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Nanosensors in the Food Industry

Small helpers in Quality Assurance with a big impact on Food Safety and against Food Fraud

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Note:

In this expert report, for better readability, the generic masculine form is frequently used for personal titles and nouns referring to persons. However, in the spirit of equal treatment, the corresponding terms are generally intended to apply to all genders. This abbreviated linguistic form is therefore adopted solely for editorial reasons and implies no value judgment.

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1. Introduction and background

In an environment characterized by constantly changing, internationally networked value chains, increasing personnel shortages, and ongoing time pressure, specialists in quality assurance and quality management face significant challenges. This situation is intensified by the fact that fraud regarding ingredients and food quality is on the rise[1], and highly dangerous pathogens - such as Listeria - are appearing with increasing frequency, as demonstrated by recent product recall statistics[2]. To support these specialists, rapid analytical methods and “intelligent” sensors – particularly nanosensors - are gaining increasing importance as tools for ensuring sustainable process efficiency in analytical testing and quality assurance. Thanks to international research efforts, the underlying technologies are becoming ever more specific, sensitive, cost-effective, and user-friendly[3]. The results generated by these technologies – often captured directly on-site – provide valuable support for company-specific decision-making regarding food safety and product quality. Among other applications, these tools enable the early detection of harmful substances, contaminants, and pathogenic bacteria (such as Listeria and Salmonella); the real-time monitoring of product freshness and quality; and the identification of adulterated foods and Food Fraud. The rapid, early, and unique identification of quality defects facilitates timely intervention and targeted action, thereby making it possible to prevent health risks, food waste, reputational damage, and financial losses, while simultaneously minimizing overall risk.

The following DLG-Expert Report aims to provide an initial overview of the use of nanosensors within the food industry, thereby offering specialists and executives insight into the innovative opportunities presented by these advanced sensing instruments.

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2. Definition and types of nanosensors

A sensor is a technical device designed for the direct measurement of a test substance or analyte within a sample. Ideally a sensor responds continuously and reversibly and does not damage the sample. The term “nanosensor” refers to a class of sensor devices or systems that operate at the nanometer scale. In this context, at least one nanostructure (1–100 nm, or 10^{-9}–10^{-7} m) is employed, and at least one nanoscale interaction (at the molecular or atomic level) serves as the basis for signal acquisition and processing, or for the detection of a known analyte or its concentration. Nanosensors enable highly sensitive and high-resolution detection, quantification, and monitoring of chemical, physical, or biological parameters, as well as changes therein. They significantly enhance accuracy, sensitivity, and speed of analytical systems compared to traditional analytical methods, thereby making them ideally suited for a wide range of application areas.

There is a wide variety of nanosensors, differing in their type, structure, detection mechanism, and field of application. A classification based on application areas can be broadly categorized as follows:

- **Physical nanosensors,** which measure physical quantities and material properties – such as temperature, magnetic fields, pressure, humidity, force, mass, or light.
- **Chemical nanosensors,** which measure chemical substances and changes in concentration – for example, pH levels or changes in the concentration of specific molecules or volatile components. For instance, a nanoscale gas sensor can detect the carbon monoxide content of the air.
- **Biological nanosensors (or bionanosensors),** which utilize biological components to detect specific biological compounds or structures – such as DNA sequences, cellular structures, proteins, enzymes, viruses, or even bacterial secretions. These find applications in various fields, including medicine - for example, by employing antibodies to identify pathogens, or in blood glucose sensors that determine blood glucose levels via an enzymatic reaction.

Nanosensors often consist of combinations of these approaches; for instance, biological structures - such as antibodies – may be utilized to generate electrical signals, or changes in pH levels may be made to trigger distinct optical signals. In the fabrication of nanosensors, a distinction is made between two primary approaches: “top-down” and “bottom-up.” In the “top-down” method, deterministic structures are transferred onto surfaces or layers using nanostructuring techniques. Examples include electron-beam or photolithography (the use of light to create minute structures on surfaces), often combined with etching processes, nanoimprint lithography, or laser deposition. The “bottom-up” method, conversely, leverages self-organizing structural formation processes – such as crystal growth, sol-gel processes, or the formation of nanostructures via molecular beam epitaxy. The latter is a high-precision thin-film technique in which atoms or molecules are precisely deposited onto a crystalline substrate surface within a high-vacuum environment, thereby creating crystalline nanolayers - layer by layer - with a defined structure.

