ppy [52–54] and hydrogel-based polymers pave a way to exploit composite structures based on these materials in the development of attachable [260], wearable [261], and other [262, 263] sensors and biosensors. Hence, conducting polymer based composites are suitable for the design of scaffolds [264–266], incorporation of living cells and some other biomedical applications [267–270].

5. Conclusions

Conducting polymers are frequently used in the design of chemical sensors and biosensors, as well as for many other technological approaches. Sensors based on MIPs are providing fast analytical responses, are operating at ambient conditions, and are characterized by good sensitivity and selectivity. Conducting polymers are appropriate for the formation of MIPs and these polymers can be designed by different polymerization methods. Electrochemical formation of CP-based structures can be controlled in many ways and enables to design of very different CP-based structures even from the same composition of polymerization-bulk solution, therefore, they are suitable for the development of a great variety of MIPs. Some conducting polymers can be overoxidized after the formation; this treatment is especially eligible for the development of MIP-based sensors because it can be applied for (i) the formation of oxidized radicals, which are increasing sensitivity/selectivity towards imprinted target molecules within MIP-based structure and (ii) the facilitation of template removal and/or regeneration of MIP-based layers.

Polypyrrole is the most used conducting polymer and it is often applied in the formation of MIPs. Moreover, the advantages of the overoxidation of this polymer are the most frequently reported. Yet this application of overoxidized polypyrrole still has a lot of room for improvement and extension in the application of polypyrrole based MIPs, because polypyrrole can be easily synthesized by chemical and electrochemical methods from various solutions based on the most frequently used solvents and overoxidation of polypyrrole can be easily performed during the synthesis and/or after formation of Ppy-based layer. Moreover, polypyrrole shows great compatibility with various biological compounds and do not irritate the immune system of mammals, therefore, is suitable for the development of implantable biomedical tools, such as sensors, biosensors and biofuel cells.

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References

- [1] Ramanaviciene, A.; Ramanavicius, A. Application of Polypyrrole for the Creation of Immunosensors. *Critical Reviews in Analytical Chemistry*, **2002**, *32* (3), 245–252. <https://doi.org/10.1080/10408340290765542>.
- [2] Ramanavicius, S.; Ramanavicius, A. Conducting Polymers in the Design of Biosensors and Biofuel Cells. *Polymers*, **2021**, *13* (1). <https://doi.org/10.3390/polym13010049>.
- [3] Chen, L.; Xu, S.; Li, J. Recent Advances in Molecular Imprinting Technology: Current Status, Challenges and Highlighted Applications. *Chemical Society Reviews*, **2011**, *40* (5), 2922–2942. <https://doi.org/10.1039/C0CS00084A>.
- [4] Lakard, B. Electrochemical Biosensors Based on Conducting Polymers: A Review. *Applied Sciences*, **2020**, *10* (18). <https://doi.org/10.3390/app10186614>.
- [5] Ramanavicius, S.; Ramanavicius, A. Progress and Insights in the Application of MXenes as New 2D Nano-Materials Suitable for Biosensors and Biofuel Cell Design. *International Journal of Molecular Sciences*, **2020**, *21* (23). <https://doi.org/10.3390/ijms21239224>.
- [6] Ramanavicius, S.; Ramanavicius, A. Insights in the Application of Stoichiometric and Non-Stoichiometric Titanium Oxides for the Design of Sensors for the Determination of Gases and VOCs (TiO_{2-x} and $\text{Ti}_n\text{O}_{2n-1}$ vs. TiO_2). *Sensors*, **2020**, *20* (23). <https://doi.org/10.3390/s20236833>.
- [7] Naseri, M.; Fotouhi, L.; Ehsani, A. Recent Progress in the Development of Conducting Polymer-Based Nanocomposites for Electrochemical Biosensors Applications: A Mini-Review. *The Chemical Record*, **2018**, *18* (6), 599–618. <https://doi.org/https://doi.org/10.1002/tcr.201700101>.
- [8] Pontes, K.; Indrusiak, T.; Soares, B. G. Poly(Vinylidene Fluoride-Co-Hexafluoropropylene)/Polyaniline Conductive Blends: Effect of the Mixing Procedure on the Electrical Properties and Electromagnetic Interference Shielding Effectiveness. *Journal of Applied Polymer Science*, **2021**, *138* (3), 49705. <https://doi.org/https://doi.org/10.1002/app.49705>.
- [9] Samukaite-Bubniene, U.; Valiūnienė, A.; Bucinskas, V.; Genys, P.; Ratautaite, V.; Ramanaviciene, A.; Aksun, E.; Tereshchenko, A.; Zeybek, B.; Ramanavicius, A. Towards Supercapacitors: Cyclic Voltammetry and Fast Fourier Transform Electrochemical Impedance Spectroscopy Based Evaluation of Polypyrrole Electrochemically Deposited on the Pencil Graphite Electrode. *Colloids and Surfaces*

- A: *Physicochemical and Engineering Aspects*, **2021**, 610, 125750. <https://doi.org/10.1016/J.COLSURFA.2020.125750>.
- [10] Zhao, Z.; Yu, T.; Miao, Y.; Zhao, X. Chloride Ion-Doped Polyaniline/Carbon Nanotube Nanocomposite Materials as New Cathodes for Chloride Ion Battery. *Electrochimica Acta*, **2018**, 270, 30–36. <https://doi.org/10.1016/J.ELECTACTA.2018.03.077>.
- [11] Wang, Y.; Chen, Y.; Liu, Y.; Liu, W.; Zhao, P.; Li, Y.; Dong, Y.; Wang, H.; Yang, J. Urchin-like Ni_{1/3}Co_{2/3}(CO₃)_{0.5}OH·0.11H₂O Anchoring on Polypyrrole Nanotubes for Supercapacitor Electrodes. *Electrochimica Acta*, **2019**, 295, 989–996. <https://doi.org/10.1016/J.ELECTACTA.2018.11.116>.
- [12] Ratautaite, V.; Ramanaviciene, A.; Oztekin, Y.; Voronovic, J.; Balevicius, Z.; Mikoliunaite, L.; Ramanavicius, A. Electrochemical Stability and Repulsion of Polypyrrole Film. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, **2013**, 418, 16–21. <https://doi.org/10.1016/J.COLSURFA.2012.10.052>.
- [13] Iroh, J. O.; Su, W. Corrosion Performance of Polypyrrole Coating Applied to Low Carbon Steel by an Electrochemical Process. *Electrochimica Acta*, **2000**, 46 (1), 15–24. [https://doi.org/10.1016/S0013-4686\(00\)00519-3](https://doi.org/10.1016/S0013-4686(00)00519-3).
- [14] Oztekin, Y.; Ramanaviciene, A.; Yazicigil, Z.; Solak, A. O.; Ramanavicius, A. Direct Electron Transfer from Glucose Oxidase Immobilized on Polyphenanthroline-Modified Glassy Carbon Electrode. *Biosensors and Bioelectronics*, **2011**, 26 (5), 2541–2546. <https://doi.org/10.1016/J.BIOS.2010.11.001>.
- [15] Emir, G.; Dilgin, Y.; Ramanaviciene, A.; Ramanavicius, A. Amperometric Nonenzymatic Glucose Biosensor Based on Graphite Rod Electrode Modified by Ni-Nanoparticle/Polypyrrole Composite. *Microchemical Journal*, **2021**, 161, 105751. <https://doi.org/10.1016/J.MICROC.2020.105751>.
- [16] Ratautaite, V.; Plausinaitis, D.; Baleviciute, I.; Mikoliunaite, L.; Ramanaviciene, A.; Ramanavicius, A. Characterization of Caffeine-Imprinted Polypyrrole by a Quartz Crystal Microbalance and Electrochemical Impedance Spectroscopy. *Sensors and Actuators B: Chemical*, **2015**, 212, 63–71.
- [17] Holguín, M.; Rojas Álvarez, O. E.; Arizabaleta, C. A.; Torres, W. Molecular Dynamics of the Interaction of L-Tryptophan with Polypyrrole Oligomers. *Computational and Theoretical Chemistry*, **2019**, 1147, 29–34. <https://doi.org/10.1016/J.COMPTC.2018.11.012>.
- [18] Kumar, V.; Mirzaei, A.; Bonyani, M.; Kim, K. H.; Kim, H. W.; Kim, S. S. Advances in Electrospun Nanofiber Fabrication for Polyaniline (PANI)-Based Chemoresistive Sensors for Gaseous Ammonia. *TrAC Trends in Analytical Chemistry*, **2020**, 129, 115938. <https://doi.org/10.1016/J.TRAC.2020.115938>.
- [19] Tekbaşoğlu, T. Y.; Soganci, T.; Ak, M.; Koca, A.; Şener, M. K. Enhancing Biosensor Properties of Conducting Polymers via Copolymerization: Synthesis of EDOT-Substituted Bis(2-Pyridylimino)Isoindolato-Palladium Complex and Electrochemical

- Sensing of Glucose by Its Copolymerized Film. *Biosensors and Bioelectronics*, **2017**, 87, 81–88. <https://doi.org/10.1016/J.BIOS.2016.08.020>.
- [20] Leonavicius, K.; Ramanaviciene, A.; Ramanavicius, A. Polymerization Model for Hydrogen Peroxide Initiated Synthesis of Polypyrrole Nanoparticles. *Langmuir*, **2011**, 27 (17), 10970–10976. <https://doi.org/10.1021/la201962a>.
- [21] Felix, F. S.; Angnes, L. Electrochemical Immunosensors – A Powerful Tool for Analytical Applications. *Biosensors and Bioelectronics*, **2018**, 102, 470–478. <https://doi.org/10.1016/J.BIOS.2017.11.029>.
- [22] Ramanavicius, A.; Andriukonis, E.; Stirke, A.; Mikoliunaite, L.; Balevicius, Z.; Ramanaviciene, A. Synthesis of Polypyrrole within the Cell Wall of Yeast by Redox-Cycling of $[\text{Fe}(\text{CN})_6]^{3-}/[\text{Fe}(\text{CN})_6]^{4-}$. *Enzyme and Microbial Technology*, **2016**, 83, 40–47. <https://doi.org/10.1016/J.ENZMICTEC.2015.11.009>.
- [23] Kisieliute, A.; Popov, A.; Apetrei, R. M.; Cârâc, G.; Morkvenaite-Vilkonciene, I.; Ramanaviciene, A.; Ramanavicius, A. Towards Microbial Biofuel Cells: Improvement of Charge Transfer by Self-Modification of Microorganisms with Conducting Polymer – Polypyrrole. *Chemical Engineering Journal*, **2019**, 356, 1014–1021. <https://doi.org/10.1016/J.CEJ.2018.09.026>.
- [24] Apetrei, R. M.; Carac, G.; Bahrim, G.; Ramanaviciene, A.; Ramanavicius, A. Modification of *Aspergillus Niger* by Conducting Polymer, Polypyrrole, and the Evaluation of Electrochemical Properties of Modified Cells. *Bioelectrochemistry*, **2018**, 121, 46–55. <https://doi.org/10.1016/J.BIOELECHEM.2018.01.001>.
- [25] Apetrei, R. M.; Carac, G.; Ramanaviciene, A.; Bahrim, G.; Tanase, C.; Ramanavicius, A. Cell-Assisted Synthesis of Conducting Polymer – Polypyrrole – for the Improvement of Electric Charge Transfer through Fungal Cell Wall. *Colloids and Surfaces B: Biointerfaces*, **2019**, 175, 671–679. <https://doi.org/10.1016/J.COLSURFB.2018.12.024>.
- [26] Ramanaviciene, A.; Ramanavicius, A. Pulsed Amperometric Detection of DNA with an SsDNA/Polypyrrole-Modified Electrode. *Analytical and Bioanalytical Chemistry*, **2004**, 379 (2), 287–293. <https://doi.org/10.1007/s00216-004-2573-6>.
- [27] Plikusiene, I.; Balevicius, Z.; Ramanaviciene, A.; Talbot, J.; Mickiene, G.; Balevicius, S.; Stirke, A.; Tereshchenko, A.; Tamosaitis, L.; Zvirblis, G.; et al. Evaluation of Affinity Sensor Response Kinetics towards Dimeric Ligands Linked with Spacers of Different Rigidity: Immobilized Recombinant Granulocyte Colony-Stimulating Factor Based Synthetic Receptor Binding with Genetically Engineered Dimeric Analyte Derivatives. *Biosensors and Bioelectronics*, **2020**, 156, 112112. <https://doi.org/10.1016/J.BIOS.2020.112112>.
- [28] Ramanavicius, A.; Oztekin, Y.; Ramanaviciene, A. Electrochemical Formation of Polypyrrole-Based Layer for Immunosensor Design. *Sensors and Actuators B: Chemical*, **2014**, 197, 237–243. <https://doi.org/10.1016/J.SNB.2014.02.072>.

