

NANOSENSORS: REVOLUTIONIZING AGRICULTURE FOR SUSTAINABLE GROWTH

Abstract

Agriculture plays a vital role in the economic landscape of developing nations such as India, serving as a cornerstone in their national economy. The effectiveness and profitability of agricultural production hinge greatly on the inputs provided and their efficiency of utilization under field conditions. To effectively manage both biotic and abiotic stressors in the face of a changing climate, additional agricultural inputs become imperative. The current landscape, marked by a surge in food demand due to population growth, underscores the need for sustainable agricultural practices to ensure food security.

In recent years, Nanotechnology emerges as a promising technological frontier in the pursuit of sustainable agriculture by enhancing the efficiency of resource utilization for agricultural inputs. This innovation holds the potential to reshape the dynamics of agricultural production, contributing to the realization of goals essential for ensuring long-term food security and resource preservation. Nanosensors, with their miniature size and heightened sensitivity, open new avenues for real-time monitoring and data acquisition in agricultural settings. Their potential to revolutionize precision farming practices becomes evident, promising optimized resource utilization and increased agricultural productivity. Nanobiosensors play a pivotal role in bridging the gap between nanotechnology and the intricacies of agricultural ecosystems, enabling precise detection of biochemical markers and pathogens crucial for crop health.

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Numerous nanosensors are currently being researched for use in the agricultural and food industries for a variety of purposes, including the ability to instantly recognize dangers in the event of probable food poisoning, detecting both internal and external conditions in food packaging, carbon nanotube-based electrochemical detectors for detecting cations, anions, and organic molecules in food, and different aptamers for detecting pesticides, heavy metals, antibiotics, microbial cells, and toxic substances are just a few of the numerous kinds of nanosensors currently being created to meet the various requirements for food analysis. Over the past decade, the fields of nanosensor and nanobiosensor research and innovation have shown phenomenal growth. This chapter made a concerted effort to provide the most recent innovations and trends in nanobiosensor and nanosensor design, fabrication, and possible applications in the food and agricultural industries.

Keywords: Nanotechnology, Nanosensors, Nanobiosensors, Precision Agriculture and Sustainable Farming

I. INTRODUCTION

Agriculture serves as a crucial part in the national economy of the developing countries like India. Being a significant contributor to the Gross domestic product, increasing the agricultural food production translates significantly in improved socio-economic conditions. The output and profitability of the agricultural production system is highly dependent on the supplied inputs and their use efficiency in field conditions. Additional agricultural inputs are required in order to manage the biotic and abiotic stressors under changing climate scenario. The current scenario of increasing food demand due to increasing population calls for sustainable agriculture in order to attain food security. The basic principle of sustainable agriculture is to create a self-sustainable agricultural production system to meet our food requirements and protection of resources for future generations. The nanotechnology is providing a new promising technology for achieving the goals of sustainable agriculture by improving resource use efficiency of agricultural inputs.

The term "nano" originates from the Greek word for "dwarf," which refers to the one billionth of a metre. According to the US Environmental Protection Agency (EPA), nanotechnology is "research and technology development at the atomic, molecular, or macromolecular levels using a length scale of approximately one to one hundred nanometers in any dimension; the creation and use of structures, devices, and systems that have novel properties and functions because of their small size; and the ability to control or manipulate matter on an atomic scale" (EPA, 2007). The fine size of the particles (< 100 nm) is the key reason for drastic changes in intrinsic properties and applications of the nano-material as compared to the bulk of the same material. The important characteristics of nano materials are:

1. Small particle size (at least one dimension < 100 nm)
2. High surface area
3. High particle mobility
4. Very high Surface-volume ratio

For Characterization of physicochemical properties of Nanoparticles X-ray diffraction, techniques that were frequently employed included X-ray photoelectron spectroscopy, TEM, infrared radiation, SEM, Brunauer-Emmett-Teller, and particle size determination (Khan et al. 2019).

Nanotechnology comprises two main components: first, the fabrication of nanoparticles (sometimes referred to as engineered nanoparticles), and second, the use of the created nanomaterial to accomplish the intended objectives. Four primary forms of engineered nanoparticles and nanomaterial are distinguished :

- Carbon-based materials e.g. carbon nanotubes
- Semiconductor and metal oxide-based materials e.g. nanogold, nanozinc, nanoscale metal oxides and quantum dots.
- Polymer nanoparticles, e.g. dendrimers, to perform specific chemical functions; and
- Composites combined nanomaterial with other nanomaterial or nanoparticles.

Nanotechnology is a novel technology which has demonstrated its potentials to deal with several emerging challenges in various sectors like electronics, energy, biomedicine and environment and agriculture. The uses of nanotechnology in agriculture will now be briefly discussed in the section after this one.