3. General structure and functionality

In principle, a nanosensor is a technical device capable of capturing data or information regarding the properties or behavior of substances at the nanoscale level within a sample and translating this information to the macroscale level in the analytical result.

The nanomaterials incorporated into various sensors react specifically and with high sensitivity to chemical, physical, or biological stimuli from the environment, or to specific analytes present in the sample. The interaction between the sensor and the analytes generates signals, which are transformed into measured values by transducers; these values are then captured, processed, and output by a detector as interpretable information.

The operating principles of nanosensors are based on one or a combination of several phenomena – for instance, optical, electrochemical, or enzymatic interactions.

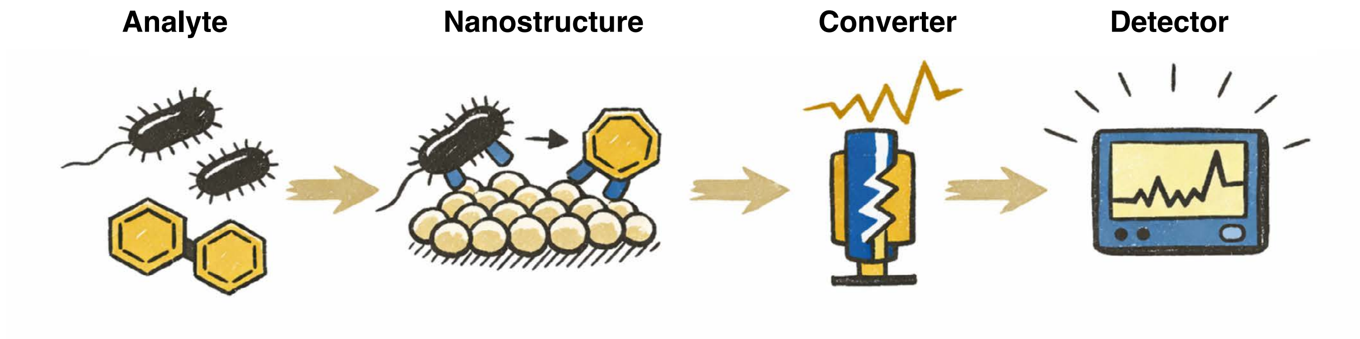

Figure 1: Schematic structure of a nanosensor

The fundamental structure can be reduced to a simple schematic, which is illustrated in figure 1. The components of nanosensors include the analyte to be identified; a nanoscale sensor designed to interact with, or to selectively bind and capture, this analyte; a transducer that detects the reaction or change in properties and converts it into detectable signals; and a detector that receives, displays, and digitizes these signals. Consequently, nanostructures interact with the target analyte. This interaction is converted by a transducer into a signal, which can subsequently be measured by a detector. These results can then be transmitted online - and, if appropriate, analyzed using artificial intelligence - and made directly accessible to decision-makers.

Based on this general overview of nanosensor architecture, the following section describes two specific types of sensors utilizing different measurement principles:

Optical nanosensors

The measurement principle of optical nanosensors is based on the optical detection of fluorescence, absorption, or scattering processes. Typically, functionalized nanoparticles are employed as the sensor material. One approach to the optical detection of bacteria using nanoparticles is illustrated in figure 2. Nanostructures, for example metallic nanoparticles, interact with specific analytes or bind selectively to the biomolecular components of bacteria.