- [29] Ramanavicius, A.; Kausaite, A.; Ramanaviciene, A. Self-Encapsulation of Oxidases as a Basic Approach to Tune the Upper Detection Limit of Amperometric Biosensors. *Analyst*, **2008**, *133* (8), 1083–1089. <https://doi.org/10.1039/B801501E>.
- [30] Lakard, B.; Magnin, D.; Deschaume, O.; Vanlancker, G.; Glinel, K.; Demoustier-Champagne, S.; Nysten, B.; Jonas, A. M.; Bertrand, P.; Yunus, S. Urea Potentiometric Enzymatic Biosensor Based on Charged Biopolymers and Electrodeposited Polyaniline. *Biosensors and Bioelectronics*, **2011**, *26* (10), 4139–4145. <https://doi.org/10.1016/J.BIOS.2011.04.009>.
- [31] German, N.; Ramanavicius, A.; Voronovic, J.; Ramanaviciene, A. Glucose Biosensor Based on Glucose Oxidase and Gold Nanoparticles of Different Sizes Covered by Polypyrrole Layer. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, **2012**, *413*, 224–230. <https://doi.org/10.1016/J.COLSURFA.2012.02.012>.
- [32] Ramanavicius, S.; Jagminas, A.; Ramanavicius, A. Advances in Molecularly Imprinted Polymers Based Affinity Sensors (Review). *Polymers*, **2021**, *13* (6). <https://doi.org/10.3390/polym13060974>.
- [33] Baleviciute, I.; Ratautaite, V.; Ramanaviciene, A.; Balevicius, Z.; Broeders, J.; Croux, D.; McDonald, M.; Vahidpour, F.; Thoelen, R.; Ceuninck, W. de; et al. Evaluation of Theophylline Imprinted Polypyrrole Film. *Synthetic Metals*, **2015**, *209*, 206–211. <https://doi.org/10.1016/J.SYNTHMET.2015.07.021>.
- [34] Sangiorgi, N.; Sangiorgi, A.; Tarterini, F.; Sanson, A. Molecularly Imprinted Polypyrrole Counter Electrode for Gel-State Dye-Sensitized Solar Cells. *Electrochimica Acta*, **2019**, *305*, 322–328. <https://doi.org/10.1016/J.ELECTACTA.2019.03.059>.
- [35] Syritski, V.; Reut, J.; Opik, A.; Idla, K. Environmental QCM Sensors Coated with Polypyrrole. *Synthetic Metals*, **1999**, *102* (1–3), 1326–1327. [https://doi.org/10.1016/S0379-6779\(98\)01047-9](https://doi.org/10.1016/S0379-6779(98)01047-9).
- [36] Cui, F.; Zhou, Z.; Zhou, H. S. Molecularly Imprinted Polymers and Surface Imprinted Polymers Based Electrochemical Biosensor for Infectious Diseases. *Sensors*, **2020**, *20* (4). <https://doi.org/10.3390/s20040996>.
- [37] Liao, J.-L.; Wang, Y.; Hjertén, S. A Novel Support with Artificially Created Recognition for the Selective Removal of Proteins and for Affinity Chromatography. *Chromatographia*, **1996**, *42* (5–6), 259–262.
- [38] Fresco-Cala, B.; Batista, A. D.; Cárdenas, S. Molecularly Imprinted Polymer Micro- and Nano-Particles: A Review. *Molecules*, **2020**, *25* (20). <https://doi.org/10.3390/molecules25204740>.
- [39] Bakirhan, N. K.; Ozcelikay, G.; Ozkan, S. A. Recent Progress on the Sensitive Detection of Cardiovascular Disease Markers by Electrochemical-Based Biosensors. *Journal of Pharmaceutical and Biomedical Analysis*, **2018**, *159*, 406–424. <https://doi.org/10.1016/J.JPBA.2018.07.021>.
- [40] Sankiewicz, A.; Romanowicz, L.; Pyc, M.; Hermanowicz, A.; Gorodkiewicz, E. SPR Imaging Biosensor for the Quantitation of Fibronectin Concentration in Blood

- Samples. *Journal of Pharmaceutical and Biomedical Analysis*, **2018**, *150*, 1–8. <https://doi.org/10.1016/J.JPBA.2017.11.070>.
- [41] Ning, C.; Zhou, Z.; Tan, G.; Zhu, Y.; Mao, C. Electroactive Polymers for Tissue Regeneration: Developments and Perspectives. *Progress in Polymer Science*, **2018**, *81*, 144–162. <https://doi.org/10.1016/J.PROGPOLYMSCI.2018.01.001>.
- [42] Popov, A.; Brasiunas, B.; Damaskaite, A.; Plikusiene, I.; Ramanavicius, A.; Ramanaviciene, A. Electrodeposited Gold Nanostructures for the Enhancement of Electrochromic Properties of PANI–PEDOT Film Deposited on Transparent Electrode. *Polymers*, **2020**, *12* (12). <https://doi.org/10.3390/polym12122778>.
- [43] German, N.; Popov, A.; Ramanaviciene, A.; Ramanavicius, A. Evaluation of Enzymatic Formation of Polyaniline Nanoparticles. *Polymer*, **2017**, *115*, 211–216. <https://doi.org/10.1016/J.POLYMER.2017.03.028>.
- [44] German, N.; Popov, A.; Ramanaviciene, A.; Ramanavicius, A. Enzymatic Formation of Polyaniline, Polypyrrole, and Polythiophene Nanoparticles with Embedded Glucose Oxidase. *Nanomaterials*, **2019**, *9* (5). <https://doi.org/10.3390/nano9050806>.
- [45] Ratautaite, V.; Bagdziunas, G.; Ramanavicius, A.; Ramanaviciene, A. An Application of Conducting Polymer Polypyrrole for the Design of Electrochromic PH and CO₂ Sensors. *Journal of the electrochemical society*, **2019**, *166* (6), B297.
- [46] Krikstolaityte, V.; Kuliesius, J.; Ramanaviciene, A.; Mikoliunaite, L.; Kausaite-Minkstimiene, A.; Oztekin, Y.; Ramanavicius, A. Enzymatic Polymerization of Polythiophene by Immobilized Glucose Oxidase. *Polymer*, **2014**, *55* (7), 1613–1620. <https://doi.org/10.1016/J.POLYMER.2014.02.003>.
- [47] Genys, P.; Aksun, E.; Tereshchenko, A.; Valiūnienė, A.; Ramanaviciene, A.; Ramanavicius, A. Electrochemical Deposition and Investigation of Poly-9,10-Phenanthrenequinone Layer. *Nanomaterials*, **2019**, *9* (5). <https://doi.org/10.3390/nano9050702>.
- [48] Kausaite-Minkstimiene, A.; Glumbokaite, L.; Ramanaviciene, A.; Ramanavicius, A. Reagent-Less Amperometric Glucose Biosensor Based on Nanobiocomposite Consisting of Poly(1,10-Phenanthroline-5,6-Dione), Poly(Pyrrole-2-Carboxylic Acid), Gold Nanoparticles and Glucose Oxidase. *Microchemical Journal*, **2020**, *154*, 104665. <https://doi.org/10.1016/J.MICROC.2020.104665>.
- [49] Gicevicius, M.; Bagdziunas, G.; Abduloglu, Y.; Ramanaviciene, A.; Gumusay, O.; Ak, M.; Soganci, T.; Ramanavicius, A. Experimental and Theoretical Investigations of an Electrochromic Azobenzene and 3, 4-Ethylenedioxythiophene-based Electrochemically Formed Polymeric Semiconductor. *ChemPhysChem*, **2018**, *19* (20), 2735–2740.
- [50] Olgac, R.; Soganci, T.; Baygu, Y.; Gök, Y.; Ak, M. Zinc(II) Phthalocyanine Fused in Peripheral Positions Octa-Substituted with Alkyl Linked Carbazole: Synthesis, Electropolymerization and Its Electro-Optic and Biosensor Applications. *Biosensors and Bioelectronics*, **2017**, *98*, 202–209. <https://doi.org/10.1016/J.BIOS.2017.06.028>.

- [51] Ramanavicius, S.; Ramanavicius, A. Charge Transfer and Biocompatibility Aspects in Conducting Polymer-Based Enzymatic Biosensors and Biofuel Cells. *Nanomaterials*, **2021**, *11* (2). <https://doi.org/10.3390/nano11020371>.
- [52] Vaitkuviene, A.; Kasetas, V.; Voronovic, J.; Ramanauskaite, G.; Biziuleviciene, G.; Ramanaviciene, A.; Ramanavicius, A. Evaluation of Cytotoxicity of Polypyrrole Nanoparticles Synthesized by Oxidative Polymerization. *Journal of Hazardous Materials*, **2013**, *250–251*, 167–174. <https://doi.org/10.1016/J.JHAZMAT.2013.01.038>.
- [53] Vaitkuviene, A.; Ratautaite, V.; Mikoliunaite, L.; Kasetas, V.; Ramanauskaite, G.; Biziuleviciene, G.; Ramanaviciene, A.; Ramanavicius, A. Some Biocompatibility Aspects of Conducting Polymer Polypyrrole Evaluated with Bone Marrow-Derived Stem Cells. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, **2014**, *442*, 152–156. <https://doi.org/10.1016/J.COLSURFA.2013.06.030>.
- [54] Ramanaviciene, A.; Kausaite, A.; Tautkus, S.; Ramanavicius, A. Biocompatibility of Polypyrrole Particles: An in-Vivo Study in Mice†. *Journal of Pharmacy and Pharmacology*, **2007**, *59* (2), 311–315. <https://doi.org/10.1211/jpp.59.2.0017>.
- [55] German, N.; Popov, A.; Ramanaviciene, A.; Ramanavicius, A. Formation and Electrochemical Characterisation of Enzyme-Assisted Formation of Polypyrrole and Polyaniline Nanocomposites with Embedded Glucose Oxidase and Gold Nanoparticles. *Journal of the Electrochemical Society*, **2020**, *167* (16), 165501.
- [56] Mazeiko, V.; Kausaite-Minkstiniene, A.; Ramanaviciene, A.; Balevicius, Z.; Ramanavicius, A. Gold Nanoparticle and Conducting Polymer-Polyaniline-Based Nanocomposites for Glucose Biosensor Design. *Sensors and Actuators B: Chemical*, **2013**, *189*, 187–193. <https://doi.org/10.1016/J.SNB.2013.03.140>.
- [57] German, N.; Ramanaviciene, A.; Ramanavicius, A. Formation of Polyaniline and Polypyrrole Nanocomposites with Embedded Glucose Oxidase and Gold Nanoparticles. *Polymers*, **2019**, *11* (2). <https://doi.org/10.3390/polym11020377>.
- [58] Bornscheuer, U. T. Immobilizing Enzymes: How to Create More Suitable Biocatalysts. *Angewandte Chemie International Edition*, **2003**, *42* (29), 3336–3337.
- [59] Sheldon, R. A.; van Pelt, S. Enzyme Immobilisation in Biocatalysis: Why, What and How. *Chemical Society Reviews*, **2013**, *42* (15), 6223–6235.
- [60] Miletić, N.; Nastasović, A.; Loos, K. Immobilization of Biocatalysts for Enzymatic Polymerizations: Possibilities, Advantages, Applications. *Bioresource Technology*, **2012**, *115*, 126–135.
- [61] Andriukonis, E.; Ramanaviciene, A.; Ramanavicius, A. Synthesis of Polypyrrole Induced by $[\text{Fe}(\text{CN})_6]^{3-}$ and Redox Cycling of $[\text{Fe}(\text{CN})_6]^{4-}/[\text{Fe}(\text{CN})_6]^{3-}$. *Polymers*, **2018**, *10* (7). <https://doi.org/10.3390/polym10070749>.
- [62] German, N.; Ramanaviciene, A.; Ramanavicius, A. Formation and Electrochemical Evaluation of Polyaniline and Polypyrrole Nanocomposites Based on Glucose Oxidase and Gold Nanostructures. *Polymers*, **2020**, *12* (12). <https://doi.org/10.3390/polym12123026>.

