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Advances in Nanotechnology-Based Biosensors for Aflatoxin Detection in Food Safety

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Abstract

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Food safety is a critical global issue, particularly regarding mycotoxin contamination such as aflatoxins, which are harmful to human health. This study aims to examine the development of biosensor technology for aflatoxin detection and to evaluate its potential application in food safety systems. The method used was a literature review of relevant scientific publications from the past five years. The results of the study indicate that biosensors, particularly those based on electrochemistry and aptamers, offer advantages in sensitivity, selectivity, and detection speed compared with conventional methods. The integration of nanotechnology, such as the use of nanoparticles and carbon-based materials, has proven capable of significantly enhancing biosensor performance. Furthermore, the development of multi-mode biosensors and their integration with digital systems offers opportunities for the development of more efficient and real-time detection systems. However, several challenges remain, such as sensor stability and application to complex samples. Therefore, further research is needed to optimize biosensor performance so that they can be widely applied to support food safety.

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1. Introduction

Food safety is one of the global issues that continues to grow and is a major concern in various sectors, including public health and the food industry. One of the most significant problems in this context is the contamination of food by mycotoxins, specifically aflatoxins, produced by fungi of the genus *Aspergillus*. Aflatoxin is known as a toxic compound that has carcinogenic, mutagenic, and immunosuppressive effects, so it has the potential to have serious impacts on human and animal health. This contamination generally occurs in food products such as grains, nuts, and their derivative products, especially in inappropriate storage conditions or environments with high humidity (Haque et al., 2020; Janik et al., 2020).

The high risk of exposure to aflatoxin makes the detection of this compound an important step in ensuring food safety. A variety of conventional methods have been developed to detect aflatoxin, including high-performance liquid chromatography (HPLC), gas chromatography (GC), and enzyme-linked immunosorbent assay (ELISA). Although the method has a high level of accuracy, its use still faces a number of limitations, such as high operational costs, relatively long analysis times, and the need for complex laboratory equipment and trained experts. This makes conventional methods less efficient for rapid detection applications in the field or on a wide scale (Yin et al., 2022).

Along with the development of science and technology, biosensors have emerged as a promising alternative detection method. A biosensor is an analytical device that combines biological elements, such as enzymes, antibodies, or nucleic acids, with a transducer system to produce a signal that can be measured quantitatively. The main advantage of biosensors lies in their ability to provide results quickly, sensitively, and portablely. In addition, biosensors also allow real-time detection, making them ideal for applications in food safety surveillance (Liu et al., 2020).

The development of biosensors is accelerating with the integration of nanomaterial technology. Nanotechnology makes a significant contribution to improving the performance of biosensors, especially in terms of sensitivity, selectivity, and detection limits. The use of metal nanoparticles, carbon-based materials, and aptamer-based technologies has allowed for increased interactions between analytes and bioreceptors. In addition, the high surface area to volume ratio of nanomaterials also supports increased detection process efficiency. Thus, nanotechnology-based biosensors are capable of detecting aflatoxin at very low concentrations with a high degree of accuracy (Guo et al., 2020).

In addition to nanotechnology, the development of biosensors is also supported by advances in the fields of electrochemistry and molecular biotechnology. Electrochemical biosensors, in particular, have been widely developed because they have advantages in terms of sensitivity and ease of integration with electronic devices. On the other hand, the use of aptasensors based on aptamers as biological identifying elements provides a more stable and specific alternative to conventional antibodies. Recent studies have shown that aptamer-based biosensors and electrochemicals have great potential in detecting aflatoxin quickly and accurately (Wang et al., 2020).

Nonetheless, the development of biosensors for aflatoxin detection still faces a number of challenges. Some of these include the long-term stability of the sensor, the reproducibility of the measurement results, and the ability to be applied to complex real samples. In addition, the integration of biosensors with modern digital systems such as the Internet of Things (IoT) also still requires further development in order to support a more efficient and integrated monitoring system (Ciobanu et al., 2023).

Based on this background, this study aims to examine the development of biosensor technology in the detection of aflatoxin and evaluate its potential application in supporting food safety systems in general. By understanding the latest technological developments and existing challenges, it is hoped that this research can contribute to the development of more effective, sensitive, and applicable detection methods in the future.