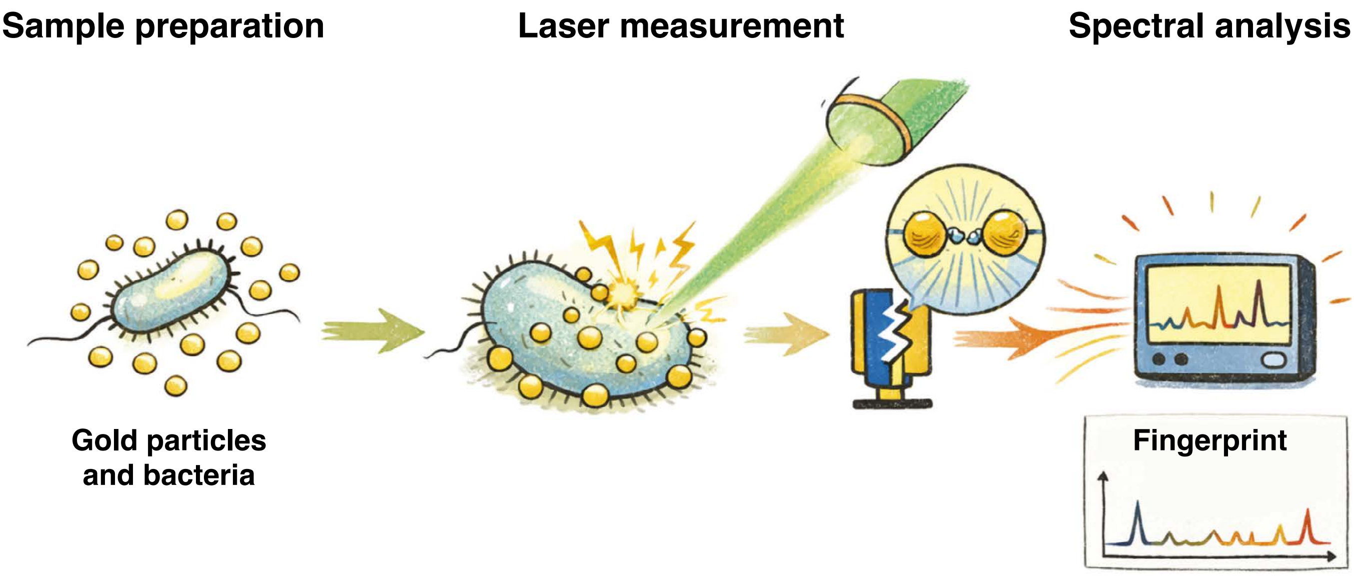

Figure 2: Schematic structure of an optical nanosensor

For context: Bacteria typically measure approximately 1–5 μm in size, making them about 10 to 1,000 times larger than metallic nanoparticles, which usually have diameters ranging from a few to several tens of nanometers. When light strikes metallic nanoparticles (typically gold or silver), their free conduction electrons are excited into collective oscillations - known as localized surface plasmons. At sharp edges, tips, or within narrow gaps between adjacent nanoparticles (at nanometer-scale distances), extremely strong local electromagnetic fields are generated. These regions of very high field enhancement are referred to as “hot spots”. If molecules - for instance, components of a bacterial cell wall - are situated in the immediate vicinity of these hot spots, their Raman scattering signal is strongly amplified, in some cases by several orders of magnitude. The evocative phrasing that “the light gathers” serves as a simplified description of the intense local increase in electromagnetic field intensity within these regions. The amplified Raman signals are subsequently captured and analyzed using optical detectors or spectrometers. The effect described here is known **as surface-enhanced Raman scattering (SERS).**

In a sample preparation step, the bacteria are mixed with nanoparticles, which may consist of, for example, metals or polymers. The nanoparticles interact with or bind to the bacteria; this can occur via simple charge effects or specific binding mechanisms, such as antibodies. Subsequently, the sample is illuminated with light (typically a laser).

The light concentrates in the immediate environment of the nanoparticles. These regions – referred to as “hotspots” – also extend to the bacteria, thereby achieving an amplification of their optical signal. In this way, intrinsic signals - such as the bacteria’s Raman signal (essentially their specific biochemical “fingerprint”) – can be detected. This enables the identification of sub-species (typing) or even the detection of resistance genes within a specific type. Alternatively, the signal emitted by the nanostructures themselves may change as a result of binding to specific partners – such as antibodies. This change is then detected. A camera – often augmented by a spectrometer – typically serves as the detector for this process. Light-based measurement allows for the rapid acquisition of signals, even from a distance or through transparent media such as packaging.