- [63] Ye, L.; Mosbach, K. Molecularly Imprinted Microspheres as Antibody Binding Mimics. *Reactive and Functional Polymers*, **2001**, *48* (1–3), 149–157. [https://doi.org/10.1016/S1381-5148\(01\)00050-5](https://doi.org/10.1016/S1381-5148(01)00050-5).
- [64] Peeters, M.; Kobben, S.; Jiménez-Monroy, K. L.; Modesto, L.; Kraus, M.; Vandenryt, T.; Gaulke, A.; van Grinsven, B.; Ingebrandt, S.; Junkers, T.; et al. Thermal Detection of Histamine with a Graphene Oxide Based Molecularly Imprinted Polymer Platform Prepared by Reversible Addition–Fragmentation Chain Transfer Polymerization. *Sensors and Actuators B: Chemical*, **2014**, *203*, 527–535. <https://doi.org/10.1016/J.SNB.2014.07.013>.
- [65] Schmidt, R. H.; Mosbach, K.; Haupt, K. A Simple Method for Spin-coating Molecularly Imprinted Polymer Films of Controlled Thickness and Porosity. *Advanced Materials*, **2004**, *16* (8), 719–722.
- [66] Lete, C.; Lakard, B.; Hihn, J. Y.; del Campo, F. J.; Lupu, S. Use of Sinusoidal Voltages with Fixed Frequency in the Preparation of Tyrosinase Based Electrochemical Biosensors for Dopamine Electroanalysis. *Sensors and Actuators B: Chemical*, **2017**, *240*, 801–809. <https://doi.org/10.1016/J.SNB.2016.09.045>.
- [67] Long, Y. Z.; Li, M. M.; Gu, C.; Wan, M.; Duvail, J. L.; Liu, Z.; Fan, Z. Recent Advances in Synthesis, Physical Properties and Applications of Conducting Polymer Nanotubes and Nanofibers. *Progress in Polymer Science*, **2011**, *36* (10), 1415–1442. <https://doi.org/10.1016/J.PROGPOLYMSCI.2011.04.001>.
- [68] Patois, T.; Lakard, B.; Martin, N.; Fievet, P. Effect of Various Parameters on the Conductivity of Free Standing Electrosynthesized Polypyrrole Films. *Synthetic Metals*, **2010**, *160* (19–20), 2180–2185. <https://doi.org/10.1016/J.SYNTHMET.2010.08.005>.
- [69] Rahman, Md. A.; Kumar, P.; Park, D.-S.; Shim, Y.-B. Electrochemical Sensors Based on Organic Conjugated Polymers. *Sensors*, **2008**, *8* (1), 118–141. <https://doi.org/10.3390/s8010118>.
- [70] Bredas, J. L.; Street, G. B. Polarons, Bipolarons, and Solitons in Conducting Polymers. *Accounts of Chemical Research*, **1985**, *18* (10), 309–315.
- [71] Srilalitha, S.; Jayaveera, K. N.; Madhvendra, S. S. THE EFFECT OF DOPANT, TEMPERATURE AND BAND GAP ON CONDUCTIVITY OF CONDUCTING POLYMERS. *International Journal of Innovative Research in Science, Engineering and Technology*, **2013**, *2*, 2694–2696.
- [72] Lakard, B.; Ploux, L.; Anselme, K.; Lallemand, F.; Lakard, S.; Nardin, M.; Hihn, J. Y. Effect of Ultrasounds on the Electrochemical Synthesis of Polypyrrole, Application to the Adhesion and Growth of Biological Cells. *Bioelectrochemistry*, **2009**, *75* (2), 148–157. <https://doi.org/10.1016/J.BIOELECHEM.2009.03.010>.
- [73] Le, T.-H.; Kim, Y.; Yoon, H. Electrical and Electrochemical Properties of Conducting Polymers. *Polymers*, **2017**, *9* (4), 150.
- [74] Bai, S.; Hu, Q.; Zeng, Q.; Wang, M.; Wang, L. Variations in Surface Morphologies, Properties, and Electrochemical Responses to Nitro-Analyte by Controlled

- Electropolymerization of Thiophene Derivatives. *ACS Applied Materials & Interfaces*, **2018**, *10* (13), 11319–11327. <https://doi.org/10.1021/acsami.8b00554>.
- [75] Kou, Y.; Xu, Y.; Guo, Z.; Jiang, D. Supercapacitive Energy Storage and Electric Power Supply Using an Aza-fused Π -conjugated Microporous Framework. *Angewandte Chemie*, **2011**, *123* (37), 8912–8916.
- [76] Jiang, J.; Su, F.; Trewin, A.; Wood, C. D.; Campbell, N. L.; Niu, H.; Dickinson, C.; Ganin, A. Y.; Rosseinsky, M. J.; Khimyak, Y. Z. Conjugated Microporous Poly (Aryleneethynylene) Networks. *Angewandte Chemie International Edition*, **2007**, *46* (45), 8574–8578.
- [77] Zhang, Q.; Yu, S.; Wang, Q.; Xiao, Q.; Yue, Y.; Ren, S. Fluorene-Based Conjugated Microporous Polymers: Preparation and Chemical Sensing Application. *Macromolecular rapid communications*, **2017**, *38* (23), 1700445.
- [78] Schneider, S.; Fuser, M.; Bolte, M.; Terfort, A. Self-Assembled Monolayers of Aromatic Pyrrole Derivatives: Electropolymerization and Electrocopolymerization with Pyrrole. *Electrochimica Acta*, **2017**, *246*, 853–863. <https://doi.org/10.1016/J.ELECTACTA.2017.06.046>.
- [79] Popov, A.; Brasiunas, B.; Mikoliunaite, L.; Bagdziunas, G.; Ramanavicius, A.; Ramanaviciene, A. Comparative Study of Polyaniline (PANI), Poly(3,4-Ethylenedioxythiophene) (PEDOT) and PANI-PEDOT Films Electrochemically Deposited on Transparent Indium Thin Oxide Based Electrodes. *Polymer*, **2019**, *172*, 133–141. <https://doi.org/10.1016/J.POLYMER.2019.03.059>.
- [80] Peng, Y.; Su, H. Recent Innovations of Molecularly Imprinted Electrochemical Sensors Based on Electropolymerization Technique. *Current Analytical Chemistry*, **2015**, *11* (4), 307–317.
- [81] Moreira Gonçalves, L. Electropolymerized Molecularly Imprinted Polymers: Perceptions Based on Recent Literature for Soon-to-Be World-Class Scientists. *Current Opinion in Electrochemistry*, **2021**, *25*, 100640. <https://doi.org/10.1016/J.COELEC.2020.09.007>.
- [82] Crapnell, R. D.; Hudson, A.; Foster, C. W.; Eersels, K.; Grinsven, B. van; Cleij, T. J.; Banks, C. E.; Peeters, M. Recent Advances in Electrosynthesized Molecularly Imprinted Polymer Sensing Platforms for Bioanalyte Detection. *Sensors*, **2019**, *19* (5). <https://doi.org/10.3390/s19051204>.
- [83] Zaabal, M.; Bakirhan, N. K.; Douliche, M.; Kaddour, S.; Saidat, B.; Ozkan, S. A. A New Approach on Sensitive Assay of Adefovir in Pharmaceutical and Biological Fluid Samples Using Polypyrrole Modified Glassy Carbon Electrode. *Sensors and Actuators B: Chemical*, **2020**, *323*, 128657. <https://doi.org/10.1016/J.SNB.2020.128657>.
- [84] Karadas, N.; Ozkan, S. A. Electrochemical Preparation of Sodium Dodecylsulfate Doped Over-Oxidized Polypyrrole/Multi-Walled Carbon Nanotube Composite on Glassy Carbon Electrode and Its Application on Sensitive and Selective Determination of Anticancer Drug: Pemetrexed. *Talanta*, **2014**, *119*, 248–254. <https://doi.org/10.1016/J.TALANTA.2013.10.065>.

- [85] Devkota, L.; Nguyen, L. T.; Vu, T. T.; Piro, B. Electrochemical Determination of Tetracycline Using AuNP-Coated Molecularly Imprinted Overoxidized Polypyrrole Sensing Interface. *Electrochimica Acta*, **2018**, *270*, 535–542. <https://doi.org/10.1016/J.ELECTACTA.2018.03.104>.
- [86] Teng, Y.; Liu, F.; Kan, X. Voltammetric Dopamine Sensor Based on Three-Dimensional Electrosynthesized Molecularly Imprinted Polymers and Polypyrrole Nanowires. *Microchimica Acta*, **2017**, *184* (8), 2515–2522. <https://doi.org/10.1007/s00604-017-2243-y>.
- [87] Li, Y.; Song, H.; Zhang, L.; Zuo, P.; Ye, B. ce; Yao, J.; Chen, W. Supportless Electrochemical Sensor Based on Molecularly Imprinted Polymer Modified Nanoporous Microrod for Determination of Dopamine at Trace Level. *Biosensors and Bioelectronics*, **2016**, *78*, 308–314. <https://doi.org/10.1016/J.BIOS.2015.11.063>.
- [88] Ratautaite, V.; Janssens, S. D.; Haenen, K.; Nesládek, M.; Ramanaviciene, A.; Baleviciute, I.; Ramanavicius, A. Molecularly Imprinted Polypyrrole Based Impedimetric Sensor for Theophylline Determination. *Electrochimica Acta*, **2014**, *130*, 361–367. <https://doi.org/10.1016/J.ELECTACTA.2014.03.035>.
- [89] Betlem, K.; Mahmood, I.; Seixas, R. D.; Sadiki, I.; Raimbault, R. L. D.; Foster, C. W.; Crapnell, R. D.; Tedesco, S.; Banks, C. E.; Gruber, J.; et al. Evaluating the Temperature Dependence of Heat-Transfer Based Detection: A Case Study with Caffeine and Molecularly Imprinted Polymers as Synthetic Receptors. *Chemical Engineering Journal*, **2019**, *359*, 505–517. <https://doi.org/10.1016/J.CEJ.2018.11.114>.
- [90] Ratautaite, V.; Nesladek, M.; Ramanaviciene, A.; Baleviciute, I.; Ramanavicius, A. Evaluation of Histamine Imprinted Polypyrrole Deposited on Boron Doped Nanocrystalline Diamond. *Electroanalysis*, **2014**, *26* (11), 2458–2464.
- [91] Zhang, W.; Zong, L.; Geng, G.; Li, Y.; Zhang, Y. Enhancing Determination of Quercetin in Honey Samples through Electrochemical Sensors Based on Highly Porous Polypyrrole Coupled with Nanohybrid Modified GCE. *Sensors and Actuators B: Chemical*, **2018**, *257*, 1099–1109. <https://doi.org/10.1016/J.SNB.2017.11.059>.
- [92] Ye, C.; Chen, X.; Xu, J.; Xi, H.; Wu, T.; Deng, D.; Zhang, J.; Huang, G. Highly Sensitive Detection to Gallic Acid by Polypyrrole-Based MIES Supported by MOFs-Co₂+@Fe₃O₄. *Journal of Electroanalytical Chemistry*, **2020**, *859*, 113839. <https://doi.org/10.1016/J.JELECHEM.2020.113839>.
- [93] Zhang, C.; Bai, W.; Yang, Z. A Novel Photoelectrochemical Sensor for Bilirubin Based on Porous Transparent TiO₂ and Molecularly Imprinted Polypyrrole. *Electrochimica Acta*, **2016**, *187*, 451–456. <https://doi.org/10.1016/J.ELECTACTA.2015.11.098>.
- [94] Nguy, T. P.; van Phi, T.; Tram, D. T. N.; Eersels, K.; Wagner, P.; Lien, T. T. N. Development of an Impedimetric Sensor for the Label-Free Detection of the Amino Acid Sarcosine with Molecularly Imprinted Polymer Receptors. *Sensors and*