2. Literature Review

2.1. Biosensors in Aflatoxin Detection

Biosensors have developed as one of the innovative analytical technologies in detecting food contaminants, including aflatoxin. In general, a biosensor is a device that integrates biological elements with a transduction system to produce a signal that can be measured quantitatively. Biological elements such as enzymes, antibodies, or aptamers serve as specific identifiers to target analytes, while transducers convert those biological interactions into electrical, optical, or other signals (Liu et al., 2020).

This approach allows for faster and more sensitive detection than conventional methods.

In the context of aflatoxin detection, biosensors offer a range of advantages, such as real-time detection capabilities, relatively small sample requirements, and the potential for portable use in the field. Electrochemical-based biosensors are one of the most developed types because they have high sensitivity and ease of integration with electronic devices. In addition, optical and piezoelectric biosensors have also been used in various studies to improve the accuracy of aflatoxin detection (Wang et al., 2020).

Recent developments show that the use of aptamers as biological identifying elements provides a more stable alternative to antibodies. Aptamers are synthetic oligonucleotides that have a high affinity for specific targets, so they can increase the selectivity of biosensors. In addition, aptasensors also have advantages in terms of chemical stability and ease of modification, so they are widely used in the development of modern biosensors for aflatoxin detection (Ciobanu et al., 2023). With these various advantages, biosensors are a promising solution in improving the efficiency and effectiveness of aflatoxin detection in food safety systems.

2.2. The Role of Nanotechnology in the Development of Biosensors

The development of nanotechnology has made a significant contribution to improving the performance of biosensors, especially in aflatoxin detection. Nanomaterials such as metal nanoparticles, graphene, and carbon nanotubes have unique properties, such as a high surface area to volume ratio and good electrical conductivity. These properties allow for increased interaction between the analyte and the bioreceptor, thereby increasing the sensitivity and detection limits of the biosensor (Guo et al., 2020).

The use of gold and silver nanoparticles, for example, has been widely applied in biosensors due to their ability to enhance detection signals as well as facilitate the immobilization of biomolecules. In addition, nanomaterials also allow miniaturization of biosensor devices, so that they can be developed into portable detection systems that are practical and efficient. This is especially important in rapid detection applications in the field, especially in food safety surveillance (Kadam & Hong, 2022).

In addition to improving sensitivity, nanotechnology also plays a role in the development of multi-mode-based biosensors, which are biosensors that combine more than one detection method, such as electrochemistry and colorimetry. This approach allows for increased accuracy and reliability of detection results. Some recent research suggests that the integration of nanotechnology in biosensors can result in faster, more selective detection systems, and has very low detection limits for aflatoxin (Yin et al., 2022; Zhang et al., 2023). Thus, nanotechnology plays an important role in driving modern biosensor innovation, particularly in improving its performance and applicability in the detection of food contaminants. The integration between biosensors and nanotechnology is expected to result in a more efficient detection system that can be widely implemented in a variety of conditions.

3. Methods

This study uses a literature study method that aims to comprehensively examine the development of biosensor technology in aflatoxin detection based on relevant scientific sources. The literature study method was chosen because it allows researchers to collect, analyze, and synthesize various previous research findings in order to gain an in-depth understanding of the topic being studied. The research process began with the identification of topics and the formulation of study focuses related to biosensors, aflatoxin, and the development of nanotechnology-based detection technology.

The next stage is data collection through searching scientific literature obtained from academic databases such as Elsevier, ResearchGate, Google Scholar and others. The inclusion criteria used in the selection of literature sources include scientific articles published in the last five years, have relevance to the topic of biosensors and aflatoxin, and come from reputable journals. The literature sources used include review articles and research articles that discuss the working principles of biosensors, types of biosensors, applications in aflatoxin detection, and the development of nanomaterial technology that supports the performance of biosensors.

After the data collection process, the literature selection and classification stage was carried out based on the suitability of the content with the focus of the research. The selected literature is then analyzed descriptively by identifying the main concepts, methods used, and reported research results. The analysis was carried out by comparing the various approaches used in the development of biosensors, including their advantages and limitations, so that a comprehensive picture of the trends and developments of existing technology can be obtained.

Furthermore, the process of information synthesis is carried out by integrating the results of analysis from various library sources into a systematic framework of understanding. This synthesis aims to identify patterns, relationships, and research gaps that still need to be studied further. In this process, the researcher also evaluates the consistency of the research results and the relevance of the technology developed to the need for aflatoxin detection in the context of food safety.