Electrochemical nanosensors

The second example involves the detection of analytes by means of electrochemical signals. The operating principle of electrochemical nanosensors is based on the detection of changes in electrical parameters - such as current, potential (or voltage), or resistance. Typically, nanoscale structures – such as carbon nanotubes (CNTs), nanowires, or nanoparticle-based electrodes – are employed as the sensor material.

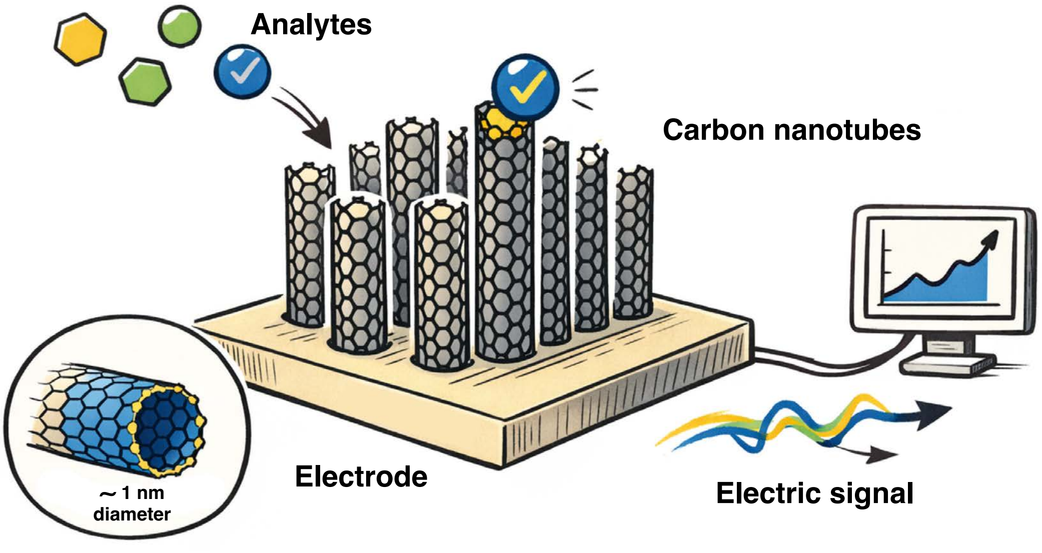

Figure 3: Schematical structure of an electrochemical nanosensor

For instance, carbon nanotubes with a diameter of one or a few nanometers can function as sensors. These structures – also referred to as carbon nanotubes (CNTs) – can be specifically engineered to interact selectively with a particular analyte. The binding of the analyte results in a change in the electrical resistance of the carbon nanotubes, which can subsequently be detected via an electrode as a change in an electrical signal (cf. figure 3).

These CNT-based sensors find application, for example, in environmental analysis for air quality monitoring or in industrial emissions monitoring - where gaseous analytes such as NO_2, NH_3, CO, H_2, and VOCs (e.g., Benzene, Toluene) can be detected[7] – or alternatively in drinking water monitoring, for instance, to detect heavy metals such as Pb^{2+}, Cd^{2+}, and Hg^{2+}, as well as Nitrite, Nitrate, and organic pollutants like Naphthalene. Biologically functionalized CNT sensors detect analytes such as Glucose, various antibodies, DNA/RNA, or enzymes[8].

4. Current research developments and application examples

For the year 2025 only, Google Scholar lists approximately 6,530 entries for the keyword combination “food security” and “nanosensor.” This demonstrates the significant interest within the research community in providing new and innovative solutions for the food industry. Despite intensive research and numerous potential applications, only a few nanotechnology-based solutions have reached the market so far. The following section presents research examples of specific applications, as well as solutions that have already transitioned into commercialization.

a) Research examples

The following examples from the field of research illustrate the detection of contaminants in food - such as mycotoxins and pesticides – as well as real-time monitoring for quality assurance and quality control.

Mycotoxins acting as contaminants and pesticides appearing as residues can pose significant risks to consumer health; consequently, they are subject to statutory regulations regarding maximum permissible levels. Analytical methods used to monitor these limits must be capable of quantifying contamination or residues (depending on the specific substance) in the parts-per-billion (ppb) range, or in exceptional cases, at even lower concentrations. For instance, by employing a combination of carbon-phosphorus nanoparticles and aptamers, Ochratoxin A can be determined linearly across a concentration range of 0.1 fg/mL to 10.0 ng/mL (where 10 ng/g corresponds to 10 ppb)[4]. In this specific application, the generated signal manifests as a change in conductivity, thereby constituting an electronic measurement.

