

Research progress of electrochemical sensors for pesticide residue detection

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ABSTRACT

Pesticides have played an important role in agricultural production as an effective means of rapid and efficient control of pests and diseases. However, their unreasonable use can lead to excessive pesticide residues in the environment and agricultural products, posing a great threat to the ecological environment and human health. Therefore, it is necessary to establish a new technique for pesticide residue analysis that is efficient, sensitive and practical. Electrochemical sensors are widely used in the detection of pesticide residues due to their high sensitivity, stability, selectivity, simplicity, fast speed and low cost. This article reviews the application and research progress of immuno, enzyme, nano and molecularly imprinted electrochemical sensors in pesticide residue detection, and gives an outlook on the future application of electrochemical sensors in pesticide residues detection.

Keywords: electrochemical sensor, pesticide residues, food, immune sensor, detection.

1. Introduction

Pesticides are generally immunotoxic, neurotoxic, genotoxic and trichotoxic, etc. In order to improve and safeguard the quality of food and the safety of life, the sensitive detection of pesticide residues has received more and more attention.

At present, pesticide residues are detected by gas chromatography (GC), high performance liquid chromatography (HPLC), chromatography/mass spectrometry (MS), capillary electrophoresis (CE), surface-enhanced Raman spectroscopy (SERMS), immunoassay, and biosensors. Gas chromatography, high performance liquid chromatography and chromatography/mass spectrometry have high separation efficiency and sensitivity, but the instrument are expensive and not easy to be miniaturized, and the pretreatment of samples is relatively complicated [1,2]; capillary electrophoresis has the advantages of multiple separation modes, high efficiency, fast analysis speed, and low consumption of reagents and samples, etc, but the diameter of the capillary is small, and the optical path is short, and the reproducibility is poor [3]; surface-enhanced Raman Surface-enhanced Raman spectroscopy has high sensitivity, but poor reproducibility and stability [4].

Immunoassay is an antibody-based technique for qualitative and quantitative analysis of proteins or other compounds through specific binding; biosensors developed on the basis of this technique have been rapidly developed in recent years with its unique advantages - highly miniaturised, automated, integrated, highly sensitive, highly selective, low cost, real-time, and simple. Electrochemical sensors have been widely used in various fields such as biology, environment, food and so on because of their low power consumption, high sensitivity, high accuracy, strong anti-interference ability, wide linear range and excellent repeatability and stability. The article mainly reviews the application and research progress of different types of electrochemical sensors in pesticide residue detection, and gives an outlook on the application of electrochemical sensors in pesticide residue detection.

2. The principle of electrochemical sensors

As shown in Fig. 1, the basic principle of electrochemical sensors is the process of electrochemical signals generated by redox reactions of electrically active analytes on the surface of electrodes at fixed or variable voltages [5]. Molecular

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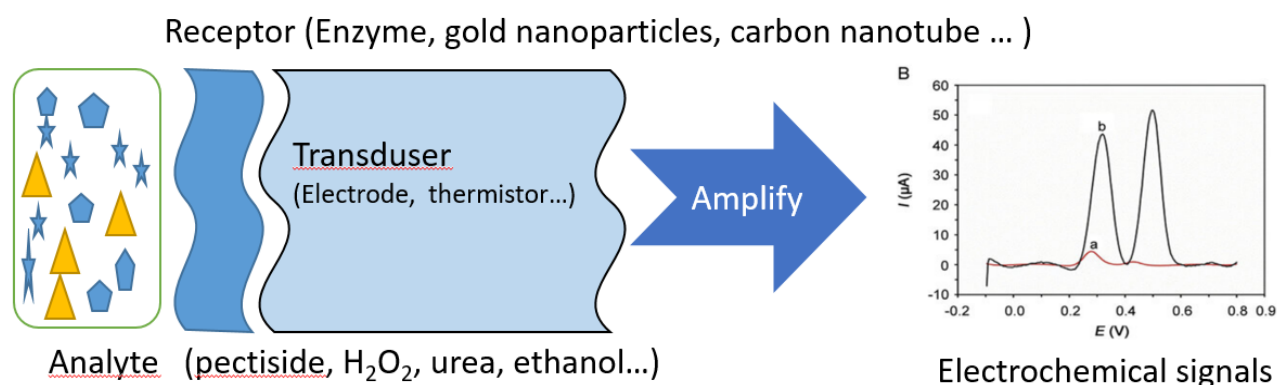