II. NANOTECHNOLOGY IN AGRICULTURE

Nanotechnology is widely recognized in the agricultural sector for its ability to improve agricultural production in a sustainable manner to ensure food security. The following are some of the uses of nanotechnology in agriculture:

- 1. Crop Improvement:** Bio-nanotechnology is successfully used in agriculture for crop improvement using nanoparticles and nano-complexes through genetic engineering.
- 2. Crop Protection:** Various nanoparticle based formulations are used to protect crop from weeds, pest and diseases and also for effective delivery of these formulations such as anti-feedants (Nanosilica), bactericide (Zinc oxide), fungicide (Chitosan), herbicide (Carboxy methyl chitosan), pesticide (Silver) and surface sterilizers (Silver).
- 3. Crop Nutrition:** Nano fertilizers like silicon, titanium, and zinc nanoparticles were used for balanced and effective nutrition of crops.
- 4. Post-Harvest Technology:** Nanosensors are employed in the manufacturing, wrapping, and transportation of food e.g. nano encapsulated flavor enhancers, to identify poisons and pathogens, monitoring environmental conditions in storage and during transport etc.
- 5. Precision Agriculture:** Nano sensors are widely used in tools for precision agriculture for effective delivery of resources. Nano sensors are employed to monitoring the soil moisture, pH, pathogens, crop growth etc.
- 6. Animal and Fisheries:** Nano devices are also used for animal health, breeding, poultry and fisheries production. Nano formulations are used for target delivery of nutrients to animals and fishes. Animal vaccines has been developed using nanotechnology.

III. NANOSENSORS

The term nanosensors is self-explanatory. It is the combination of two words “nano” and “sensor”. Nano basically stands for the dimension (1-100 nm) as explained earlier, while the sensors in the physical sense is a device that detects a physical, biological or chemical input from the environment and converts it into an output usually in form of a signal, which is processed in a human readable form. A nanosensor is basically a nanoscale device which is capable of detecting and conveying data about the behavior of nanoparticles to the macroscopic level. Nanosensors can detect the presence of nanoparticles or it may monitor the physical or chemical behavior of the nanoparticle in a system to retrieve information from nanoscale, and convert this information into macroscopic level for further processing. Nanosensors are emerging as an encouraging tools for agricultural applications as compared traditional methods.

Types of Nanosensors

1. **Biological:** Designed to detect specific biological material using a biological sensing element *i.e.* Nanobiosensors.
2. **Optical:** Designed to detect presence of any object or its motion, mostly used for automations, e.g. ambient light sensors, proximity sensors.
3. **Chemical:** A chemical receptor and is used as sensor attached with a transducer.
4. **Physical:** Designed to sense physical changes in the environment like mass, volume, density, force, acceleration e.g. nanoindentor, force sensor etc.

IV. NANOBIOSENSORS

The nanosensor which combines the knowledge of biology and nanotechnology is called nanobiosensors. Biosensors basically works on the principle of biological recognition of specific material and its sensing like proteins, enzymes, antibodies etc. The nanobiosensors are combination of nanotechnology with biosensors.

Nanobiosensor (or any biosensor) has three main components which are:

- **Bioreceptor:** To sense/analyze specific biological material. It acts as template for the biological material to be analyzed or detected.
- **Transducer:** To convert biochemical response in electrical signal. It converts one form of the energy to another.
- **Detector:** To detect and amplify transducer signal into readable form.

Further, based on the transduction mechanism the nanosensor or nanobiosensors are classified as:

1. **Electrochemical Nanosensors:** These sensors' operating theory relies on the estimation of electrons in the electrochemical signal generated during the interaction using electrochemical methodology. These sensors are simplistic in nature and provide high sensitivity at low cost, good compatibility, robustness and require minimum maintenance. They are further classified in 3 categories based on the working principle *i.e.*,
 - **Amperometric:** Measures continuous current generated from redox reaction.
 - **Voltametric:** Measures current by varying potential difference.
 - **Potentiometric:** Determines the working electrode's potential in relation to a standard.
2. **Optical Nanosensor:** These nanosensors' operating theory focuses on alterations in the optical properties of nanoparticle and quantum dots. They are usually based on optical methods like fluorescence spectroscopy, interferometry etc.

3. **Mass Nanosensor:** They are supported by the piezoelectric and physical characteristics of crystals and micro cantilevers, accordingly. However, they are rarely used for agricultural applications.

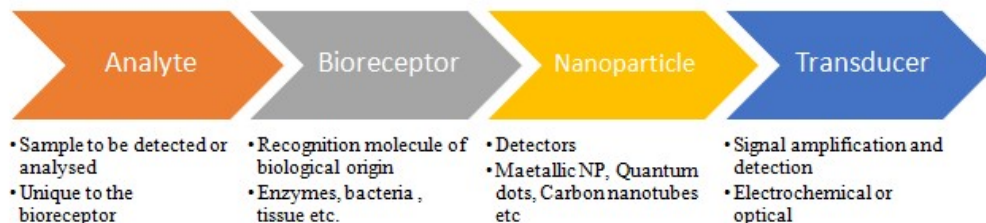


Figure 1: Components of Nanobiosensors

Table 1 : Nanomaterials used in Biosensor Technology

S.	Nanomaterial	Application
1.	Noble metal nanoparticles	Bio-molecular detection and signal amplification
2.	Carbon nanotubes	Receptors in biological modification
3.	Quantum dots	Biological probe
4.	Magnetic nanoparticles	Highly sensitive sensors , catalyzing
5.	Carbon dots	Metal ion detection
6.	Graphene	Catalyst carrier
7.	Nanowires and Nano rods	Highly sensitive sensors