Nanosensors can also be integrated directly into packaging, enabling real-time monitoring from the moment of packaging right through to the point of sale. Metabolites off gassing from pathogenic bacteria can be detected using a surface coated with gold nanostars. The signal can be read out optically, directly through the unopened packaging. Pork inoculated with *Escherichia coli, Staphylococcus aureus,* and *Pseudomonas aeruginosa* has been successfully detected in this manner.

In the field of olive oil quality control, for instance, a combination of surface-enhanced Raman spectroscopy and complex data analysis allows for the rapid, on-site determination of an olive oil’s quality and composition. In this process, a very small sample volume is mixed with gold nanoparticles and irradiated with a laser. From the complex scattering

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signal captured by means of a spectrometer, individual components can be extracted, thereby allowing different compositions to be directly determined.

A key aspect that has recently gained traction in current research is the analysis of sensor results using artificial intelligence. Particularly when dealing with large datasets, artificial intelligence can detect hidden patterns, thereby enhancing the speed and reliability of result analysis – or even making such analysis possible in the first place. Specifically, combining data from multiple types of nanosensors can yield valuable new insights when analyzed using artificial intelligence; this is because the inherent complexity of the results makes “manual” analysis difficult, whereas the larger and more diverse dataset significantly boosts the analytical power of an AI-driven approach.

b. Specific application examples in Food Quality Assurance: Food Safety and Quality Control

Despite the promising potential of nanosensors for the food industry, few commercial applications currently exist. This is due in part to the often significant hurdles involved in transitioning from research to industrial application, a topic that will be addressed further in chapter 5.

As a first example, consider the use of nanoparticles for the rapid optical detection of bacteria. In this area, NanoStruct GmbH offers a comprehensive solution capable of identifying *L. monocytogenes* directly from the initial enrichment culture after approximately eight hours. NanoStruct´s nanoparticle-based sensors can be immersed directly into the untreated growth medium during food testing and subsequently inserted into the measurement device. Technically complex procedures – such as those required for PCR (e.g., DNA extraction) – as well as stringent purity requirements and the need for a dedicated laboratory environment are thus eliminated. This offers significant analytical advantages for food testing laboratories, both in terms of time – enabling same-day results – and regarding the environmental requirements for testing. Development is currently underway to enable the direct implementation of this solution at food manufacturing facilities, thereby offering industry-compatible methods for quality assurance.

For the detection of mycotoxins, SAFIA Technologies GmbH, for example, offers a solution based on optical nanosensors. In this system, the toxins bind competitively – via an antigen-antibody interaction – to optically labeled nano- or microparticles. This results in a secondary binding event involving a second optical marker. Consequently, a signal correlation between both markers is measured in a flow cytometer or FACS (Fluorescence-Activated Cell Sorting) device, indicating the presence of the target molecules. Within a timeframe of 30 to 90 minutes, the presence of the nine most common mycotoxins can thus be determined within legal detection limits. This is feasible for virtually all types of matrices, ranging from solid food products like grains to beverages such as beer.

5. Potential and challenges of nanosensors

a) Potential

Nanosensors offer the capability to generate highly specific, rapid, and reliable measurement results within an extremely small, compact form factor, thereby enabling the timely implementation of necessary measures in quality assurance.
In this regard, they can match the sensitivity of large, laboratory-based measurement systems or even surpass them through the use of nanoscale sensing elements and are thus capable of detecting even very low concentrations of substances. Furthermore, their operation is straightforward, meaning that specially trained personnel are often not required for their use. Consequently, their potential applications in food quality assurance and environmental analysis are extremely diverse.