Fig. 1. The basic principle of electrochemical sensors [6].

recognition and information conversion are the two core components of biosensors, the molecular recognition component refers to immobilised enzymes, nucleic acids, antibodies, tissues, cells or microorganisms, etc., and the signal conversion component generally consists of thermistors, field effect tubes (FETs), electrochemical measurement devices (ECDs), piezoelectric elements, photodiodes and optical fibres. Electrochemical sensors, like other biosensors, consist of both molecular recognition and information conversion. The principle is that biologically active materials or chemical composites are immobilised on the surface of the electrode, which specifically identify the analyte, and the electrode transmits this identification information to the information converter to form a detectable output signal. Qualitative or quantitative analysis of the substance to be measured, based on the amount of change in the electrical signal before and after recognition [6].

3. The types of electrochemical sensors and their application in pesticide detection

Depending on the identifying substances or modifying materials used in the detection of pesticide residues, electrochemical sensors can be divided into the following categories: electrochemical immunosensors, electrochemical enzyme sensors and other electrochemical sensors [7-12].

3.1. Electrochemical immunosensors and their application in pesticide detection

3.1.1. Potential-based immunosensors

Potentiometric immunosensors are biosensors based on the change of potential induced by the

specific binding of antigen and antibody. The working principle is to make use of the characteristic of antigen or antibody in aqueous solution that the amphiphilic dissociation itself is electrically charged, fix the antibody on the electrode surface, and when the antigen (antibody) combines with it to form an antigen-antibody complex, the original membrane charge density will change, which will cause a change in the membrane Donnan potential (the difference in potential between the two-phase interfaces due to the uneven distribution of charge and the formation of a double layer) and the migration of ions. This causes a change in the membrane Donnan potential (the potential difference between the twophase interfaces due to the uniform charge distribution and the formation of a double layer) and ion migration, which ultimately leads to a change in membrane potential. The whole reaction process can be described by the Nernst Eq. (1):

$$E = E^0 + \frac{RT}{nF} \ln a \text{ or } E = E^0 - \frac{RT}{nF} \ln a \quad (1)$$

In that equation:

E – voltage to be measured, V;

E^0 – standard potential difference, as a constant, V;

R – ideal gas constant, 8.314472 J/(K·mol);

T – temperature, K;

a – activity of oxidizing and reducing chemicals (activity = concentration × activity coefficient), mol/L;

F – Faraday's constant, 1 F is equal to 96,4853399 C/mol;

n – number of electron transfers of the reaction formula, mol.

Potentiometric electrochemical sensors have been applied to pesticide detection since 1996 [13]. Dzantiev et al. [14] successfully detected dichlorophenoxyacetic

acid (2,4-dichlorophenoxyacetic acid, 2,4-D) and trichlorophenoxyacetic acid (2,4,5-trichlorophenoxyacetic acid, 2,4,5-T) using potentiometric electrochemical immunosensors, in which peroxidase-labeled pesticides and unlabeled pesticides were competitively conjugated with antibodies immobilized on the surface of the graphite electrodes, which were placed in a base solution containing aminosalicic acid and hydrogen peroxide for signal detection. The pesticides were competitively bound to the antibodies immobilized on the graphite electrode, which was then placed in a base solution containing aminosalicic acid and hydrogen peroxide for signal detection. Since the redox reaction of peroxidase leads to a change in the reduction potential, the pesticides were detected by measuring the peroxidase activity in the immunocomplex, and the limits of detection were 40 ng/mL for 2,4-D and 50 ng/mL for 2,4,5-T. The electrode can be used for 60 consecutive determinations. Yu Laev et al. [15] also applied the above labeled immunocompetitive assay, and the detection limit of simazine was 3 ng/mL, and the service life of this sensor was 15 d. Compared with the standard enzyme immunoassay, this sensor is more cost-effective and less time-consuming.

