Microfluidics Techniques for Pesticide Residues Detection in Food

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Food safety is a significant issue that affects people worldwide and is tied to their lives and health. The issue of pesticide residues in food is just one of many issues related to food safety, which leave residues in crops and are transferred through the food chain to human consumption. Foods contaminated with pesticide residues pose a serious risk to human health, including carcinogenicity, neurotoxicity, and endocrine disruption. Although traditional methods, including gas chromatography, high-performance liquid chromatography, chromatography, and mass spectrometry, can be used to achieve a quantitative analysis of pesticide residues, the disadvantages of these techniques, such as being time-consuming and costly and requiring specialist staff, limit their application.

pesticide residues microfluidic rapid detection food samples

1. Introduction

Pesticides are crucial in contemporary agriculture because they prevent crop losses from pests. They also protect crop growth and yields. The wide application of new pesticides has improved agricultural production, but the food safety problem caused by them has attracted more and more attention. Pollution caused by pesticides has gradually become a global public health problem [1][2][3][4]. The excessive intake of pesticides seriously harms human health [5][6][7]. Overuse, heavy reliance, and improper processing have left residues in crops and enriched them in the human food chain [8]. The consumption of foods that are high in pesticides can cause endocrine disorders, cancer, and neurological diseases [9][10][11]. The risks posed by pesticide residues are more acute for children and expectant women [12][13]. The entire food business faces a severe challenge due to this focus. The food business and producers are subject to more intense scrutiny and demand to ensure the quality and safety of food due to greater regulatory enforcement and customer awareness. One of their most essential tasks is identifying pesticide residues in food to safeguard people's lives and health [14]. However, conventional pesticide detection technologies have numerous shortcomings that mean they cannot be used as rapid on-site detection technology [15][16][17].

The primary traditional methods for detecting pesticide residues are gas chromatography, high-performance liquid chromatography, and mass spectrometry [18][19][20][21]. These detection techniques have the advantages of accuracy and sensitivity. However, their sample processing and pretreatment procedure is complicated, time-consuming, expensive, and labor-intensive. As a result, traditional detection technology cannot meet the needs of consumers for the rapid and convenient detection of pesticide residues. Therefore, developing a technology that can rapidly, conveniently, efficiently, and sensitively detect pesticide residues in food is essential. The demand for point-of-care testing for food safety is answered by microfluidics. Microfluidics provides a platform for rapidly detecting trace pesticide residues with a small sample. Combining microfluidic technology with pesticide residue detection devices effectively overcomes the shortages of traditional methods and realizes on-site detection [22][23][24][25][26].

Microfluidics integrates various functional units in submillimeter microchannels for a variety of analytical chemistry operations such as purification [27][28], reaction [29][30], separation [31][32], and detection [33][34]. Microfluidic sensors have the advantages of high throughput, miniaturization, portability, and small reagent consumption [35][36][37][38][39][40][41], which can rapidly obtain more accurate detection results. It is significant for food safety to develop on-site detection technologies and portable equipment [42][43][44]. Microfluidic sensors can identify specific analytes through biomolecules and enhance them into detectable signals [45][46][47][48].

2. Microfluidic Devices for Pesticide Detection

2.1. Organophosphates Compounds

Pesticides with an organophosphate chemical as their primary component are known as organophosphate pesticides [49][50]. These insecticides are commonly used in horticulture and agriculture to improve crop yield and quality while controlling various pests and illnesses. Organophosphate pesticides primarily poison pests via acetylcholinesterase inhibition [51][52]. However, the nervous system of people might also be impacted by this [53]. Prolonged or excessive exposure to organophosphate residues may cause neurological symptoms such as headache, dizziness, nausea, vomiting, muscle cramps, neurasthenia, and memory loss [54][55][56]. There are numerous studies on the detection of organophosphate pesticides [57][58][59][60][61][62][63]. Shi and colleagues used phage and horseradish peroxidase to create an eco-friendly and safe electrochemical immunosensor [64].

A microfluidic device based on fluorescence intensity for quick pesticide residue detection in food has higher sensitivity compared to the conventional method [65][66][67][68][69][70][71], and Hu et al. (2019) developed a microfluidic array sensor based on QD-AchE aerogel that can detect organophosphates pesticide residues quickly and with high sensitivity [24]. Quantum dots' fluorescence intensity gradually increases with an increase in organophosphate concentration. Since acetylcholine catalyzes the production of thiochotine, organophosphates inhibit its activity and restore the fluorescence intensity of acetylcholine-quenched quantum dots. With detection limits of less than 1.2 pM and a detection range of 10^{-5} M–10^{-12} M, the researchers evaluated three popular organophosphate pesticides, including paraoxon, parathion, and dichlorvos. This further proved that the sensor has high sensitivity and a broad detection range.

Electrochemical technologies [72][73][74][75] are more straightforward and sensitive than fluorescence detection because they directly transform difficult-to-measure chemical parameters into simple-to-measure electrical ones. Common electrochemical identification techniques frequently demand intricate electrode production procedures and expensive detection costs. Yang et al. suggested a method for identifying pesticide residues based on multilayer paper-based microfluidic chips to address this issue [76]. After spraying pesticides on lettuce, the avermectin, phoxim, and dimethoate identification accuracy remained consistent at 93%. A stopper microfluidics-based organophosphate-pesticide-detecting system was created by Wang et al. (2014) [77].