Measurements can be performed on-site, in some cases even inline and continuously. By connecting to a cloud, information can be analyzed in near real-time and utilized directly for decision-making. The collection and aggregation of large volumes of data, in conjunction with artificial intelligence, makes it possible to detect anomalous patterns whether a contamination or a quality deviation more rapidly, or indeed to identify them at all.

b. Challenges

Apart from the enormous potential that nanosensors offer the food industry, there are the challenges associated with their successful implementation. In addition to significant technical hurdles, these challenges also extend to the economic and regulatory spheres. On the technical front, the primary requirements concern the test itself: it must offer high sensitivity and selectivity, coupled with a level of stability and reproducibility that makes industrial application feasible. As a bridge to economic viability, this technical performance must be paired with cost-effective, scalable production. Implementation will only occur if a clear cost advantage for manufacturers is evident.

Finally and to ensure that manufacturers are able to utilize these tests at all, the regulatory framework must be clarified and secured. For instance, it must be guaranteed that the use of nanoparticles poses no risk to consumers or to personnel involved in the production process. This is particularly relevant for nanosensors integrated directly into the value chain (inline) or embedded within product packaging, where released nanoparticles could potentially be ingested or inhaled. A further complicating factor is that the toxicity of nanoparticles is often insufficiently or not at all researched. The magnitude and urgency of these requirements depend heavily on the specific application case. However, for new applications, this can constitute a significant hurdle, one that must be cleared up before commercialization can take place. Furthermore, in the specific application context of “pathogen detection”, rigorous quality assurance protocols are required to ensure that results are not reported incorrectly as “false negatives”. Functional testing involving active pathogens can and should only be conducted within a suitably equipped laboratory environment. Developments in this area remain ongoing, too.

6. Suppliers (Selection)

Table 1 below presents a selection of suppliers focusing on food safety who utilize nanosensors with different technological approaches.

NanoStruct GmbH develops optical nanosensors based on specially structured gold surfaces. These amplify optical signals so strongly that even very small quantities of bacterial components or contaminants can be reliably detected. The measuring system, illustrated in figure 4, can automatically measure entire microtiter plates, e.g. with 24 or 96 wells, in a single pass lasting just a few minutes. Positive or negative results are displayed directly in graphical form.