3.1.2 Current type immunosensors

Current-based immunosensors are voltammetric sensors that detect analytes by measuring electrical currents. There are two main types of detection methods: the former is to use enzyme-labeled antibody, and the antibody immobilized on the surface of the electrode combined with the antigen to form a sandwich structure, which catalyzes the redox reaction, resulting in a change in current; the latter is to place the labeled antigen and the sample in the same solution, and the immobilized electrode surface of the antibody to compete with the binding, resulting in a change in the current [16]. The usual linear diffusion current for planar electrodes can be expressed by Cottrell's Eq. (2):

$$i_d(t) = \frac{nFAD_0^{1/2}C_0^*}{(\pi t)^{1/2}} \quad (2)$$

In that equation:

i_d – (t) limiting diffusion current, A;

n – number of electrons exchanged for the electrode reaction, mol;

F – Faraday's constant, 1 F is equal to 96,485.3399 C/mol;

A – effective area of the electrode, cm²;

D_0 – Diffusion coefficient of the electrode reactant;

C_0^* – body concentration of the electrode reactant, mol/L;

t – reaction time, s – reaction time, s

From equation (2), it can be seen that the current is directly proportional to the concentration of the reaction substance, which is the basis for the quantitative analysis of the polarographic method. At the same time through this formula can be analogous to the relationship between power and time, so as to obtain the basis for quantitative analysis of the chrono-electricity method.

Current-based immunosensors are versatile due to the variety of substances they recognise and can be used to detect pesticide residues either directly or indirectly. Therefore, this type of sensor has a good prospect of application in the detection of pesticide residues. Tran's group [17] combined hydroxylated atrazine with nitrogen-(6-(4-hydroxy-6-isopropylamino-1,3,5-triazacyclo-2-aminoalkyl) hexyl)5-hydroxy-1,4-naphthoquinone-3-propanamide electropolymer monomer and immobilised it on the surface of a glassy carbon electrode, and then conjugated atrazine monoclonal antibody to the monoclonal monomer. The monoclonal antibody to atrazine is then bound to the hydroxylated atrazine on the electropolymer, and the atrazine standard is passed through the electrode. As the atrazine binds the antibody more strongly than the hydroxylated atrazine, the antibody is displaced from the electrode surface, and atrazine is then detected by square-wave voltammetry. This process utilises the electropolymerisation of the hydroxyl group, the transduction of the quinone group, and the role of hydroxylated atrazine as a bioreceptor. The detection range was from 0.1 pmol/L to 10 μmol/L, and the detection limit was 1 pmol/L. In addition, Sun et al. [18] used a novel non-labelled current-type immunosensor to quantitatively and ultrasensitively detect the insecticide carbufuran. The 4,4'-thiobiobenzenethiol (DM-DPSE) was combined with deposited gold nano-crystals (DpAc), which were used for the determination of the insecticide carbufuran, and the DpAc was used for the detection of the insecticide. DpAu) and gold nano crystals (DpAu) were modified onto the surface of the gold electrode by layer-by-layer assembly to form a {DpAu /DMDPSE}n/Au – modified electrode, and then the carbachol antibody was adsorbed onto the surface of the electrode by physical adsorption method for the detection of carbachol antibody. Under the optimal conditions, the detection range of carbufuran was 0.1-1.0×10⁶ ng/mL, and the limit of detection was 0.06

ng/mL. The recoveries of carbufuran in a series of real samples, such as lettuce and Chinese cabbage, ranged from 82.0% to 109.2%, and the standard deviations ranged from 3.15% to 5.23%, which demonstrated that the method is feasible for quantitative analysis of carbufuran and that the method has a wide range of detection capabilities, and is also suitable for quantitative analysis of carbufuran in a wide range of samples. This method has the advantages of wide detection range, good reproducibility and stability.

3.1.3 Impedance Immunosensor

Impedance, resistance, conductivity and capacitance are different detection systems, but they are closely related to each other. Some researchers [7] also refer to impedance sensors as conductance/resistance/capacitance sensors. Impedance immunosensors measure changes in the overall electric field, including the conductivity of the electrolyte and the interaction of antigens and antibodies on the electrode surface. Electrochemical impedance spectroscopy is a sensitive technique that uses periodic small amplitude alternating current (AC) signals to measure the electrical response of a system [7].