- Actuators B: Chemical*, **2017**, *246*, 461–470. <https://doi.org/10.1016/J.SNB.2017.02.101>.
- [95] Zhang, J.; Xiong, Z.; Chen, Z. Ultrasensitive Electrochemical Microcystin-LR Immunosensor Using Gold Nanoparticle Functional Polypyrrole Microsphere Catalyzed Silver Deposition for Signal Amplification. *Sensors and Actuators B: Chemical*, **2017**, *246*, 623–630. <https://doi.org/10.1016/J.SNB.2017.02.134>.
- [96] Tadi, K. K.; Motghare, R. v.; Ganesh, V. Electrochemical Detection of Sulfanilamide Using Pencil Graphite Electrode Based on Molecular Imprinting Technology. *Electroanalysis*, **2014**, *26* (11), 2328–2336.
- [97] Zaidi, S. A. Utilization of an Environmentally-Friendly Monomer for an Efficient and Sustainable Adrenaline Imprinted Electrochemical Sensor Using Graphene. *Electrochimica Acta*, **2018**, *274*, 370–377. <https://doi.org/10.1016/J.ELECTACTA.2018.04.119>.
- [98] Gholivand, M. B.; Karimian, N. Fabrication of a Highly Selective and Sensitive Voltammetric Ganciclovir Sensor Based on Electropolymerized Molecularly Imprinted Polymer and Gold Nanoparticles on Multiwall Carbon Nanotubes/Glassy Carbon Electrode. *Sensors and Actuators B: Chemical*, **2015**, *215*, 471–479. <https://doi.org/10.1016/J.SNB.2015.04.007>.
- [99] Plausinaitis, D.; Sinkevicius, L.; Samukaite-Bubniene, U.; Ratautaite, V.; Ramanavicius, A. Evaluation of Electrochemical Quartz Crystal Microbalance Based Sensor Modified by Uric Acid-Imprinted Polypyrrole. *Talanta*, **2020**, *220*, 121414. <https://doi.org/10.1016/J.TALANTA.2020.121414>.
- [100] Yola, M. L.; Atar, N. A Novel Detection Approach for Serotonin by Graphene Quantum Dots/Two-Dimensional (2D) Hexagonal Boron Nitride Nanosheets with Molecularly Imprinted Polymer. *Applied Surface Science*, **2018**, *458*, 648–655. <https://doi.org/10.1016/J.APSUSC.2018.07.142>.
- [101] Syritski, V.; Reut, J.; Menaker, A.; Gyurcsányi, R. E.; Öpik, A. Electrosynthesized Molecularly Imprinted Polypyrrole Films for Enantioselective Recognition of L-Aspartic Acid. *Electrochimica Acta*, **2008**, *53* (6), 2729–2736. <https://doi.org/10.1016/J.ELECTACTA.2007.10.032>.
- [102] Gu, J.; Dai, H.; Kong, Y.; Tao, Y.; Chu, H.; Tong, Z. Chiral Electrochemical Recognition of Cysteine Enantiomers with Molecularly Imprinted Overoxidized Polypyrrole-Au Nanoparticles. *Synthetic Metals*, **2016**, *222*, 137–143. <https://doi.org/10.1016/J.SYNTHMET.2016.05.007>.
- [103] Işık, D.; Şahin, S.; Caglayan, M. O.; Üstündağ, Z. Electrochemical Impedimetric Detection of Kanamycin Using Molecular Imprinting for Food Safety. *Microchemical Journal*, **2021**, *160*, 105713. <https://doi.org/10.1016/J.MICROC.2020.105713>.
- [104] Bolat, G.; Yaman, Y. T.; Abaci, S. Molecularly Imprinted Electrochemical Impedance Sensor for Sensitive Dibutyl Phthalate (DBP) Determination. *Sensors and Actuators B: Chemical*, **2019**, *299*, 127000. <https://doi.org/10.1016/J.SNB.2019.127000>.

- [105] Radi, A.-E.; El-Naggar, A.-E.; Nassef, H. M. Determination of Coccidiostat Clopidol on an Electropolymerized-Molecularly Imprinted Polypyrrole Polymer Modified Screen Printed Carbon Electrode. *Analytical Methods*, **2014**, *6* (19), 7967–7972.
- [106] Zhou, H.; Xu, G.; Zhu, A.; Zhao, Z.; Ren, C.; Nie, L.; Kan, X. A Multiporous Electrochemical Sensor for Epinephrine Recognition and Detection Based on Molecularly Imprinted Polypyrrole. *Rsc Advances*, **2012**, *2* (20), 7803–7808.
- [107] Xing, X.; Liu, S.; Yu, J.; Lian, W.; Huang, J. Electrochemical Sensor Based on Molecularly Imprinted Film at Polypyrrole-Sulfonated Graphene/Hyaluronic Acid-Multiwalled Carbon Nanotubes Modified Electrode for Determination of Tryptamine. *Biosensors and Bioelectronics*, **2012**, *31* (1), 277–283. <https://doi.org/10.1016/J.BIOS.2011.10.032>.
- [108] Liu, W.; Ma, Y.; Sun, G.; Wang, S.; Deng, J.; Wei, H. Molecularly Imprinted Polymers on Graphene Oxide Surface for EIS Sensing of Testosterone. *Biosensors and Bioelectronics*, **2017**, *92*, 305–312. <https://doi.org/10.1016/J.BIOS.2016.11.007>.
- [109] Nezhadali, A.; Feizy, J.; Beheshti, H. R. A Molecularly Imprinted Polymer for the Selective Extraction and Determination of Fenvalerate from Food Samples Using High-Performance Liquid Chromatography. *Food Analytical Methods*, **2015**, *8* (5), 1225–1237. <https://doi.org/10.1007/s12161-014-0004-7>.
- [110] Agrisuelas, J.; Gabrielli, C.; García-Jareño, J. J.; Perrot, H.; Sanchis-Gual, R.; Sel, O.; Vicente, F. Evaluation of the Electrochemical Anion Recognition of NO₃⁻-Imprinted Poly(Azure A) in NO₃⁻/Cl⁻ Mixed Solutions by Ac-Electrogravimetry. *Electrochimica Acta*, **2016**, *194*, 292–303. <https://doi.org/10.1016/J.ELECTACTA.2016.02.036>.
- [111] Ayankojo, A. G.; Reut, J.; Ciocan, V.; Öpik, A.; Syritski, V. Molecularly Imprinted Polymer-Based Sensor for Electrochemical Detection of Erythromycin. *Talanta*, **2020**, *209*, 120502. <https://doi.org/10.1016/J.TALANTA.2019.120502>.
- [112] Bozal-Palabiyik, B.; Erkmén, C.; Uslu, B. Molecularly Imprinted Electrochemical Sensors: Analytical and Pharmaceutical Applications Based on Ortho-Phenylenediamine Polymerization. *Current Pharmaceutical Analysis*, **2020**, *16* (4), 350–366.
- [113] Raziq, A.; Kidakova, A.; Boroznjak, R.; Reut, J.; Öpik, A.; Syritski, V. Development of a Portable MIP-Based Electrochemical Sensor for Detection of SARS-CoV-2 Antigen. *Biosensors and Bioelectronics*, **2021**, *178*, 113029. <https://doi.org/10.1016/J.BIOS.2021.113029>.
- [114] Ozcelikay, G.; Karadas-Bakirhan, N.; Taskin-Tok, T.; Ozkan, S. A. A Selective and Molecular Imaging Approach for Anticancer Drug: Pemetrexed by Nanoparticle Accelerated Molecularly Imprinting Polymer. *Electrochimica Acta*, **2020**, *354*, 136665. <https://doi.org/10.1016/J.ELECTACTA.2020.136665>.
- [115] Ozcelikay, G.; Kurbanoglu, S.; Zhang, X.; Kosak Soz, C.; Wollenberger, U.; Ozkan, S. A.; Yarman, A.; Scheller, F. W. Electrochemical MIP Sensor for

- Butyrylcholinesterase. *Polymers*, **2019**, *11* (12).
<https://doi.org/10.3390/polym11121970>.
- [116] Lu, Z.; Li, Y.; Liu, T.; Wang, G.; Sun, M.; Jiang, Y.; He, H.; Wang, Y.; Zou, P.; Wang, X.; et al. A Dual-Template Imprinted Polymer Electrochemical Sensor Based on AuNPs and Nitrogen-Doped Graphene Oxide Quantum Dots Coated on NiS₂/Biomass Carbon for Simultaneous Determination of Dopamine and Chlorpromazine. *Chemical Engineering Journal*, **2020**, *389*, 124417. <https://doi.org/10.1016/J.CEJ.2020.124417>.
- [117] Kumar Prusty, A.; Bhand, S. Molecularly Imprinted Polyresorcinol Based Capacitive Sensor for Sulphanilamide Detection. *Electroanalysis*, **2019**, *31* (9), 1797–1808.
- [118] Yang, J.; Hu, Y.; Li, Y. Molecularly Imprinted Polymer-Decorated Signal on-off Ratiometric Electrochemical Sensor for Selective and Robust Dopamine Detection. *Biosensors and Bioelectronics*, **2019**, *135*, 224–230. <https://doi.org/10.1016/J.BIOS.2019.03.054>.
- [119] Piri, S.; Piri, F.; Yaftian, M. R.; Zamani, A. Imprinted Azorubine Electrochemical Sensor Based upon Composition of MnO₂ and 1-Naphthylamine on Graphite Nanopowder. *Journal of the Iranian Chemical Society*, **2018**, *15* (12), 2713–2720. <https://doi.org/10.1007/s13738-018-1459-z>.
- [120] Yarman, A.; Kurbanoglu, S.; Jetzschmann, K. J.; Ozkan, S. A.; Wollenberger, U.; Scheller, F. W. Electrochemical MIP-Sensors for Drugs. *Current medicinal chemistry*, **2018**, *25* (33), 4007–4019.
- [121] Gokoglan, T. C.; Soylemez, S.; Kesik, M.; Unay, H.; Sayin, S.; Yildiz, H. B.; Cirpan, A.; Toppare, L. A Novel Architecture Based on a Conducting Polymer and Calixarene Derivative: Its Synthesis and Biosensor Construction. *RSC Advances*, **2015**, *5* (45), 35940–35947.
- [122] Ahuja, T.; Mir, I. A.; Kumar, D.; Rajesh. Biomolecular Immobilization on Conducting Polymers for Biosensing Applications. *Biomaterials*, **2007**, *28* (5), 791–805. <https://doi.org/10.1016/J.BIOMATERIALS.2006.09.046>.
- [123] Neo, W. T.; Ye, Q.; Chua, S.-J.; Xu, J. Conjugated Polymer-Based Electrochromics: Materials, Device Fabrication and Application Prospects. *Journal of Materials Chemistry C*, **2016**, *4* (31), 7364–7376.
- [124] Soylemez, S.; Hacıoglu, S. O.; Kesik, M.; Unay, H.; Cirpan, A.; Toppare, L. A Novel and Effective Surface Design: Conducting Polymer/ β -Cyclodextrin Host–Guest System for Cholesterol Biosensor. *ACS Applied Materials & Interfaces*, **2014**, *6* (20), 18290–18300. <https://doi.org/10.1021/am5054493>.
- [125] Wang, B.; Tang, J.; Wang, F. Electrochemical Polymerization of Aniline. *Synthetic Metals*, **1987**, *18* (1–3), 323–328. [https://doi.org/10.1016/0379-6779\(87\)90899-X](https://doi.org/10.1016/0379-6779(87)90899-X).
- [126] Mollarasouli, F.; Kurbanoglu, S.; Ozkan, S. A. The Role of Electrochemical Immunosensors in Clinical Analysis. *Biosensors*, **2019**, *9* (3), 86.
- [127] Makaraviciute, A.; Ramanaviciene, A. Site-Directed Antibody Immobilization Techniques for Immunosensors. *Biosensors and Bioelectronics*, **2013**, *50*, 460–471. <https://doi.org/10.1016/J.BIOS.2013.06.060>.

- [128] Ramanavicius, A.; Ryskevicius, N.; Oztekin, Y.; Kausaite-Minkstiniene, A.; Jursenas, S.; Baniukevicius, J.; Kirlyte, J.; Bubniene, U.; Ramanaviciene, A. Immunosensor Based on Fluorescence Quenching Matrix of the Conducting Polymer Polypyrrole. *Analytical and Bioanalytical Chemistry*, **2010**, *398* (7), 3105–3113. <https://doi.org/10.1007/s00216-010-4265-8>.
- [129] Baleviciute, I.; Balevicius, Z.; Makaraviciute, A.; Ramanaviciene, A.; Ramanavicius, A. Study of Antibody/Antigen Binding Kinetics by Total Internal Reflection Ellipsometry. *Biosensors and Bioelectronics*, **2013**, *39* (1), 170–176. <https://doi.org/10.1016/J.BIOS.2012.07.017>.
- [130] Rattanarat, P.; Suea-Ngam, A.; Ruecha, N.; Siangproh, W.; Henry, C. S.; Srisa-Art, M.; Chailapakul, O. Graphene-Polyaniline Modified Electrochemical Droplet-Based Microfluidic Sensor for High-Throughput Determination of 4-Aminophenol. *Analytica Chimica Acta*, **2016**, *925*, 51–60. <https://doi.org/10.1016/J.ACA.2016.03.010>.
- [131] Gurudatt, N. G.; Chung, S.; Kim, J. M.; Kim, M. H.; Jung, D. K.; Han, J. Y.; Shim, Y. B. Separation Detection of Different Circulating Tumor Cells in the Blood Using an Electrochemical Microfluidic Channel Modified with a Lipid-Bonded Conducting Polymer. *Biosensors and Bioelectronics*, **2019**, *146*, 111746. <https://doi.org/10.1016/J.BIOS.2019.111746>.
- [132] Shi, H.; Tsai, W.-B.; Garrison, M. D.; Ferrari, S.; Ratner, B. D. Template-Imprinted Nanostructured Surfaces for Protein Recognition. *Nature*, **1999**, *398* (6728), 593–597.
- [133] Turner, N. W.; Jeans, C. W.; Brain, K. R.; Allender, C. J.; Hlady, V.; Britt, D. W. From 3D to 2D: A Review of the Molecular Imprinting of Proteins. *Biotechnology progress*, **2006**, *22* (6), 1474–1489. <https://doi.org/10.1021/bp060122g>.
- [134] Li, S.; Cao, S.; Whitcombe, M. J.; Piletsky, S. A. Size Matters: Challenges in Imprinting Macromolecules. *Progress in Polymer Science*, **2014**, *39* (1), 145–163. <https://doi.org/10.1016/J.PROGPOLYMSCI.2013.10.002>.
- [135] Ramanaviciene, A.; Ramanavicius, A. Molecularly Imprinted Polypyrrole-Based Synthetic Receptor for Direct Detection of Bovine Leukemia Virus Glycoproteins. *Biosensors and Bioelectronics*, **2004**, *20* (6), 1076–1082. <https://doi.org/10.1016/J.BIOS.2004.05.014>.
- [136] Takeuchi, T.; Hishiya, T. Molecular Imprinting of Proteins Emerging as a Tool for Protein Recognition. *Organic & biomolecular chemistry*, **2008**, *6* (14), 2459–2467.
- [137] Erdo(double acute)ssy, J.; Horváth, V.; Yarman, A.; Scheller, F. W.; Gyurcsányi, R. E. Electrosynthesized Molecularly Imprinted Polymers for Protein Recognition. *TrAC Trends in Analytical Chemistry*, **2016**, *79*, 179–190. <https://doi.org/10.1016/J.TRAC.2015.12.018>.
- [138] Kryscio, D. R.; Fleming, M. Q.; Peppas, N. A. Protein Conformational Studies for Macromolecularly Imprinted Polymers. *Macromolecular Bioscience*, **2012**, *12* (8), 1137–1144. <https://doi.org/https://doi.org/10.1002/mabi.201200068>.