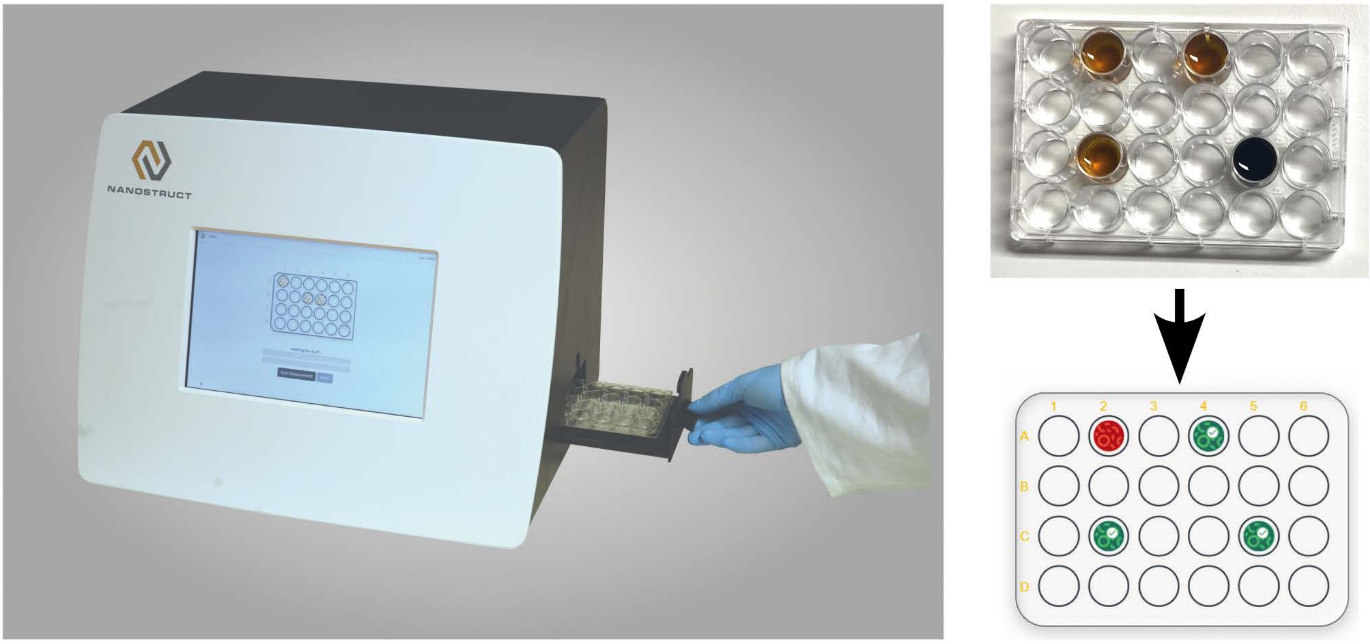

Figure 4: NanoStruct Measuring System

SAFIA Technologies GmbH is also pursuing an optical nanobiosensor approach, combined with biological recognition mechanisms. Micro- and nanoparticles coated with antibodies specifically bind target analytes to their surfaces via specific antigen-antibody reactions. These binding events are detected through fluorescence signals and are employed, in particular, for the analysis of mycotoxins in food testing.

FluIDect technology differs significantly from the approaches described previously, as it involves the development of industrial optical biosensors designed for the continuous, real-time, and inline monitoring of liquid processes. The sensor elements consist of freely moving, functionalized microparticles (µBeads) suspended within the sample, which bind microorganisms or proteins with high sensitivity at the molecular or nanoscale level. These interactions are detected optically and contact-free, via photonic resonance effects, directly within the production facility. This highly sensitive, “nano-enabled” biosensor technology finds application in fields such as food production, fermentation, and water monitoring.

Oxford Nanopore Technologies, by contrast, employs electrochemical nanosensing, in which nanopores serve as sensing elements. Individual DNA or RNA molecules are guided through pores in the nanometer range, during which changes in the ionic current are measured, data from which genetic information is derived. This technology finds application in genetic analysis and diagnostics, as well as in the food sector for the identification of microorganisms (particularly pathogens), the analysis of microbial communities in fermentation processes, and the detection of spoilage and process contamination, including, among other uses, for authenticity and allergen testing.

While optical nanobiosensors enable the rapid detection of biological analytes via light-based effects, Oxford Nanopore utilizes a third-generation sequencing technology in which genetic information is electrochemically extracted from changes in the ionic current of individual DNA or RNA molecules within nanopores.

Company	Technology	Scope of application	Website
NanoStruct GmbH	SERS, Raman Spectroscopy	Food Safety	www.nanostruct.eu
SAFIA Technologies GmbH	Fluorescent labeling	Food Safety	www.safia.tech
FluIDect GmbH	Fluorescence, Optical/ Photonic Resonance Measurement	Water, Food Safety	www. fluidect.com
Oxford Nanopore Technologies	Third Generation Nanopore Sequencing, Ion current measurement	Water, Food Safety	www. nanoporetech.com

Table: Selection of suppliers of nanosensors or nano-/microbio-analytical mesurement systems

7. Conclusion and outlook

Cost-effective, user-friendly nanosensors, integrated seamlessly into the information flow, provide the potential to enable the monitoring of critical parameters across the entire value chain, at every relevant stage. This process can start in the field or in the barn and continue right through to the point of sale, for instance, by being scanned alongside the product barcode at the checkout.

Leveraging modern data infrastructures and the application of artificial intelligence, sensor data can be analyzed centrally to identify overarching patterns; this yields a significantly greater informational gain than could be achieved through individual, isolated measurements alone.

Biosensors and nanosensors are classified as “Advanced Sensor Technologies” and are regarded as key technologies for the sustainable future of food safety monitoring, environmental surveillance, and health diagnostics. Their high sensitivity and specificity, combined with rapid analysis times, open up new possibilities, particularly in the early detection of food-related risks, that are only achievable to a limited extent using conventional methods.

However, challenges still exist, such as high production costs, limited industrial scalability, and the sensitivity of nanoscale materials to environmental and process conditions. Current research approaches therefore focus on cost-efficient materials, additive manufacturing processes, and robust coating and packaging concepts. Furthermore, adapted regulatory frameworks are required to facilitate the transfer of innovative sensor technologies into market-ready applications. Close collaboration among research, industry, and regulatory bodies is considered crucial in this regard.

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