In recent years, electrochemical impedance has also been reported in the detection of pesticide residues. Ramón-Azcón et al. [19] applied a fork-finger array electrode to an impedance-type immunosensor and detected atrazine non-labelled with a limit of detection of 0.04 µg/L, which is much smaller compared to that of solid-state extraction; and Valera et al. [20] detected the herbicide atrazine in red wine by a conductivity-type immunosensor. Valera et al. [20] used a conductivity-based immunosensor to detect the herbicide atrazine in red wine. The lowest detection limits for gold nanoparticle-labelled antibodies were 0.034 µg/L (25 mV) and 0.489 µg/L (100 mV) at forked finger array electrodes at different potentials, and Ionescu et al [21]. Modified a layer of polypyrrole on the surface of a gold electrode, and after protein anchoring and binding of the antibody, an impedance immunosensor directly detected atrazine in the range of 10 pg/mL to 1 µg/mL. The detection range was from 10 pg/mL to 1 µg/mL, and the detection limit was 10 pg/mL, which highlights the high sensitivity of the impedance sensor. Jin et al. [22] used the furaltadone (5-morpholino-3-amino-2-oxazo-lidone) as a detection method for atrazine, and the detection limit was 10 pg/mL. Jin et al [22]. Immobilized the monoclonal antibody of furazolidone (5-morpholino-3-amino-2-oxazo-lidone (AMOZ))

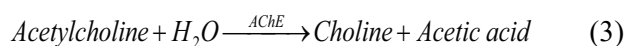
on the surface of gold electrode modified with gold nanoparticles using dimercaptothiol as a connecting layer, and detected furazolidone by an unlabelled impedance immunosensor, with the detection limit of 1.0 ng/mL, and the detection limit of 1.0 ng/mL in pig meat, shrimp, and pig intestine coat. The limits of detection were 1.0 ng/mL, and the recoveries ranged from 91.4% to 105.0% in six foodstuffs, including pork, shrimp, pig intestines, honey, egg and muscle.

3.2. Electrochemical enzyme sensors and their application in pesticide detection

The electrochemical enzyme sensors can also be classified into potentiometric and galvanometric types. Since there are comparatively few reports about potentiometric enzyme sensors in pesticide detection in recent years, the article mainly reviews the application of two galvanometric enzyme sensors, namely, dual enzyme-modified and single enzyme-modified ones, in pesticide detection.

3.2.1 Dual enzyme-modified electrochemical enzyme sensors

Acetylcholine esterase (AChE)-choline oxidase (ChO) dual enzyme sensor: The enzyme reaction process of AChE-ChO dual enzyme sensor is shown in Eqs. (3-4) [7], which includes two processes, the decomposition of acetylcholine by AChE and the oxidation of choline by ChO.

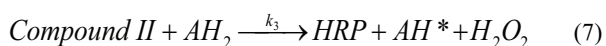


Lee et al. fixed ChO on the surface of gold electrode through the electrostatic effect of polylysine and the cross-linking effect of glutaraldehyde, and then combined AChE with different concentrations of diazinon-oxon (DZN) pesticide to inhibit AChE, and then fixed it on the surface of the electrode modified with ChO, and then put it in a phosphate buffer containing a certain amount of ferrocene and acetylcholine to carry on the electrochemical detection, which demonstrated that the measured electrical signals and the concentration of DZN showed a linear relationship with the linear range of 0-8 µmol/L [23]. The result of this study shows that the measured electrical signal and the concentration of DZN are in the same range as those of DZN, and the linear range is 0-8 µmol/L.

Organophosphorus hydrolase (OPH)-horseradish peroxidase (HRP) dual enzyme sensor: Unlike the

above dual enzyme system, the phenolic compounds produced after the hydrolysis of organophosphorus pesticides by OPH are used as an effective intermediary for electron transfer, shuttling between the electrode surface and the HRP, while the pesticide itself does not have any inhibitory effect on the OPH, and the electrical signals are different in the concentration of this intermediary, which enables the detection of pesticide residues accordingly.