2.2. Carbamate Compounds

Carbamate pesticides are widely used in agriculture and forestry because of their high selectivity, easy decomposition, little residual toxicity, and low toxicity to humans and animals [78][79][80][81]. However, carbamate pesticides with heavy usage in foods spread through the food chain and accumulate in the human body through the digestive system and the skin's mucous barrier [9][82][83][84]. In various studies, carbamate pesticides have been shown to quickly produce nitroso compounds with nitrite in food (bread, yogurt, cheese, soy sauce, and vinegar), which can substantially harm human health [85][86]. They are also mutagenic, teratogenic, and carcinogenic under acidic circumstances in the stomach [87]. In this case, some researchers have proposed various methods of detecting carbamate [88][89][90][91]. However, the sample handling and pretreatment steps required for these procedures are complex and time-consuming. To solve these problems, desirable methods like fluorescence, colorimetry, and electrochemistry were proposed with high sensitivity and rapidity [92][93][94].

Microfluidic devices [95][96] offer a viable solution to achieve the detection of carbamate and overcome the issues associated with complex procedures and transportation. Interestingly, microfluidics widely utilize unitary and multiple signal readouts [97][98][99][100][101]. For instance, based on colorimetry, M.D. Fernández-Ramos (2020) suggests a bioactive microfluidic paper device for pesticide determination in water [102]. The proposed device contains three independent regions: a μPAD at the bottom for sampling, two microchannels separated by deposited acetylcholinesterase and AChCl solutions, and a top μPAD containing a pH indicator for detection. The paper device, working at room temperature, sets the reducing reaction's rate as an analytical signal to be quantified based on the color of μPAD.

Meanwhile, multiple readouts are successfully utilized to achieve the detection of carbamate, increasing sensitivity and integration. Zhao et al. (2021) built a portable automatic double-readout detector integrated with a 3D-printed microfluidic nanosensor on the foundation of the colorimetric method [23].

2.3. Other Pesticides

Organochlorine pesticides are organic compounds containing chlorine in their chemical structure, which are fat-soluble and kill insects by interfering with the function of the nervous system [103][104][105][106][107]. They are widely used worldwide because of their low price, broad spectrum of insecticidal efficiency, and ease of use. The excessive use of organochlorine pesticides will not only affect the environment but also cause harm to the human body [108][109][110]. Organochlorine pesticides mainly affect human health through food, respiration, and skin contact and can destroy certain hormones, enzymes, growth factors, and neurotransmitters in the body. Changes in relative homeostasis conditions within cells lead to oxidative stress and rapid cell death, leading to Parkinson's [111], cancer [112], and endocrine and reproductive diseases.

In order to detect organochlorine pesticide residues, many people have carried out research. Malik et al. successfully determined organochlorine pesticide residues using an electron capture detector (GC-ECD) in 2011 [113], and Chowdhury et al. achieved the same in 2013 using gas chromatography–tandem mass spectrometry (GC-MS) [114]. However, the testing equipment used requires professional personnel to operate it, and the equipment is expensive.

Pyrethroid pesticides are synthesized by simulating the chemical structure of natural pyrethroids, also known as biomimetic synthetic pesticides. They have a wide insecticidal spectrum, high efficacy, sterilization, and mold inhibition [115]. Pyrethroids have effectively reduced the incidence of malaria in Africa and other places [116], but overuse has seriously affected people's health, causing cardiovascular diseases, reproductive diseases, and so on [117][118][119][120][121]. Pyrethroid analysis is routinely used in gas chromatography–electron capture detector (GC-ECD), gas chromatography–mass spectrometry (GC-MS), liquid chromatography–ultraviolet (LC-UV), and liquid chromatography–mass spectrometry (LC-MS). The instrument technologies mentioned above have high accuracy and precision, good sensitivity, and very low detection limits, but they are expensive, complex to operate, and unsuitable for most environments.

2.4. Commercialized Products

For the quick and precise detection of pesticides in food and environmental samples, a number of microfluidic devices have been developed. The portable, highly sensitive My-coLab^{TM} AflaQuick^{TM} by EnviroLogix Inc. can identify aflatoxins in just 10 min. EnviroLogix Inc.'s Quick^{TM} has a high sensitivity and mobility level and can detect aflatoxins in under 10 min. Multiplexed pesticide detection is available with the Advanced Animal Diagnostics Raptor^{TM} Integrated Analysis Platform, although it is more expensive and demands specialist training. Pesticide identification is possible with the Biosensing Instrument Inc. ToxiQuant^{TM} Pesticide Microarray Kit. However, it requires refrigeration and has longer test times. The portable microfluidic sensor with SERS technology from GBC Scientific Equipment allows for label-free detection but calls for SERS equipment. The RapidChek® SELECT^{TM} Salmonella from Romer Labs quickly identifies salmonella but has low sensitivity. Although it needs specialist equipment, Detection's BioFlash Biological Identifier offers quick and sensitive findings. Mass spectrometry equipment is necessary for the ATHENA Integrated System, a lab-on-a-chip with quick results and customizable choices.

The microfluidic devices mentioned above have special features and capabilities to detect pesticides in food and environmental samples. While each technology has benefits like quick results, portability, and customizability choices, it also has drawbacks like con-strained detection targets, reduced sensitivity, the need for specialized equipment, and a range of prices. These aspects are important when choosing the best microfluidic device to meet the unique pesticide detection and food safety application demands.

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