- [139] Menaker, A.; Syritski, V.; Reut, J.; Öpik, A.; Horváth, V.; Gyurcsányi, R. E. Electrosynthesized Surface-Imprinted Conducting Polymer Microrods for Selective Protein Recognition. *Advanced Materials*, **2009**, *21* (22), 2271–2275. <https://doi.org/https://doi.org/10.1002/adma.200803597>.
- [140] Poma, A.; Guerreiro, A.; Whitcombe, M. J.; Piletska, E. v; Turner, A. P. F.; Piletsky, S. A. Solid-Phase Synthesis of Molecularly Imprinted Polymer Nanoparticles with a Reusable Template—“Plastic Antibodies.” *Advanced Functional Materials*, **2013**, *23* (22), 2821–2827. <https://doi.org/https://doi.org/10.1002/adfm.201202397>.
- [141] Ambrosini, S.; Beyazit, S.; Haupt, K.; Tse Sum Bui, B. Solid-Phase Synthesis of Molecularly Imprinted Nanoparticles for Protein Recognition. *Chem. Commun.*, **2013**, *49* (60), 6746–6748. <https://doi.org/10.1039/C3CC41701H>.
- [142] Zhang, G.; Yu, Y.; Guo, M.; Lin, B.; Zhang, L. A Sensitive Determination of Albumin in Urine by Molecularly Imprinted Electrochemical Biosensor Based on Dual-Signal Strategy. *Sensors and Actuators B: Chemical*, **2019**, *288*, 564–570. <https://doi.org/10.1016/J.SNB.2019.03.042>.
- [143] Tretjakov, A.; Syritski, V.; Reut, J.; Boroznjak, R.; Volobujeva, O.; Öpik, A. Surface Molecularly Imprinted Polydopamine Films for Recognition of Immunoglobulin G. *Microchimica Acta*, **2013**, *180* (15), 1433–1442. <https://doi.org/10.1007/s00604-013-1039-y>.
- [144] Tamboli, V. K.; Bhalla, N.; Jolly, P.; Bowen, C. R.; Taylor, J. T.; Bowen, J. L.; Allender, C. J.; Estrela, P. Hybrid Synthetic Receptors on MOSFET Devices for Detection of Prostate Specific Antigen in Human Plasma. *Analytical Chemistry*, **2016**, *88* (23), 11486–11490. <https://doi.org/10.1021/acs.analchem.6b02619>.
- [145] Zeng, Q.; Huang, X.; Ma, M. A Molecularly Imprinted Electrochemical Sensor Based on Polypyrrole/Carbon Nanotubes Composite for the Detection of S-Ovalbumin in Egg White. *Int. J. Electrochem. Sci*, **2017**, *12*, 3965–3981.
- [146] Shumyantseva, V. v.; Bulko, T. v.; Sigolaeva, L. v.; Kuzikov, A. v.; Archakov, A. I. Electrosynthesis and Binding Properties of Molecularly Imprinted Poly-o-Phenylenediamine for Selective Recognition and Direct Electrochemical Detection of Myoglobin. *Biosensors and Bioelectronics*, **2016**, *86*, 330–336. <https://doi.org/10.1016/J.BIOS.2016.05.101>.
- [147] Stojanovic, Z.; Erdőssy, J.; Keltai, K.; Scheller, F. W.; Gyurcsányi, R. E. Electrosynthesized Molecularly Imprinted Polyscopoletin Nanofilms for Human Serum Albumin Detection. *Analytica Chimica Acta*, **2017**, *977*, 1–9. <https://doi.org/10.1016/J.ACA.2017.04.043>.
- [148] Yarman, A.; Dechtrirat, D.; Bossert, M.; Jetzschmann, K. J.; Gajovic-Eichelmann, N.; Scheller, F. W. Cytochrome C-Derived Hybrid Systems Based on Molecularly Imprinted Polymers. *Electroanalysis*, **2015**, *27* (3), 573–586. <https://doi.org/https://doi.org/10.1002/elan.201400592>.
- [149] Qian, L.-W.; Hu, X.-L.; Guan, P.; Gao, B.; Wang, D.; Wang, C.-L.; Li, J.; Du, C.-B.; Song, W.-Q. Thermal Preparation of Lysozyme-Imprinted Microspheres by Using

- Ionic Liquid as a Stabilizer. *Analytical and Bioanalytical Chemistry*, **2014**, 406 (28), 7221–7231. <https://doi.org/10.1007/s00216-014-8133-9>.
- [150] Dolak, I.; Canpolat, G.; Ersöz, A.; Say, R. Metal Chelate Based Site Recognition of Ceruloplasmin Using Molecularly Imprinted Polymer/Cryogel System. *Separation Science and Technology*, **2020**, 55 (2), 199–208. <https://doi.org/10.1080/01496395.2019.1577446>.
- [151] Kalecki, J.; Cieplak, M.; Dąbrowski, M.; Lisowski, W.; Kuhn, A.; Sharma, P. S. Hexagonally Packed Macroporous Molecularly Imprinted Polymers for Chemosensing of Follicle-Stimulating Hormone Protein. *ACS Sensors*, **2020**, 5 (1), 118–126. <https://doi.org/10.1021/acssensors.9b01878>.
- [152] Lai, Y.; Zhang, C.; Deng, Y.; Yang, G.; Li, S.; Tang, C.; He, N. A Novel α -Fetoprotein-MIP Immunosensor Based on AuNPs/PTh Modified Glass Carbon Electrode. *Chinese Chemical Letters*, **2019**, 30 (1), 160–162. <https://doi.org/10.1016/J.CCLET.2018.07.011>.
- [153] Karami, P.; Bagheri, H.; Johari-Ahar, M.; Khoshsafar, H.; Arduini, F.; Afkhami, A. Dual-Modality Impedimetric Immunosensor for Early Detection of Prostate-Specific Antigen and Myoglobin Markers Based on Antibody-Molecularly Imprinted Polymer. *Talanta*, **2019**, 202, 111–122. <https://doi.org/10.1016/J.TALANTA.2019.04.061>.
- [154] Wu, S.; Tan, W.; Xu, H. Protein Molecularly Imprinted Polyacrylamide Membrane: For Hemoglobin Sensing. *Analyst*, **2010**, 135 (10), 2523–2527. <https://doi.org/10.1039/C0AN00191K>.
- [155] Karimian, N.; Turner, A. P. F.; Tiwari, A. Electrochemical Evaluation of Troponin T Imprinted Polymer Receptor. *Biosensors and Bioelectronics*, **2014**, 59, 160–165. <https://doi.org/10.1016/J.BIOS.2014.03.013>.
- [156] Jafari, S.; Dehghani, M.; Nasirizadeh, N.; Azimzadeh, M. An Azithromycin Electrochemical Sensor Based on an Aniline MIP Film Electropolymerized on a Gold Nano Urchins/Graphene Oxide Modified Glassy Carbon Electrode. *Journal of Electroanalytical Chemistry*, **2018**, 829, 27–34. <https://doi.org/10.1016/J.JELECHEM.2018.09.053>.
- [157] Nikitina, V. N.; Zaryanov, N. v.; Kochetkov, I. R.; Karyakina, E. E.; Yatsimirsky, A. K.; Karyakin, A. A. Molecular Imprinting of Boronate Functionalized Polyaniline for Enzyme-Free Selective Detection of Saccharides and Hydroxy Acids. *Sensors and Actuators B: Chemical*, **2017**, 246, 428–433. <https://doi.org/10.1016/J.SNB.2017.02.073>.
- [158] Chen, X.; Yang, Z.; Si, S. Potentiometric Urea Biosensor Based on Immobilization of Urease onto Molecularly Imprinted TiO₂ Film. *Journal of Electroanalytical Chemistry*, **2009**, 635 (1), 1–6. <https://doi.org/10.1016/J.JELECHEM.2009.07.005>.
- [159] Zhang, X.; Caserta, G.; Yarman, A.; Supala, E.; Waffo, A. F. T.; Wollenberger, U.; Gyurcsányi, R. E.; Zebger, I.; Scheller, F. W. “Out of Pocket” Protein Binding—A Dilemma of Epitope Imprinted Polymers Revealed for Human Hemoglobin. *Chemosensors*, **2021**, 9 (6). <https://doi.org/10.3390/chemosensors9060128>.

- [160] Uzun, L.; Turner, A. P. F. Molecularly-Imprinted Polymer Sensors: Realising Their Potential. *Biosensors and Bioelectronics*, **2016**, *76*, 131–144. <https://doi.org/10.1016/J.BIOS.2015.07.013>.
- [161] Refaat, D.; Aggour, M. G.; Farghali, A. A.; Mahajan, R.; Wiklander, J. G.; Nicholls, I. A.; Piletsky, S. A. Strategies for Molecular Imprinting and the Evolution of MIP Nanoparticles as Plastic Antibodies—Synthesis and Applications. *International Journal of Molecular Sciences*, **2019**, *20* (24). <https://doi.org/10.3390/ijms20246304>.
- [162] Slinchenko, O.; Rachkov, A.; Miyachi, H.; Ogiso, M.; Minoura, N. Imprinted Polymer Layer for Recognizing Double-Stranded DNA. *Biosensors and Bioelectronics*, **2004**, *20* (6), 1091–1097. <https://doi.org/10.1016/J.BIOS.2004.06.027>.
- [163] Babamiri, B.; Salimi, A.; Hallaj, R. A Molecularly Imprinted Electrochemiluminescence Sensor for Ultrasensitive HIV-1 Gene Detection Using EuS Nanocrystals as Luminophore. *Biosensors and Bioelectronics*, **2018**, *117*, 332–339. <https://doi.org/10.1016/J.BIOS.2018.06.003>.
- [164] Muti, M.; Soysal, M.; Nacak, F. M.; Gençdağ, K.; Karagözler, A. E. A Novel DNA Probe Based on Molecularly Imprinted Polymer Modified Electrode for the Electrochemical Monitoring of DNA. *Electroanalysis*, **2015**, *27* (6), 1368–1377. <https://doi.org/https://doi.org/10.1002/elan.201400672>.
- [165] Zamora-Gálvez, A.; Morales-Narváez, E.; Mayorga-Martinez, C. C.; Merkoçi, A. Nanomaterials Connected to Antibodies and Molecularly Imprinted Polymers as Bio/Receptors for Bio/Sensor Applications. *Applied Materials Today*, **2017**, *9*, 387–401. <https://doi.org/10.1016/J.APMT.2017.09.006>.
- [166] Jia, M.; Zhang, Z.; Li, J.; Ma, X.; Chen, L.; Yang, X. Molecular Imprinting Technology for Microorganism Analysis. *TrAC Trends in Analytical Chemistry*, **2018**, *106*, 190–201. <https://doi.org/10.1016/J.TRAC.2018.07.011>.
- [167] Iskierko, Z.; Sharma, P. S.; Bartold, K.; Pietrzyk-Le, A.; Noworyta, K.; Kutner, W. Molecularly Imprinted Polymers for Separating and Sensing of Macromolecular Compounds and Microorganisms. *Biotechnology Advances*, **2016**, *34* (1), 30–46. <https://doi.org/10.1016/J.BIOTECHADV.2015.12.002>.
- [168] Chen, S.; Chen, X.; Zhang, L.; Gao, J.; Ma, Q. Electrochemiluminescence Detection of Escherichia Coli O157:H7 Based on a Novel Polydopamine Surface Imprinted Polymer Biosensor. *ACS Applied Materials & Interfaces*, **2017**, *9* (6), 5430–5436. <https://doi.org/10.1021/acsami.6b12455>.
- [169] Ait Lahcen, A.; Arduini, F.; Lista, F.; Amine, A. Label-Free Electrochemical Sensor Based on Spore-Imprinted Polymer for Bacillus Cereus Spore Detection. *Sensors and Actuators B: Chemical*, **2018**, *276*, 114–120. <https://doi.org/10.1016/J.SNB.2018.08.031>.
- [170] Hayden, O.; Lieberzeit, P. A.; Blaas, D.; Dickert, F. L. Artificial Antibodies for Bioanalyte Detection—Sensing Viruses and Proteins. *Advanced Functional Materials*, **2006**, *16* (10), 1269–1278. <https://doi.org/https://doi.org/10.1002/adfm.200500626>.