Equations (5) to (7) are the reaction equations of OPH and HRP in the electrolysis process [24]. Among them, AH₂ is the intermediary of electron transfer, which is the product of OPH after hydrolysis of pesticides.



In order to extend the detection range of organophosphorus compounds, Sahin et al. used the OPH-HRP dual enzyme system for the determination of organophosphorus pesticides at low potential using the above principle. The limit of detection (LOD) and sensitivity (S/N=0.095±0.024) were 24 μmol/L and (0.095±0.024) nA/μM, respectively.

3.2.2 Monoenzyme - modified electrochemical sensors

The main enzymes immobilised on the surface of electrochemical sensors to detect pesticides are: acetylcholinesterase, alkaline phosphatase, acid phosphatase, tyrosinase, organophosphorus hydrolase, aldehyde dehydrogenase. Other enzymes include acetolactate synthase, glutathione S-transferase, ethanol dehydrogenase, carboxylesterase, etc. [24-25]. However, acetylcholinesterase, phosphohydrolase, tyrosinase, and tyrosinase are the most frequently used enzymes.

Cesarino et al. [26] mixed carbon nanotubes with polyaniline and modified a glassy carbon electrode, and then immobilised acetylcholinesterase on the surface of the electrode, and utilised carbon nanotubes to promote the electron transfer reaction and the high conductivity and stability of the electropolymer as well as the synergistic effect between the two to detect carbamate pesticides with a high degree of sensitivity. The detection limits of carbaryl and methomyl were 1.4 and 0.95 μmol/L, respectively, which

demonstrated the advantages of this kind of sensor. Mulchandani et al. [27] reviewed the electrochemical sensors based on organophosphorus hydrolases. In recent years, Lee et al. [28] used phosphate hydrolase to catalyse the decomposition of organophosphorus and produce electroactive substances that can undergo redox reactions on the electrode surface, and fixed carbon nanotubes on the electrode surface to detect organophosphorus pesticides directly. The results showed that the detection limit and sensitivity of this method were 0.12 μmol/L and 198 nA/μM for paraoxon, respectively.

Tyrosinase can catalyse the oxidation of phenolic substances in the presence of oxygen to produce o-quinone, and o-quinone can be reduced at a lower potential without the aid of any medium, so it can be quantitatively detected by detecting the changes in the amount of o-quinone reduced before and after the addition of pesticides. Liu et al. [29] fixed the tyrosinase and platinum nanoparticles on the surface of the glassy carbon electrode, and detected three kinds of pesticides, chlorpyrifos, bromopropylphos and marathion, with the use of o-quinone as a substrate. The detection limits were 0.2, 0.8 and 3.0 μg/L for chlorpyrifos, bromopropylphos and malathion, respectively. The sensitivity, reproducibility and stability of these sensors have been well demonstrated. Recently, researchers [30] investigated a new enzyme sensor, in which laccase was immobilised on the electrode surface by a new matrix-montmorillonite-supported ionic liquid phase (platinum nanoparticles and boron ethyl-3-methylimidazolium tetrafluoroborate ionic liquid phase), and the detection of mitochondria was based on the pesticide inhibition of the enzyme, and the limit of detection was obtained to be 2.35×10^{-7} mol/l, which was detected in the real samples, with results validated by high performance liquid chromatography, the results were verified by high performance liquid chromatography (HPLC), which fully demonstrated the advantages of the enzyme sensor.

Compared with other electrochemical sensors, the sensitivity of electrochemical enzyme sensors in the detection of pesticides is relatively insufficient, and the substances that can inhibit the enzyme activity may also be other metal cations, organic or inorganic substances, and many pesticides on the enzyme inhibition is irreversible, which leads to enzyme-modified electrodes for the detection of a sample of the specificity is not strong, and the need to be re-modified every time the detection of a sample, thus increasing the time of detection.

Other electrochemical sensors and their application in pesticide detection.

4.1 Nanomaterial based electrochemical sensors

Nanomaterials with strong adsorption capacity, high catalytic efficiency, large specific surface area, increased active sites due to incomplete coordination of surface atoms, high surface activity, and labelling of specific biomolecules have been widely used for amplification of biosensor signals.