The final stage of this research method is the preparation of the results of the study in the form of a structured scientific narrative. All the information that has been analyzed and synthesized is presented systematically to provide a clear picture of the development of biosensors and their potential applications in aflatoxin detection. By using the literature study method, this research is expected to be able to contribute in the form of a comprehensive understanding and become the basis for further research in the development of more effective and applicable biosensor technology.

4. Results

The results of the literature review show that the development of biosensor technology in aflatoxin detection has made very significant progress in recent years. This is driven by the growing need for fast, sensitive, and widely applicable detection methods in food safety systems. Biosensors have evolved from simple technologies to complex detection systems with the integration of various disciplines, including biotechnology, analytical chemistry, and nanotechnology. Different types of biosensors have been developed to detect aflatoxin with different characteristics, both in terms of working principle, type of transducer, and biological identifying element used (Liu et al., 2020).

One of the most widely developed types of biosensors is electrochemical biosensors. This type of biosensor works based on changes in electrical signals generated due to the interaction between the analyte and the bioreceptor. The main advantages of electrochemical biosensors are high sensitivity, fast response times, and ease in miniaturizing devices. In addition, electrochemical biosensors are also relatively easy to integrate with electronic systems, so they have great potential to be developed into portable devices. Various studies have shown that electrochemical biosensors are capable of detecting aflatoxin at very low concentrations with a high degree of accuracy (Wang et al., 2020; Zhang et al., 2023).

In addition to electrochemical biosensors, optical biosensors are also widely used in aflatoxin detection. Optical biosensors work based on changes in optical properties, such as absorbance or fluorescence, that occur as a result of the interaction between analytes and biological elements. The advantage of optical biosensors lies in their ability to provide fast results and do not require direct contact with the sample. However, in some cases, optical biosensors require relatively complex additional equipment, so their use is still limited to specific laboratories. However, the development of optical technology continues to improve, especially with the integration of nanomaterials that can improve detection sensitivity (Kadam & Hong, 2022).

The use of bio-identifying elements in biosensors has also undergone significant development. Initially, antibodies were the most widely used element because they had a high specificity to the target analyte. However, in recent years, the use of aptamers as an alternative to antibodies has been increasing. Aptamers are synthetic oligonucleotide molecules that have the ability to bind specifically to specific targets. The advantages of aptamers over antibodies include higher stability, lower production costs, and ease of chemical modification. This makes aptamer an attractive option in the development of modern biosensors for aflatoxin detection (Ciobanu et al., 2023).

The development of nanotechnology has made a huge contribution to improving the performance of biosensors. Nanomaterials such as gold nanoparticles, silver nanoparticles, graphene, and carbon nanotubes have been widely used in the development of biosensors because they have unique physical and chemical properties. One of the main advantages of nanomaterials is their high surface area to volume ratio, thus improving the interaction between the analyte and the bioreceptor. In addition, nanomaterials also have good electrical conductivity, so they can improve detection signals on electrochemical biosensors (Guo et al., 2020).

The use of gold nanoparticles in biosensors, for example, has been shown to significantly improve the sensitivity of aflatoxin detection. Gold nanoparticles can be used as a platform for biomolecular immobilization, thereby improving the stability and efficiency of interactions between analytes and bioreceptors. In addition, gold nanoparticles can also serve as signal amplifiers in detection systems, thus enabling the detection of aflatoxin at very low concentrations (Kadam & Hong, 2022). The use of other nanomaterials, such as graphene and carbon nanotubes, has also shown promising results in improving the performance of biosensors, especially in terms of conductivity and stability.

In addition to improving sensitivity, nanotechnology also allows the development of multi-mode-based biosensors, i.e. biosensors that combine more than one detection method. This approach allows for increased accuracy and reliability of detection results. For example, the combination of electrochemical and colorimetric methods can provide more comprehensive results than using a single method. Several studies have shown that multi-mode biosensors are able to detect aflatoxin with lower detection limits and have a higher level of selectivity (Yin et al., 2022; Zhang et al., 2023).