- [171] Takátsy, A.; Végvári, Á.; Hjertén, S.; Kilár, F. Universal Method for Synthesis of Artificial Gel Antibodies by the Imprinting Approach Combined with a Unique Electrophoresis Technique for Detection of Minute Structural Differences of Proteins, Viruses and Cells (Bacteria). *Ib. Gel Antibodies against Proteins (Hemoglobins). ELECTROPHORESIS*, **2007**, *28* (14), 2345–2350. <https://doi.org/https://doi.org/10.1002/elps.200600191>.
- [172] Hayden, O.; Dickert, F. L. Selective Microorganism Detection with Cell Surface Imprinted Polymers. *Advanced Materials*, **2001**, *13* (19), 1480–1483. [https://doi.org/https://doi.org/10.1002/1521-4095\(200110\)13:19<1480::AID-ADMA1480>3.0.CO;2-V](https://doi.org/https://doi.org/10.1002/1521-4095(200110)13:19<1480::AID-ADMA1480>3.0.CO;2-V).
- [173] Zaidi, S. A. Bacterial Imprinting Methods and Their Applications: An Overview. *Critical Reviews in Analytical Chemistry*, **2020**, 1–10. <https://doi.org/10.1080/10408347.2020.1755822>.
- [174] Golabi, M.; Kuralay, F.; Jager, E. W. H.; Beni, V.; Turner, A. P. F. Electrochemical Bacterial Detection Using Poly(3-Aminophenylboronic Acid)-Based Imprinted Polymer. *Biosensors and Bioelectronics*, **2017**, *93*, 87–93. <https://doi.org/10.1016/J.BIOS.2016.09.088>.
- [175] Pan, J.; Chen, W.; Ma, Y.; Pan, G. Molecularly Imprinted Polymers as Receptor Mimics for Selective Cell Recognition. *Chem. Soc. Rev.*, **2018**, *47* (15), 5574–5587. <https://doi.org/10.1039/C7CS00854F>.
- [176] Gupta, G.; Singh, P. K.; Boopathi, M.; Kamboj, D. v.; Singh, B.; Vijayaraghavan, R. Molecularly Imprinted Polymer for the Recognition of Biological Warfare Agent Staphylococcal Enterotoxin B Based on Surface Plasmon Resonance. *Thin Solid Films*, **2010**, *519* (3), 1115–1121. <https://doi.org/10.1016/J.TSF.2010.08.054>.
- [177] Bartold, K.; Pietrzyk-Le, A.; D'Souza, F.; Kutner, W. Oligonucleotide Analogs and Mimics for Sensing Macromolecular Biocompounds. *Trends in Biotechnology*, **2019**, *37* (10), 1051–1062. <https://doi.org/10.1016/J.TIBTECH.2019.04.003>.
- [178] Lowdon, J. W.; Diliën, H.; Singla, P.; Peeters, M.; Cleij, T. J.; van Grinsven, B.; Eersels, K. MIPs for Commercial Application in Low-Cost Sensors and Assays – An Overview of the Current Status Quo. *Sensors and Actuators B: Chemical*, **2020**, *325*, 128973. <https://doi.org/10.1016/J.SNB.2020.128973>.
- [179] Whitcombe, M. J.; Kirsch, N.; Nicholls, I. A. Molecular Imprinting Science and Technology: A Survey of the Literature for the Years 2004–2011. *Journal of Molecular Recognition*, **2014**, *27* (6), 297–401.
- [180] Wang, Z.; Xu, L.; Wu, G.; Zhu, L.; Lu, X. Development and Application of the Serotonin Voltametric Sensors Based on Molecularly Imprinting Technology. *Journal of The Electrochemical Society*, **2015**, *162* (8), B201–B206. <https://doi.org/10.1149/2.0521508jes>.
- [181] Guerreiro, J. R. L.; Bochenkov, V. E.; Runager, K.; Aslan, H.; Dong, M.; Enghild, J. J.; de Freitas, V.; Ferreira Sales, M. G.; Sutherland, D. S. Molecular Imprinting of Complex Matrices at Localized Surface Plasmon Resonance Biosensors for Screening

- of Global Interactions of Polyphenols and Proteins. *ACS Sensors*, **2016**, *1* (3), 258–264. <https://doi.org/10.1021/acssensors.5b00054>.
- [182] Lin, Z.-T.; DeMarr, V.; Bao, J.; Wu, T. Molecularly Imprinted Polymer-Based Biosensors: For the Early, Rapid Detection of Pathogens, Biomarkers, and Toxins in Clinical, Environmental, or Food Samples. *IEEE Nanotechnology Magazine*, **2018**, *12* (1), 6–13. <https://doi.org/10.1109/MNANO.2017.2779718>.
- [183] Rachkov, A. E.; Cheong, S.-H.; El'skaya, A. v; Yano, K.; Karube, I. Molecularly Imprinted Polymers as Artificial Steroid Receptors. *Polymers for Advanced Technologies*, **1998**, *9* (8), 511–519. [https://doi.org/https://doi.org/10.1002/\(SICI\)1099-1581\(199808\)9:8<511::AID-PAT790>3.0.CO;2-H](https://doi.org/https://doi.org/10.1002/(SICI)1099-1581(199808)9:8<511::AID-PAT790>3.0.CO;2-H).
- [184] des Azevedo, S.; Lakshmi, D.; Chianella, I.; Whitcombe, M. J.; Karim, K.; Ivanova-Mitseva, P. K.; Subrahmanyam, S.; Piletsky, S. A. Molecularly Imprinted Polymer-Hybrid Electrochemical Sensor for the Detection of β -Estradiol. *Industrial & Engineering Chemistry Research*, **2013**, *52* (39), 13917–13923. <https://doi.org/10.1021/ie302999j>.
- [185] Spychalska, K.; Zając, D.; Baluta, S.; Halicka, K.; Cabaj, J. Functional Polymers Structures for (Bio)Sensing Application—A Review. *Polymers*, **2020**, *12* (5). <https://doi.org/10.3390/polym12051154>.
- [186] Yoshikawa, M.; Tharpa, K.; Dima, Ş.-O. Molecularly Imprinted Membranes: Past, Present, and Future. *Chemical Reviews*, **2016**, *116* (19), 11500–11528. <https://doi.org/10.1021/acs.chemrev.6b00098>.
- [187] Wackerlig, J.; Lieberzeit, P. A. Molecularly Imprinted Polymer Nanoparticles in Chemical Sensing – Synthesis, Characterisation and Application. *Sensors and Actuators B: Chemical*, **2015**, *207* (Part A), 144–157. <https://doi.org/10.1016/J.SNB.2014.09.094>.
- [188] Flory, P. J. Thermodynamics of High Polymer Solutions. *The Journal of Chemical Physics*, **1942**, *10* (1), 51–61. <https://doi.org/10.1063/1.1723621>.
- [189] Lu, H.; Du, S. A Phenomenological Thermodynamic Model for the Chemo-Responsive Shape Memory Effect in Polymers Based on Flory–Huggins Solution Theory. *Polym. Chem.*, **2014**, *5* (4), 1155–1162. <https://doi.org/10.1039/C3PY01256E>.
- [190] HANSEN; M., C. Three Dimensional Solubility Parameter and Solvent Diffusion Coefficient. Importance in Surface Coating Formulation. *Doctoral Dissertation*, **1967**.
- [191] Antipchik, M.; Dzhuzha, A.; Sirotov, V.; Tennikova, T.; Korzhikova-Vlakh, E. Molecularly Imprinted Macroporous Polymer Monolithic Layers for L-Phenylalanine Recognition in Complex Biological Fluids. *Journal of Applied Polymer Science*, **2021**, *138* (12), 50070. <https://doi.org/https://doi.org/10.1002/app.50070>.
- [192] Hildebrand, J. H. Intermolecular Forces in Liquids. *Physical Review*, **1929**, *34* (6), 984–993. <https://doi.org/10.1103/PhysRev.34.984>.
- [193] Hildebrand, J. H. The Term ‘Regular Solution.’ *Nature*, **1951**, *168* (4281), 868.

- [194] Menge, H.; Hotopf, S.; Pönitzsch, S.; Richter, S.; Arndt, K. F.; Schneider, H.; Heuert, U. Investigation on the Swelling Behaviour in Poly(Dimethylsiloxane) Rubber Networks Using Nmr and Compression Measurements. *Polymer*, **1999**, *40* (19), 5303–5313. [https://doi.org/10.1016/S0032-3861\(98\)00750-2](https://doi.org/10.1016/S0032-3861(98)00750-2).
- [195] Lu, H.; Liu, Y.; Leng, J.; Du, S. Qualitative Separation of the Physical Swelling Effect on the Recovery Behavior of Shape Memory Polymer. *European Polymer Journal*, **2010**, *46* (9), 1908–1914. <https://doi.org/10.1016/J.EURPOLYMJ.2010.06.013>.
- [196] Zanuy, D.; Fabregat, G.; Ferreira, C. A.; Alemán, C. A Molecular Dynamics Study on Glucose Molecular Recognition by a Non-Enzymatic Selective Sensor Based on a Conducting Polymer. *Phys. Chem. Chem. Phys.*, **2019**, *21* (15), 8099–8107. <https://doi.org/10.1039/C9CP00567F>.
- [197] Boroznjak, R.; Reut, J.; Tretjakov, A.; Lomaka, A.; Öpik, A.; Syritski, V. A Computational Approach to Study Functional Monomer-Protein Molecular Interactions to Optimize Protein Molecular Imprinting. *Journal of Molecular Recognition*, **2017**, *30* (10), e2635. <https://doi.org/https://doi.org/10.1002/jmr.2635>.
- [198] Lach, P.; Sharma, P. S.; Golebiewska, K.; Cieplak, M.; D'Souza, F.; Kutner, W. Molecularly Imprinted Polymer Chemosensor for Selective Determination of an N-Nitroso-L-Proline Food Toxin. *Chem. A Eur. J*, **2017**, *23*, 1942–1949.
- [199] Sharma, P. S.; Garcia-Cruz, A.; Cieplak, M.; Noworyta, K. R.; Kutner, W. 'Gate Effect' in Molecularly Imprinted Polymers: The Current State of Understanding. *Current Opinion in Electrochemistry*, **2019**, *16*, 50–56. <https://doi.org/10.1016/J.COELEC.2019.04.020>.
- [200] Jetzschmann, K. J.; Zhang, X.; Yarman, A.; Wollenberger, U.; Scheller, F. W. Label-Free MIP Sensors for Protein Biomarkers. In *Label-Free Biosensing*; Springer, 2017; pp 291–321.
- [201] Zhang, L.; Wang, G.; Wu, D.; Xiong, C.; Zheng, L.; Ding, Y.; Lu, H.; Zhang, G.; Qiu, L. Highly Selective and Sensitive Sensor Based on an Organic Electrochemical Transistor for the Detection of Ascorbic Acid. *Biosensors and Bioelectronics*, **2018**, *100*, 235–241. <https://doi.org/10.1016/J.BIOS.2017.09.006>.
- [202] Deshmukh, M. A.; Gicevicius, M.; Ramanaviciene, A.; Shirsat, M. D.; Viter, R.; Ramanavicius, A. Hybrid Electrochemical/Electrochromic Cu(II) Ion Sensor Prototype Based on PANI/ITO-Electrode. *Sensors and Actuators B: Chemical*, **2017**, *248*, 527–535. <https://doi.org/10.1016/J.SNB.2017.03.167>.
- [203] Thomas, J. P.; Rahman, M. A.; Srivastava, S.; Kang, J.-S.; McGillivray, D.; Abd-Ellah, M.; Heinig, N. F.; Leung, K. T. Highly Conducting Hybrid Silver-Nanowire-Embedded Poly(3,4-Ethylenedioxythiophene):Poly(Styrenesulfonate) for High-Efficiency Planar Silicon/Organic Heterojunction Solar Cells. *ACS Nano*, **2018**, *12* (9), 9495–9503. <https://doi.org/10.1021/acsnano.8b04848>.
- [204] Benachio, I.; Lobato, A.; Gonçalves, L. M. Employing Molecularly Imprinted Polymers in the Development of Electroanalytical Methodologies for Antibiotic