Therefore, as shown in the Fig. 2, in recent years, it has been widely used in electrochemical sensors and electrochemical biosensor, for the detection of pesticides, which has greatly improved the sensitivity, stability, selectivity and reproducibility of the sensor.

Mani - sankar's group [32] used the functional groups on the surface of the electropolymer polyaniline and polypyrrole, which were immobilised on the surface of a glassy carbon electrode with multi-walled carbon nanotubes, and then immobilised the electropolymers under electrodeposition to detect some commonly used pesticides with the use of functional groups on the surface of the electropolymer and the electrocatalytic properties of the carbon nanotubes. The test showed that the most effective electropolymer was polyaniline, and the detection range of isoproturon and cypermethrin pesticides was 0.01-10 mg/L, with detection limits of 0.1 and 0.05 $\mu\text{g/L}$, respectively. Carbon nanotubes, with their unique properties, have gradually become one of the commonly used nanomaterials in electrochemical sensors. Parham et al. [33] directly immobilised zirconia nanomaterials on carbon paste electrodes and used zirconia's strong affinity for the phosphate group in methyl parathion for the detection of methyl parathion pesticides. The detection limit of this sensor was 2.0 ng/mL by using square wave voltammetry. Compared with them, Gong et al. [34], in order to further improve the sensitivity of pesticide detection, used zirconia and graphene nanosheets modified glassy carbon electrode for the detection of methyl parathion, with the lowest detection limit of 0.6 ng/mL, and the spiked recoveries of 96.5%~104.4%, which proved that this kind of sensor not only has a very good practicability but also shows that zirconia nanoparticles have a special affinity for methyl parathion. The test results not only proved the practicality of this sensor, but also showed that zirconia nanoparticles have special affinity for methyl parathion. However, since there are many types of organophosphorus pesticides,

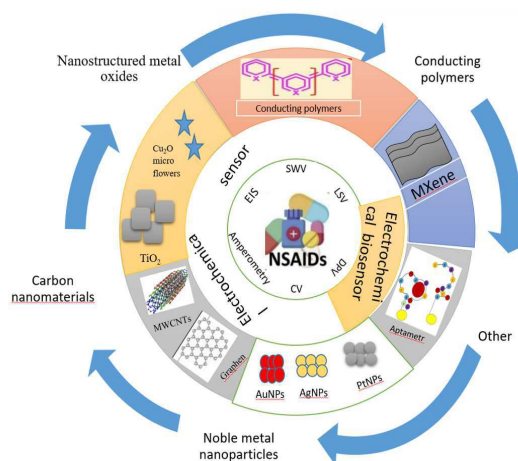


Fig. 2. Nanomaterial - based electrochemical sensors and electrochemical biosensor [10].

this type of sensor cannot accurately determine the different types of organophosphorus pesticides.

4.2 Molecularly imprinted electrochemical sensor

A commonly used method for the detection of pesticide residues is the molecularly imprinted electrochemical sensor. The detection method mainly uses the template molecules and the special bonding of the imprinted material, such as gel - sol mixed with the analyte, fixed on the electrode surface to form a molecular film, and then the analyte will be eluted, the analyte on the electrode to leave the vacancies that is molecularly imprinted, and then use these molecularly imprinted by electrochemical detection method of this analyte for highly sensitive, highly selective detection. In as early as 1999, Kroger et al. [35] proposed a fast and simple method for the detection of herbicides - molecularly imprinted method. Two different compounds, dichlorophenol and dihydroxyphenylacetic acid, were immobilised on a disposable printing electrode by a molecularly imprinted polymer as templates, and the binding ability of the analyte, dichlorophenol, and the electrically active probe, dihydroxyphenylacetic acid, to the imprinted polymer was determined after elution. This molecularly imprinted method was found to be selective, stable and reproducible, economical and short in detection time by differential pulse voltammetry. Zhang et al. [36] applied the molecularly imprinted method to detect parathion pesticide, and the results showed that the detection range of the pesticide was $1.0 \times 10^{-4} \sim 5.0 \times 10^{-7}$ mol/l, the limit of detection was 2.0×10^{-7} mol/l, and the recoveries of the actual samples were 98.0% ~ 104%, which proved the high selectivity and sensitivity of

this type of sensor. Yang et al. [37] detected parathion in vegetables by applying molecularly imprinted films of polyethyleneimine combined with silica gel, which also showed high selectivity. In addition to the above pesticides, the molecularly imprinted method has also been applied to the detection of atrazine [38], trichlorfon [39], and carbendazim [40].