In addition, the development of biosensor technology has also led to integration with digital systems, such as the Internet of Things (IoT). This integration allows for real-time and remote monitoring of aflatoxin contamination, making it very useful in food safety surveillance systems. Despite this, the development of IoT-based biosensors still faces various challenges, such as the need for stable systems, low energy consumption, and guaranteed data security (Ciobanu et al., 2023).

The results of the study also show that although biosensors have many advantages, there are still some limitations that need to be considered. One of the main challenges is the long-term stability of the sensor. Some biosensors experience a decrease in performance after being used for a certain amount of time, especially those that use biological elements that are susceptible to changes in environmental conditions. In addition, the reproducibility of measurement results is also an important concern, especially in industrial-scale applications (Liu et al., 2020).

In addition, the application of biosensors on complex real samples is also still a challenge in itself. Food samples generally contain various other compounds that can interfere with the detection process, so a biosensor system that has high selectivity is needed. Several studies have developed strategies to address this problem, such as the use of nanomaterials and sample purification techniques, but more research is still needed to improve the performance of biosensors in real-world conditions (Haque et al., 2020). Recent developments also show that there are innovations in the use of CRISPR-based technology in biosensors. This technology allows the detection of aflatoxin with a very high level of sensitivity as well as good specificity. Although still in the development stage, CRISPR-based biosensors have great potential to be a future solution in the detection of food contaminants (Wu et al., 2023).

In addition, immunosensor-based biosensors are also still widely used because they have high reliability in detecting aflatoxin. Immunosensors utilize antigen-antibody interactions to detect the presence of target analytes. Despite having advantages in terms of specificity, immunosensors still face limitations in terms of stability and production costs, so they need to be further developed to compete with other biosensor technologies (Chen et al., 2023).

Based on the research that has been conducted, the results of the study show that biosensors have great potential in supporting faster, sensitive, and more efficient aflatoxin detection systems. The integration of various technologies, such as nanotechnology, biotechnology, and digital systems, has driven the development of biosensors towards more sophisticated and applicative detection systems. However, further research efforts are still needed to address the various existing challenges, so that biosensors can be widely implemented in food safety systems in the future (Sun et al., 2023).

5. Discussion

Based on the results of the literature review, it can be understood that biosensors have great potential in supporting aflatoxin detection systems that are more effective than conventional methods. The main advantage of biosensors lies in their ability to deliver results quickly, sensitively, and portablely. This makes biosensors a relevant solution in answering increasingly complex food safety challenges. Compared to conventional methods that require long analysis time and complex laboratory equipment, biosensors offer higher efficiency as well as flexibility in their use (Liu et al., 2020).

In addition, the development of biosensors is inseparable from the contribution of nanotechnology that significantly improves sensor performance. The use of nanomaterials has been proven to be able to improve the sensitivity and selectivity of biosensors through increasing surface area and material conductivity. This allows the detection of aflatoxin at very low concentrations, which was previously difficult to achieve with traditional methods. The integration of nanotechnology has also allowed the development of smaller, lighter, and portable biosensors, so that they can be used directly in the field (Guo et al., 2020).

Nevertheless, although biosensors show significant advantages, there are still some challenges that need to be considered. One of the main challenges is the stability of biological elements used in biosensors, such as antibodies and enzymes, which tend to be sensitive to environmental changes. Conditions such as temperature, pH, and humidity can affect the performance of the biosensor, so it is necessary to develop new materials or methods that can improve the stability of the sensor in the long term. In addition, the reproducibility of the results is also an important factor that must be considered so that biosensors can be widely used in industrial applications (Wang et al., 2020).

Another challenge is the application of biosensors on real samples that have complex matrices. Under real conditions, food samples contain various compounds that can interfere with the detection process, thereby reducing the accuracy of measurement results. Therefore, strategies are needed to increase the selectivity of biosensors, such as the use of aptamers or a combination with sample purification techniques. The development of aptamer-based biosensors has shown promising results in improving the specificity and stability of sensors compared to conventional antibodies (Ciobanu et al., 2023).

In addition to the technical aspect, the integration of biosensors with digital technology is also an important factor in the development of modern detection systems. The use of Internet of Things (IoT)-based systems allows real-time and integrated monitoring of aflatoxin contamination. This can improve the efficiency of the food surveillance system and allow for a faster response to potential contamination. However, the implementation of this technology still requires further development, especially in terms of energy efficiency, data security, and system compatibility (Kadam & Hong, 2022). Biosensors have very promising prospects in supporting food safety systems in the future. Despite the ongoing challenges, ongoing technological developments show that biosensors have the potential to be a primary detection method that is faster, more sensitive, and more applicable than conventional methods.

