Nanosensors Based on Lignocellulosic Materials

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In recent years, lignocellulosic materials have become regarded as attractive and noteworthy natural resources owing to their renewability, recyclability, easy processability, abundance, biodegradability, and low cost. The developments in nanotechnology have opened new doors in the field of bio-based nanosensor technology, which is utilized in electronics, optical products, communication, automotive, packaging, tissue engineering, biomedical, textile, *etc.* This paper mainly focuses on the usage of lignocellulosic materials in nanosensors.

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Sensor Terminology and Classification

Recently, nanotechnology has shown great progress in its development and applications, which include biosensing, theragnostic tests, drug delivery, and biomedical imaging. Sensors answer to different stimulating factors and are found to determine external factors such as light, motion, humidity, temperature, sound, or chemicals (Langari *et al*. 2023). Sensors can be divided into physical and chemical, pressure/strain, proximity, temperature, humidity, gas, and biosensors. They have been designed and developed by using nanomaterials (NMs) and bio-nanomaterials. Among these types of sensors, biosensors are analytical devices that can define specific analytes using biological molecules and convert them into quantifiable signals using some kinds of technical mechanisms such as thermal, optical, or electrochemical (Durmaz *et al*. 2023). Biosensors are also important for detecting various bio-based ingredients in clinical, forensics, pharmaceutical, food quality, and environmental tracking (Mercy *et al*. 2023).

Biosensors

Biosensors can be categorized depending on their size, form, and structure. As shown in Fig. 1, there are six main components of a biosensor: i) analyte, ii) detected and measured substance, iii) receptor that communicates with the target, iv) transducer transforming the feature of the sample into a signal, v) electronic component tracing these signals, and vi) a display unit/detector to view the analog (Mercy *et al*. 2023). The biosensors are divided depending on the bioreceptor and transducer. Under the category of bioreceptor, the biosensors are sub-divided into immunosensors, enzymatic biosensors, aptamers-based biosensors, nucleic acid biosensors, *etc*. Under the category of transducer, they can be subdivided into electrochemical biosensors, optical biosensors, thermal biosensors, and acoustic biosensors. However, some biosensors are subdivided based on detection procedures, including electrical, optical, thermal, acoustic, magnetic, and mechanical biosensors. Biosensors have been developed for some biomedical applications (Kumar *et al*. 2022; Mercy *et al*. 2023; Harini *et al*. 2023). The electrochemical biosensors can be divided into potentiometric, amperometric, voltammetric, impedimetric, and conductometric biosensors. The optical biosensors can be divided into fluorescence-based biosensors, chemiluminescence-based, SPR-based, and optical fiber-based (Mercy *et al*. 2023).

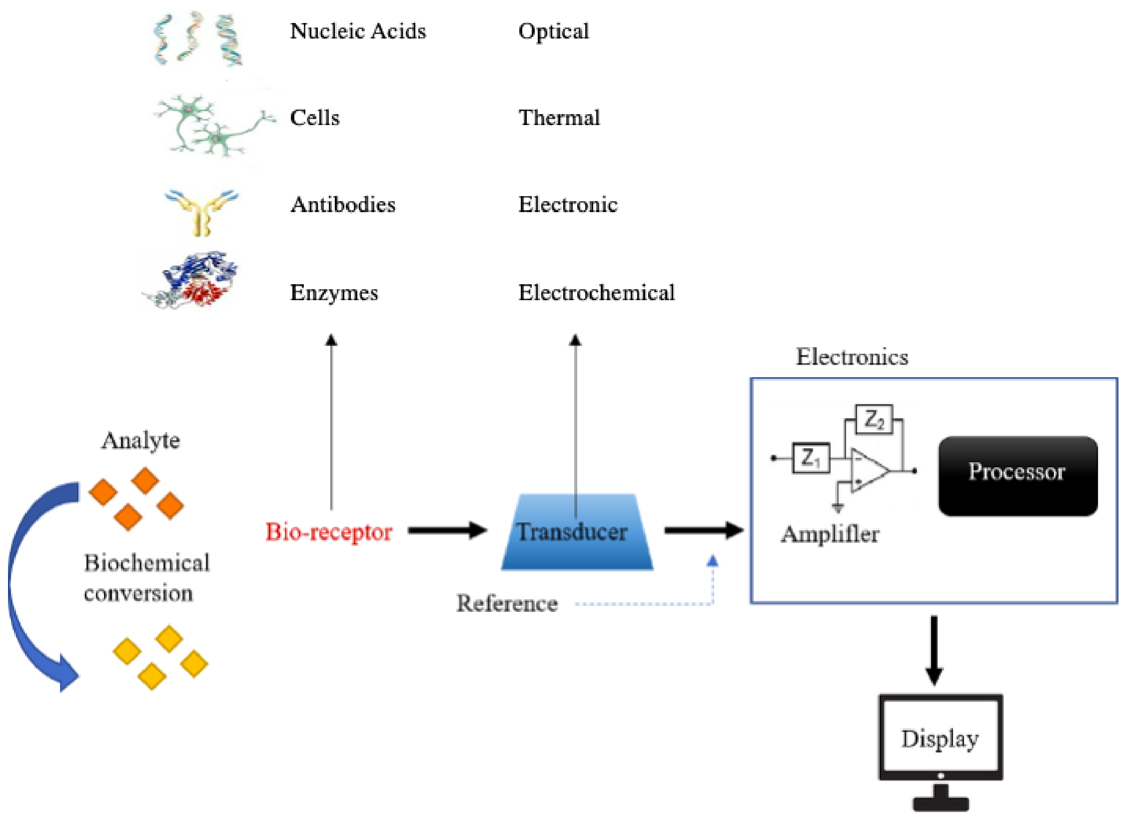

Fig. 1. Principle of biosensors (Reproduced from Mercy *et al*. 2023)