5. Conclusion

Electrochemical sensors are widely used in pesticide residue detection due to their convenience, high sensitivity, low cost and practicality. In order to meet the needs of practical detection, electrochemical sensors are also developing rapidly. According to the current research status and practical development, electrochemical sensors in pesticide detection can be developed in the following aspects.

1) At present, the pesticides detected by electrochemical sensors are mainly organophosphorus, organochlorine and carbamate, while the research on organonitrogen, organometallic and pyrethroid pesticides is relatively small, and the expansion of pesticide detection is still one of the main directions for the development of electrochemical sensors.

2) Developing technologies that combine electrochemical sensors with other detection methods, such as surface plasmon resonance, can effectively expand their detection range and accuracy;

3) Development of more economical, simple and different types of electrodes, such as different types of screen-printed electrodes. The automation of multi-sample and multi-component detection will become a new trend in the application of electrochemical sensors. With the diversified development of electrochemical sensors and the maturity of new technologies, we believe that there is a broad prospect for the future application of pesticide detection.

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Достижения в области электрохимических сенсоров для обнаружения остаточных количеств пестицидов

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АННОТАЦИЯ

Пестициды играют важную роль в сельскохозяйственном производстве как эффективное средство быстрой и действенной борьбы с вредителями и болезнями. Однако их неправильное применение может привести к избыточному содержанию остатков пестицидов в окружающей среде и сельскохозяйственной продукции, что представляет большую угрозу экологической обстановке и здоровью людей. Поэтому необходимо создать новую методику анализа остатков пестицидов, которая была бы эффективной, чувствительной и практичной. Электрохимические сенсоры широко используются для обнаружения остатков пестицидов благодаря их высокой чувствительности, стабильности, селективности, простоте, быстродействию и низкой стоимости.

В данной статье рассматривается применение и ход исследований иммунных, ферментных, нано- и молекулярно-импринтированных электрохимических сенсоров для обнаружения остатков пестицидов, а также дается прогноз на будущее применение электрохимических сенсоров для обнаружения остатков пестицидов.

Ключевые слова: электрохимический сенсор, остатки пестицидов, продукты питания, иммунный сенсор, обнаружения.

Пестицидтердің қалдықтарын анықтаудағы электрохимиялық сенсорларды зерттеу барысы

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АННОТАЦИЯ

Пестицидтер зиянкестер мен аурулармен тез және тиімді күресудің тиімді құралы ретінде ауыл шаруашылығы өндірісінде маңызды рөл атқарады. Алайда, оларды негізсіз пайдалану қоршаған орта мен ауыл шаруашылығы өнімдерінде пестицидтер қалдықтарының шамадан тыс мөлшеріне әкелуі мүмкін, бұл экологиялық жағдайға және адам денсаулығына үлкен қауіп төндіреді. Сондықтан пестицидтердің қалдықтарын талдаудың тиімді, сезімтал және практикалық жаңа әдістемесін құру қажет. Электрохимиялық датчиктер жоғары сезімталдығы, тұрақтылығы, таңдамалылығы, қарапайымдылығы, жылдамдығы және арзандығына байланысты пестицидтердің қалдықтарын анықтау үшін кеңінен қолданылады. Бұл мақалада пестицидтердің қалдықтарын анықтауға арналған иммундық, ферменттік, нано- және молекулалық таңбаланған электрохимиялық датчиктер бойынша зерттеулердің қолданылуы мен барысы талқыланады, сонымен қатар пестицидтердің қалдықтарын анықтау үшін электрохимиялық сенсорларды болашақта қолдану болжамы қарастырылған.

Түйін сөздер: электрохимиялық сенсор, пестицид қалдықтары, тағам, иммундық сенсор, анықтау.