6. Conclusion

Based on the results of the study conducted, it can be concluded that biosensors are a highly promising technology for the rapid, sensitive, and efficient detection of aflatoxins. Advances in biosensors, supported by progress in nanotechnology and biotechnology, have led to various innovations in detection systems capable of overcoming the limitations of conventional methods. Biosensors not only offer advantages in terms of speed and accuracy but also enable portable use, allowing them to be applied directly in the field. Various types of biosensors, such as electrochemical, optical, and aptamer-based biosensors, have demonstrated good performance in detecting aflatoxins at low concentrations. The integration of nanomaterials into biosensors has proven capable of enhancing the sensitivity, selectivity, and stability of detection systems.

Furthermore, the development of multi-mode biosensors and their integration with digital technology offers opportunities to create more modern and integrated monitoring systems. Nevertheless, several challenges remain to be addressed, such as sensor stability, reproducibility of results, and application to complex real-world samples. Therefore, further research is needed to optimize biosensor performance for widespread implementation in food safety systems. With continued development, biosensors are expected to become a primary solution in supporting aflatoxin detection in the future.

References

Chen, X., Wu, H., Tang, X., Zhang, Z., & Li, P. (2023). Recent advances in electrochemical sensors for mycotoxin detection in food. *Electroanalysis*, *35*(2), e202100223.

Ciobanu, D., Hosu-Stancioiu, O., Melinte, G., Ognean, F., Simon, I., & Cristea, C. (2023). Recent progress of electrochemical aptasensors toward AFB1 detection (2018–2023). *Biosensors*, *14*(1), 7.

Guo, X., Wen, F., Zheng, N., Saive, M., Fauconnier, M. L., & Wang, J. (2020). Aptamer-based biosensor for detection of mycotoxins. *Frontiers in Chemistry*, *8*, 195.

Haque, M. A., Wang, Y., Shen, Z., Li, X., Saleemi, M. K., & He, C. (2020). Mycotoxin contamination and control strategy in human, domestic animal and poultry: A review. *Microbial pathogenesis*, *142*, 104095.

Janik, E., Niemcewicz, M., Ceremuga, M., Stela, M., Saluk-Bijak, J., Siadkowski, A., & Bijak, M. (2020). Molecular aspects of mycotoxins—A serious problem for human health. *International journal of molecular sciences*, *21*(21), 8187.

Kadam, U. S., & Hong, J. C. (2022). Advances in aptameric biosensors designed to detect toxic contaminants from food, water, human fluids, and the environment. *Trends in Environmental Analytical Chemistry*, *36*, e00184.

Liu, D., Li, W., Zhu, C., Li, Y., Shen, X., Li, L., ... & You, T. (2020). Recent progress on electrochemical biosensing of aflatoxins: A review. *TrAC trends in analytical chemistry*, *133*, 115966.

Sun, L., Li, R., Tai, B., Hussain, S., Wang, G., Liu, X., & Xing, F. (2023). Current status of major mycotoxins contamination in food and feed in Asia─ a review. *ACS Food Science & Technology*, *3*(2), 231-244.

Wang, Q., Yang, Q., & Wu, W. (2020). Progress on structured biosensors for monitoring aflatoxin B1 from biofilms: a review. *Frontiers in microbiology*, *11*, 408.

Wu, Z., Sun, D. W., Pu, H., & Wei, Q. (2023). A novel fluorescence biosensor based on CRISPR/Cas12a integrated MXenes for detecting Aflatoxin B1. *Talanta*, *252*, 123773.

Yin, S., Niu, L., & Liu, Y. (2022). Recent progress on techniques in the detection of aflatoxin B1 in edible oil: a mini review. *Molecules*, *27*(19), 6141.

Zhang, H., Ye, S., Huang, L., Fan, S., Mao, W., Hu, Y., ... & Fu, F. (2023). An electrochemical biosensor for the detection of aflatoxin B1 based on the specific aptamer and HCR biological magnification. *Analytical methods*, *15*(1), 99-108.