- Determination. *Journal of Molecular Recognition*, **2021**, *34* (3), e2878. <https://doi.org/https://doi.org/10.1002/jmr.2878>.
- [205] Yarman, A.; Scheller, F. W. How Reliable Is the Electrochemical Readout of MIP Sensors? *Sensors*, **2020**, *20* (9). <https://doi.org/10.3390/s20092677>.
- [206] Yarman, A. Development of a Molecularly Imprinted Polymer-Based Electrochemical Sensor for Tyrosinase. *Turkish Journal of Chemistry*, **2018**, *42* (2), 346–354.
- [207] Burow, M.; Minoura, N. Molecular Imprinting: Synthesis of Polymer Particles with Antibody-like Binding Characteristics for Glucose Oxidase. *Biochemical and Biophysical Research Communications*, **1996**, *227* (2), 419–422. <https://doi.org/10.1006/BBRC.1996.1522>.
- [208] Jetzschmann, K. J.; Jágerszki, G.; Dechtrirat, D.; Yarman, A.; Gajovic-Eichelmann, N.; Gilsing, H.-D.; Schulz, B.; Gyurcsányi, R. E.; Scheller, F. W. Vectorially Imprinted Hybrid Nanofilm for Acetylcholinesterase Recognition. *Advanced Functional Materials*, **2015**, *25* (32), 5178–5183. <https://doi.org/https://doi.org/10.1002/adfm.201501900>.
- [209] Wang, C. Y.; Chen, Y. C.; Sheu, D. C.; Chou, T. C. Molecularly Imprinted Polymers for the Recognition of Sodium Dodecyl Sulfate Denatured Creatine Kinase. *Journal of the Taiwan Institute of Chemical Engineers*, **2012**, *43* (2), 188–194. <https://doi.org/10.1016/J.JTICE.2011.10.001>.
- [210] Jetzschmann, K. J.; Yarman, A.; Rustam, L.; Kielb, P.; Urlacher, V. B.; Fischer, A.; Weidinger, I. M.; Wollenberger, U.; Scheller, F. W. Molecular LEGO by Domain-Imprinting of Cytochrome P450 BM3. *Colloids and Surfaces B: Biointerfaces*, **2018**, *164*, 240–246. <https://doi.org/10.1016/J.COLSURFB.2018.01.047>.
- [211] Peng, L.; Yarman, A.; Jetzschmann, K. J.; Jeoung, J.-H.; Schad, D.; Dobbek, H.; Wollenberger, U.; Scheller, F. W. Molecularly Imprinted Electropolymer for a Hexameric Heme Protein with Direct Electron Transfer and Peroxide Electrocatalysis. *Sensors*, **2016**, *16* (3). <https://doi.org/10.3390/s16030272>.
- [212] Yarman, A. Electrosynthesized Molecularly Imprinted Polymer for Laccase Using the Inactivated Enzyme as the Target. *Bulletin of the Korean Chemical Society*, **2018**, *39* (4), 483–488. <https://doi.org/https://doi.org/10.1002/bkcs.11413>.
- [213] Bossi, A.; Piletsky, S. A.; Piletska, E. v.; Righetti, P. G.; Turner, A. P. F. Surface-Grafted Molecularly Imprinted Polymers for Protein Recognition. *Analytical Chemistry*, **2001**, *73* (21), 5281–5286. <https://doi.org/10.1021/ac0006526>.
- [214] Yang, S.; Bai, C.; Teng, Y.; Zhang, J.; Peng, J.; Fang, Z.; Xu, W. Study of Horseradish Peroxidase and Hydrogen Peroxide Bi-Analyte Sensor with Boronate Affinity-Based Molecularly Imprinted Film. *Canadian Journal of Chemistry*, **2019**, *97* (12), 833–839.
- [215] Wang, Q.; Xue, R.; Guo, H.; Wei, Y.; Yang, W. A Facile Horseradish Peroxidase Electrochemical Biosensor with Surface Molecular Imprinting Based on Polyaniline Nanotubes. *Journal of Electroanalytical Chemistry*, **2018**, *817*, 184–194. <https://doi.org/10.1016/J.JELECHEM.2018.04.013>.

- [216] Guo, L.; Zheng, H.; Zhang, C.; Qu, L.; Yu, L. A Novel Molecularly Imprinted Sensor Based on PtCu Bimetallic Nanoparticle Deposited on PSS Functionalized Graphene with Peroxidase-like Activity for Selective Determination of Puerarin. *Talanta*, **2020**, *210*, 120621. <https://doi.org/10.1016/J.TALANTA.2019.120621>.
- [217] Cutivet, A.; Schembri, C.; Kovensky, J.; Haupt, K. Molecularly Imprinted Microgels as Enzyme Inhibitors. *Journal of the American Chemical Society*, **2009**, *131* (41), 14699–14702. <https://doi.org/10.1021/ja901600e>.
- [218] Merkoçi, A.; Alegret, S. New Materials for Electrochemical Sensing IV. Molecular Imprinted Polymers. *TrAC Trends in Analytical Chemistry*, **2002**, *21* (11), 717–725. [https://doi.org/10.1016/S0165-9936\(02\)01119-6](https://doi.org/10.1016/S0165-9936(02)01119-6).
- [219] Emir Diltemiz, S.; Keçili, R.; Ersöz, A.; Say, R. Molecular Imprinting Technology in Quartz Crystal Microbalance (QCM) Sensors. *Sensors*, **2017**, *17* (3). <https://doi.org/10.3390/s17030454>.
- [220] Eslami, M. R.; Alizadeh, N. Nanostructured Conducting Molecularly Imprinted Polypyrrole Based Quartz Crystal Microbalance Sensor for Naproxen Determination and Its Electrochemical Impedance Study. *RSC advances*, **2016**, *6* (12), 9387–9395.
- [221] Pietrzyk, A.; Suriyanarayanan, S.; Kutner, W.; Chitta, R.; D'Souza, F. Selective Histamine Piezoelectric Chemosensor Using a Recognition Film of the Molecularly Imprinted Polymer of Bis(Bithiophene) Derivatives. *Analytical Chemistry*, **2009**, *81* (7), 2633–2643. <https://doi.org/10.1021/ac8025652>.
- [222] Haupt, K.; Noworyta, K.; Kutner, W. Imprinted Polymer-Based Enantioselective Acoustic Sensor Using a Quartz Crystal Microbalance. *Analytical Communications*, **1999**, *36* (11–12), 391–393.
- [223] Eslami, M. R.; Alizadeh, N. A Dual Usage Smart Sorbent/Recognition Element Based on Nanostructured Conducting Molecularly Imprinted Polypyrrole for Simultaneous Potential-Induced Nanoextraction/Determination of Ibuprofen in Biomedical Samples by Quartz Crystal Microbalance Sensor. *Sensors and Actuators B: Chemical*, **2015**, *220*, 880–887. <https://doi.org/10.1016/J.SNB.2015.06.017>.
- [224] Dabrowski, M.; Lach, P.; Cieplak, M.; Kutner, W. Nanostructured Molecularly Imprinted Polymers for Protein Chemosensing. *Biosensors and Bioelectronics*, **2018**, *102*, 17–26. <https://doi.org/10.1016/J.BIOS.2017.10.045>.
- [225] Boysen, R. I.; Schwarz, L. J.; Nicolau, D. v; Hearn, M. T. W. Molecularly Imprinted Polymer Membranes and Thin Films for the Separation and Sensing of Biomacromolecules. *Journal of Separation Science*, **2017**, *40* (1), 314–335. <https://doi.org/https://doi.org/10.1002/jssc.201600849>.
- [226] Saylan, Y.; Yilmaz, F.; Özgür, E.; Derazshamshir, A.; Yavuz, H.; Denizli, A. Molecular Imprinting of Macromolecules for Sensor Applications. *Sensors*, **2017**, *17* (4). <https://doi.org/10.3390/s17040898>.
- [227] Karaseva, N. A.; Pluhar, B.; Beliaeva, E. A.; Ermolaeva, T. N.; Mizaikoff, B. Synthesis and Application of Molecularly Imprinted Polymers for Trypsin

- Piezoelectric Sensors. *Sensors and Actuators B: Chemical*, **2019**, *280*, 272–279. <https://doi.org/10.1016/J.SNB.2018.10.022>.
- [228] Liu, S.; Zhou, D.; Guo, T. Construction of a Novel Macroporous Imprinted Biosensor Based on Quartz Crystal Microbalance for Ribonuclease A detection. *Biosensors and Bioelectronics*, **2013**, *42* (1), 80–86. <https://doi.org/10.1016/J.BIOS.2012.11.002>.
- [229] Chunta, S.; Suedee, R.; Boonsriwong, W.; Lieberzeit, P. A. Biomimetic Sensors Targeting Oxidized-Low-Density Lipoprotein with Molecularly Imprinted Polymers. *Analytica Chimica Acta*, **2020**, *1116*, 27–35. <https://doi.org/10.1016/J.ACA.2020.04.017>.
- [230] Bartold, K.; Pietrzyk-Le, A.; Huynh, T.-P.; Iskierko, Z.; Sosnowska, M.; Noworyta, K.; Lisowski, W.; Sannicolò, F.; Caeteruccio, S.; Licandro, E.; et al. Programmed Transfer of Sequence Information into a Molecularly Imprinted Polymer for Hexakis(2,2'-Bithien-5-Yl) DNA Analogue Formation toward Single-Nucleotide-Polymorphism Detection. *ACS Applied Materials & Interfaces*, **2017**, *9* (4), 3948–3958. <https://doi.org/10.1021/acsami.6b14340>.
- [231] Mosch, H. L. K. S.; Akintola, O.; Plass, W.; Höppener, S.; Schubert, U. S.; Ignaszak, A. Specific Surface versus Electrochemically Active Area of the Carbon/Polypyrrole Capacitor: Correlation of Ion Dynamics Studied by an Electrochemical Quartz Crystal Microbalance with BET Surface. *Langmuir*, **2016**, *32* (18), 4440–4449. <https://doi.org/10.1021/acs.langmuir.6b00523>.
- [232] Hu, Y.; Xing, H.; Li, G.; Wu, M. Magnetic Imprinted Polymer-Based Quartz Crystal Microbalance Sensor for Sensitive Label-Free Detection of Methylene Blue in Groundwater. *Sensors*, **2020**, *20* (19). <https://doi.org/10.3390/s20195506>.
- [233] Sakata, T.; Nishitani, S.; Kajisa, T. Molecularly Imprinted Polymer-Based Bioelectrical Interfaces with Intrinsic Molecular Charges. *RSC Advances*, **2020**, *10* (29), 16999–17013.
- [234] Turemis, M.; Zappi, D.; Giardi, M. T.; Basile, G.; Ramanaviciene, A.; Kapralovs, A.; Ramanavicius, A.; Viter, R. ZnO/Polyaniline Composite Based Photoluminescence Sensor for the Determination of Acetic Acid Vapor. *Talanta*, **2020**, *211*, 120658. <https://doi.org/10.1016/J.TALANTA.2019.120658>.
- [235] Jing, L.; Zhang, Q.; Wang, Y.; Liu, X.; Wei, T. Surface Plasmon Resonance Sensor for Theophylline Using a Water-Compatible Molecularly Imprinted Film. *Anal. Methods*, **2016**, *8* (11), 2349–2356. <https://doi.org/10.1039/C6AY00028B>.
- [236] Bhunia, S.; Dey, N.; Pradhan, A.; Bhattacharya, S. A Conjugated Microporous Polymer Based Visual Sensing Platform for Aminoglycoside Antibiotics in Water. *Chem. Commun.*, **2018**, *54* (54), 7495–7498. <https://doi.org/10.1039/C8CC02865F>.
- [237] Tan, J.; Chen, W. J.; Guo, J. Conjugated Microporous Polymers with Distinctive π -Electronic Properties Exhibiting Enhanced Optical Applications. *Chinese Chemical Letters*, **2016**, *27* (8), 1405–1411. <https://doi.org/10.1016/J.CCLET.2016.06.050>.

