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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