Lignocellulosic NMs-reinforced Nanosensors

NMs have been synthesized and designed to improve the performances of the nanosensors. Due to the advanced physicochemical features, NMs have been used in the sensor technology area. Because of the toxic effects of some NMs on the environment and human health, researchers have considered using bio-nanomaterials generated from natural sources. Recently, the development of sensors based on nanomaterials, especially cellulose and its derivatives have gained attention in biomedical research to monitor and manage human health (Durmaz *et al*. 2023). Some nanocellulose-based materials have excellent mechanical, thermal, chemical, physical, and barrier properties and they are chemically inert (Reshmy *et al*. 2020). For example, nanocellulose (NC)-based hydrogels have prominent features and a wide range of functionalities that are outstanding in the development of flexible strain biosensors. Based on the type of bio-transducer used, cellulose-based biosensors can be divided into two categories: electrochemical and optical biosensors. A biosensor generally has three parts: a biologically active element immobilized on a suitable component such as cellulose or its derivatives, a transducer, and a signal processor. An enzyme, antibody, protein, entire cell, or DNA can be the physiologically active ingredient (Monosík *et al*. 2012; Lopez-Blanco *et al*. 2019; Reshmy *et al*. 2020; Kumar *et al*. 2022; Candan *et al*. 2022; Durmaz *et al*. 2023; Harini *et al*. 2023; Mercy *et al*. 2023; Abolore *et al*. 2024).

NC hydrogel-based biosensors are ideal for point-of-care diagnostic devices due to their biocompatibility and ability to ensure rapid and certain results. They are also valuable for detecting environmental pollutants or toxins. Glucose biosensors and pH sensors can also be improved using cellulose hydrogels, which are important for monitoring blood glucose levels in diabetic patients and detecting pH variations (Monosík *et al*. 2012; Lopez-Blanco *et al*. 2019; Abolore *et al*. 2024). For example, Neubauerova *et al*. (2020) studied the colorimetric-based biosensor using nanocellulose-based supports for glucose detection in point-of-care testing. Microcrystalline cellulose (MCC) samples were TEMPO-oxidized, sodium hypochlorite, and potassium bromide to have carboxylated nanocellulose. The NC-based biosensor was developed for detecting glucose in the urine samples of diabetes. The biosensor was designed by structuring GOx on the carboxyl-NC/cellulose substrate. The test strip was calibrated by incubating it in different concentrations of glucose. The test results showed that 1.5 to 13.0 mM linear response was determined for glucose. Zhao *et al.* (2021), designed and developed cellulose-based electronic skin with an impressive ability to detect external environmental changes using pure cellulose. The electronic skins were designed to be most especially sensitive to changes in the external environment, affected by the rapid transit of ions between epidermal neurons in human skin.

Discussion and Future Aspects

Nanosensors span a wide range of diverse fields, involving electrical engineering, physics, biology, materials science, and biochemistry. This can involve several fundamental ideas that underpin nanomaterials, nanotechnology, and their crucial function in novel sensing properties and uses. At the nanoscale, this technique handles exciting transdisciplinary scientific and technical knowledge to collect fundamental physical distinctions on nanosensors. Chemical and biological procedures can be researched at a level and in a dimension made possible by nanosensors. Nanoparticles can be preferred to create laboratory-on-a-chip biosensors to observe water quality and health, as well as gas/vapor sensors the size of an ultrasonic stamp. Because of their inherent small size and special magnetic, optical, catalytic, and mechanical properties, optical nanotechnology and nanosensors have advanced tremendously. Information about nanoparticles is transferred to the macroscopical environment *via* any operational, biological, or chemical point. These are mostly used in the biomedical, health, and nanotechnology industries as well as in the synthesis of other nanoproducts. The utilization of nanosensors in diverse bio fabrication procedures amplifies tissue production; advancements in bioprinting science and technology can augment nanosensor production for more intricate and audacious objectives.

Although nanosensors have the potential to help data-driven decision-making improve the quality of human life and shape the future, there are some factors to be considered. Making sure the data is accurate and reliable is one of the biggest problems. Accumulating and transmitting large amounts of sensitive information raises concerns regarding data privacy and security. Data validation and interpretation become essential to maintain data integrity as nanosensors become more complex. As to materials used in nanosensor development, bio-nanomaterials should be considered to overcome the inhibitions of inflexibility and brittleness of some sensing equipment used in the human body. Thanks to their excellent characteristics like biocompatibility, biodegradability, enhanced electrical and thermal conductivity, high specific surface area, high physical and mechanical properties, non-toxicity, and catalytic activity, lignocellulosic bio-based nanomaterials including nanocellulose and nanolignin will draw more attention as very promising raw materials. As the performance of the properties of the bio-nanomaterials with various modifications improves, the properties of biosensors will also improve.

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