- [238] Zhang, B.; Li, B.; Wang, Z. Creation of Carbazole-Based Fluorescent Porous Polymers for Recognition and Detection of Various Pesticides in Water. *ACS Sensors*, **2020**, *5* (1), 162–170. <https://doi.org/10.1021/acssensors.9b01954>.
- [239] Liu, H.; Wang, Y.; Mo, W.; Tang, H.; Cheng, Z.; Chen, Y.; Zhang, S.; Ma, H.; Li, B.; Li, X. Dendrimer-Based, High-Luminescence Conjugated Microporous Polymer Films for Highly Sensitive and Selective Volatile Organic Compound Sensor Arrays. *Advanced Functional Materials*, **2020**, *30* (13), 1910275. <https://doi.org/https://doi.org/10.1002/adfm.201910275>.
- [240] Ramanavicius, A.; Kurilcik, N.; Jursenas, S.; Finkelsteinas, A.; Ramanaviciene, A. Conducting Polymer Based Fluorescence Quenching as a New Approach to Increase the Selectivity of Immunosensors. *Biosensors and Bioelectronics*, **2007**, *23* (4), 499–505. <https://doi.org/10.1016/J.BIOS.2007.06.013>.
- [241] Lahcen, A. A.; Baleb, A. A.; Baker, P.; Iwuoha, E.; Amine, A. Synthesis and Electrochemical Characterization of Nanostructured Magnetic Molecularly Imprinted Polymers for 17- β -Estradiol Determination. *Sensors and Actuators B: Chemical*, **2017**, *241*, 698–705. <https://doi.org/10.1016/J.SNB.2016.10.132>.
- [242] Zhang, X.; Peng, Y.; Bai, J.; Ning, B.; Sun, S.; Hong, X.; Liu, Y.; Liu, Y.; Gao, Z. A Novel Electrochemical Sensor Based on Electropolymerized Molecularly Imprinted Polymer and Gold Nanomaterials Amplification for Estradiol Detection. *Sensors and Actuators B: Chemical*, **2014**, *200*, 69–75. <https://doi.org/10.1016/J.SNB.2014.04.028>.
- [243] Duan, D.; Si, X.; Ding, Y.; Li, L.; Ma, G.; Zhang, L.; Jian, B. A Novel Molecularly Imprinted Electrochemical Sensor Based on Double Sensitization by MOF/CNTs and Prussian Blue for Detection of 17 β -Estradiol. *Bioelectrochemistry*, **2019**, *129*, 211–217. <https://doi.org/10.1016/J.BIOELECTCHEM.2019.04.014>.
- [244] Lee, M.-H.; Chen, Y.-C.; Ho, M.-H.; Lin, H.-Y. Optical Recognition of Salivary Proteins by Use of Molecularly Imprinted Poly (Ethylene-Co-Vinyl Alcohol)/Quantum Dot Composite Nanoparticles. *Analytical and bioanalytical chemistry*, **2010**, *397* (4), 1457–1466.
- [245] Zeng, L.; Cui, H.; Chao, J.; Huang, K.; Wang, X.; Zhou, Y.; Jing, T. Colorimetric Determination of Tetrabromobisphenol A Based on Enzyme-Mimicking Activity and Molecular Recognition of Metal-Organic Framework-Based Molecularly Imprinted Polymers. *Microchimica Acta*, **2020**, *187* (2), 142. <https://doi.org/10.1007/s00604-020-4119-9>.
- [246] Bossertdt, M.; Erdossy, J.; Lautner, G.; Witt, J.; Köhler, K.; Gajovic-Eichelmann, N.; Yarman, A.; Wittstock, G.; Scheller, F. W.; Gyurcsányi, R. E. Microelectrospotting as a New Method for Electrosynthesis of Surface-Imprinted Polymer Microarrays for Protein Recognition. *Biosensors and Bioelectronics*, **2015**, *73*, 123–129. <https://doi.org/10.1016/J.BIOS.2015.05.049>.
- [247] Chen, W.; Meng, Z.; Xue, M.; Shea, K. J. Molecular Imprinted Photonic Crystal for Sensing of Biomolecules. *Molecular Imprinting*, **2016**, *4* (1), 1–12.

- [248] Cieplak, M.; Węglowski, R.; Iskierko, Z.; Węglowska, D.; Sharma, P. S.; Noworyta, K. R.; D'Souza, F.; Kutner, W. Protein Determination with Molecularly Imprinted Polymer Recognition Combined with Birefringence Liquid Crystal Detection. *Sensors*, **2020**, *20* (17). <https://doi.org/10.3390/s20174692>.
- [249] Petruleviciene, M.; Juodkazyte, J.; Parvin, M.; Tereshchenko, A.; Ramanavicius, S.; Karpicz, R.; Samukaite-Bubniene, U.; Ramanavicius, A. Tuning the Photo-Luminescence Properties of WO₃ Layers by the Adjustment of Layer Formation Conditions. *Materials*, **2020**, *13* (12). <https://doi.org/10.3390/ma13122814>.
- [250] Gicevicius, M.; Kucinski, J.; Ramanaviciene, A.; Ramanavicius, A. Tuning the Optical PH Sensing Properties of Polyaniline-Based Layer by Electrochemical Copolymerization of Aniline with o-Phenylenediamine. *Dyes and Pigments*, **2019**, *170*, 107457. <https://doi.org/10.1016/J.DYEPIG.2019.04.002>.
- [251] Gicevicius, M.; Celiesiute, R.; Kucinski, J.; Ramanaviciene, A.; Bagdziunas, G.; Ramanavicius, A. Analytical Evaluation of Optical PH-Sensitivity of Polyaniline Layer Electrochemically Deposited on ITO Electrode. *Journal of The Electrochemical Society*, **2018**, *165* (14), H903.
- [252] Balint, R.; Cassidy, N. J.; Cartmell, S. H. Conductive Polymers: Towards a Smart Biomaterial for Tissue Engineering. *Acta Biomaterialia*, **2014**, *10* (6), 2341–2353. <https://doi.org/10.1016/J.ACTBIO.2014.02.015>.
- [253] Lakard, S.; Morrand-Villeneuve, N.; Lesniewska, E.; Lakard, B.; Michel, G.; Herlem, G.; Gharbi, T.; Fahys, B. Synthesis of Polymer Materials for Use as Cell Culture Substrates. *Electrochimica Acta*, **2007**, *53* (3), 1114–1126. <https://doi.org/10.1016/J.ELECTACTA.2007.04.098>.
- [254] Tomczykowa, M.; Plonska-Brzezinska, M. E. Conducting Polymers, Hydrogels and Their Composites: Preparation, Properties and Bioapplications. *Polymers*, **2019**, *11* (2). <https://doi.org/10.3390/polym11020350>.
- [255] Zhao, X.; Li, P.; Guo, B.; Ma, P. X. Antibacterial and Conductive Injectable Hydrogels Based on Quaternized Chitosan-Graft-Polyaniline/Oxidized Dextran for Tissue Engineering. *Acta Biomaterialia*, **2015**, *26*, 236–248. <https://doi.org/10.1016/J.ACTBIO.2015.08.006>.
- [256] Zhao, F.; Bae, J.; Zhou, X.; Guo, Y.; Yu, G. Nanostructured Functional Hydrogels as an Emerging Platform for Advanced Energy Technologies. *Advanced Materials*, **2018**, *30* (48), 1801796. <https://doi.org/https://doi.org/10.1002/adma.201801796>.
- [257] Shi, Y.; Wang, M.; Ma, C.; Wang, Y.; Li, X.; Yu, G. A Conductive Self-Healing Hybrid Gel Enabled by Metal–Ligand Supramolecule and Nanostructured Conductive Polymer. *Nano Letters*, **2015**, *15* (9), 6276–6281. <https://doi.org/10.1021/acs.nanolett.5b03069>.
- [258] Wang, Y.; Shi, Y.; Pan, L.; Yang, M.; Peng, L.; Zong, S.; Shi, Y.; Yu, G. Multifunctional Superhydrophobic Surfaces Templated From Innately Microstructured Hydrogel Matrix. *Nano Letters*, **2014**, *14* (8), 4803–4809. <https://doi.org/10.1021/nl5019782>.

- [259] Motia, S.; Bouchikhi, B.; el Bari, N. An Electrochemical Molecularly Imprinted Sensor Based on Chitosan Capped with Gold Nanoparticles and Its Application for Highly Sensitive Butylated Hydroxyanisole Analysis in Foodstuff Products. *Talanta*, **2021**, *223*, 121689. <https://doi.org/10.1016/J.TALANTA.2020.121689>.
- [260] Ullah, S.; Hamade, F.; Bubniene, U.; Engblom, J.; Ramanavicius, A.; Ramanaviciene, A.; Ruzgas, T. In-Vitro Model for Assessing Glucose Diffusion through Skin. *Biosensors and Bioelectronics*, **2018**, *110*, 175–179. <https://doi.org/10.1016/J.BIOS.2018.03.039>.
- [261] Chen, J.; Wen, H.; Zhang, G.; Lei, F.; Feng, Q.; Liu, Y.; Cao, X.; Dong, H. Multifunctional Conductive Hydrogel/Thermochromic Elastomer Hybrid Fibers with a Core–Shell Segmental Configuration for Wearable Strain and Temperature Sensors. *ACS Applied Materials & Interfaces*, **2020**, *12* (6), 7565–7574. <https://doi.org/10.1021/acsami.9b20612>.
- [262] Li, L.; Shi, Y.; Pan, L.; Shi, Y.; Yu, G. Rational Design and Applications of Conducting Polymer Hydrogels as Electrochemical Biosensors. *J. Mater. Chem. B*, **2015**, *3* (15), 2920–2930. <https://doi.org/10.1039/C5TB00090D>.
- [263] Li, L.; Wang, Y.; Pan, L.; Shi, Y.; Cheng, W.; Shi, Y.; Yu, G. A Nanostructured Conductive Hydrogels-Based Biosensor Platform for Human Metabolite Detection. *Nano Letters*, **2015**, *15* (2), 1146–1151. <https://doi.org/10.1021/nl504217p>.
- [264] Xu, Y.; Cui, M.; Patsis, P. A.; Günther, M.; Yang, X.; Eckert, K.; Zhang, Y. Reversibly Assembled Electroconductive Hydrogel via a Host–Guest Interaction for 3D Cell Culture. *ACS Applied Materials & Interfaces*, **2019**, *11* (8), 7715–7724. <https://doi.org/10.1021/acsami.8b19482>.
- [265] Dong, R.; Zhao, X.; Guo, B.; Ma, P. X. Self-Healing Conductive Injectable Hydrogels with Antibacterial Activity as Cell Delivery Carrier for Cardiac Cell Therapy. *ACS Applied Materials & Interfaces*, **2016**, *8* (27), 17138–17150. <https://doi.org/10.1021/acsami.6b04911>.
- [266] Mawad, D.; Stewart, E.; Officer, D. L.; Romeo, T.; Wagner, P.; Wagner, K.; Wallace, G. G. A Single Component Conducting Polymer Hydrogel as a Scaffold for Tissue Engineering. *Advanced Functional Materials*, **2012**, *22* (13), 2692–2699. <https://doi.org/https://doi.org/10.1002/adfm.201102373>.
- [267] Ginting, M.; Pasaribu, S. P.; Masmur, I.; Kaban, J. Self-Healing Composite Hydrogel with Antibacterial and Reversible Restorability Conductive Properties. *RSC Advances*, **2020**, *10* (9), 5050–5057.
- [268] Bhat, A.; Amanor-Boadu, J. M.; Guiseppi-Elie, A. Toward Impedimetric Measurement of Acidosis with a PH-Responsive Hydrogel Sensor. *ACS Sensors*, **2020**, *5* (2), 500–509. <https://doi.org/10.1021/acssensors.9b02336>.
- [269] Luo, C.; Wei, N.; Sun, X.; Luo, F. Fabrication of Self-Healable, Conductive, and Ultra-Strong Hydrogel from Polyvinyl Alcohol and Grape Seed–Extracted Polymer. *Journal of Applied Polymer Science*, **2020**, *137* (37), 49118. <https://doi.org/https://doi.org/10.1002/app.49118>.

[270] Wang, S.; Guo, G.; Lu, X.; Ji, S.; Tan, G.; Gao, L. Facile Soaking Strategy Toward Simultaneously Enhanced Conductivity and Toughness of Self-Healing Composite Hydrogels Through Constructing Multiple Noncovalent Interactions. *ACS Applied Materials & Interfaces*, **2018**, *10* (22), 19133–19142. <https://doi.org/10.1021/acsami.8b04999>.