V. ADOPTION OF NANOBIOSENSORS AND NANOSENSORS IN AGRICULTURE

The use of nanosensors ensures more efficient application of agricultural inputs as compared to the conventional techniques. Bionanosensors and electrical nanosensors are two most commonly used sensor in agriculture. The nanosensors are employed in agriculture for detection or monitoring of:

1. Crop growth and condition
2. Soil conditions: pH, moisture, temperature, oxygen
3. Macro and micronutrients in crop and soil
4. Root exudates
5. Pest and diseases of plants and animals
6. Pesticide residue detection
7. Environmental pollution

Several plant growth hormones including Abscisic acid (ABA), Auxin, amino acids etc. were detected using nano sensors. ABA is well known for its stress response in crop and its control over plant growth and development. ABA was successfully measured in real time in the plant cells using nano sensors in genetically engineered plants (Jones et al. 2014).

Similarly, most abundant form of auxin (IAA) can also be detected using nanoscale chromatography or mass spectrometry (Petersson et al. 2009).

Assessing both the temperature and water content of the soil is crucial in agriculture. MicroElectroMechanical System (MEMS) sensors based on nanotechnology were created to measure soil humidity and temperature (Jackson et al. 2014). Variations in the soil moisture and temperature can be detected using a piezoresistor circuit by employing nano MEMS sensors made of micromachined MEMS cantilever beams fitted with moisture sensitive nanopolymer and piezoresistive temperature sensors. MEMS delivers output signal linearly proportional to soil moisture and temperature. Piezoresistive polymer nano-composite microcantilever platform were also used to estimate relative humidity and moisture in soil (Patil et al. 2014). Graphene oxide based micro sensors were also used to for *in situ* moisture and humidity measurements. These sensors are fabricated using the MEMS technology and are highly robust and sensitive for both moisture and temperature (Palaparthi et al. 2018). Graphene quantum dots (GQDs) of size 3-5 nm has also been synthesized and successfully used for soil moisture detection in silt loam and clayey soil (Kalita et al. 2020). When it comes to maximising water use efficiency, particularly in places with limited water resources, automated operation of irrigation networks employing continuous tracking of soil water content and temperature using nanosensors is essential.

Nanosensors are effectively used to assess the soil quality along with the nutrient content, pesticides and heavy metal contamination, which allows farmers to take appropriate measures to overcome the nutrient deficiency and soil management with minimum input.

Pesticides have wider applications in agriculture for management of insects, pests, and diseases to reduce the economical losses. Nevertheless, due to negligent usage in field circumstances, both water and soil have become contaminated, and their buildup in agricultural products has also been noted, which has seriously affected humans and animals. Various types of nanomaterial including nanoparticles, nano composites, and nanotubes are widely used in electrochemical estimation of pesticide residue. Nanosensors provide a number of benefits, including smaller dimensions, a high degree of sensitivity, narrow detection ranges, and quick responses.

Table 2: Some Pesticides Detected Along with their Sensitivity

S. No.	Pesticide	Sensitivity	Reference
1.	Imazapyr	0.2 ppm	Kumar et al 2020
2.	Glyphosate	0.67 ppb	Chang et al 2016
3.	Methyl parathion	1.21 ppb	Tian et al 2018
4.	Glyphosate	0.5 nM	Liu et al 2020
5.	Malathion	0.001 ng/mL	Prabhakar et al 2016
6.	Malathion	0.01 nM	Xie et al 2018
7.	Dimethoate	0.002 ppm	Pham et al 2020
8.	Metribuzin	6.8×10^{-8} M	Saleh et al 2020
9.	Fenitrothion	38 nM	Kant (2020)

10.	Atrazine	0.7134 ng/mL	Yılmaz et al 2017
11.	Carbofuran	0.06 µg/dm ³	Sun et al. 2014
12.	Chlorpyrifos	0.08 µg/dm ³	Sun et al. 2014

Apart from the above mentioned many more pesticides including pirimicarb, dichlorvos, paraoxon, monocrotophos, carbaryl, pyrethroid, cypermethrin, permethrin etc. has been detected using varieties of nanosensors. For the detection and monitoring of organophosphorus herbicides like paraoxon and dichlorvos, liposome-based biosensors have been generated (Kumar et al. 2020).

The content of plant roots metabolites or plant exudates into the rhizosphere can also be determined using nanosensors. Carbohydrate exudates like hexoses, disaccharides, and disaccharides, glucose, sugars and amino acids released in soil by plants can be determined using nanosensors. Foster resonance energy transfer (FRET) based nanosensors were used to detect ribose, glucose, maltose etc. Glucose is also sensed using electrochemical biosensors fabricated with multiwalled carbon nanotubes (Zheng et al. 2013). Karnal bunt of wheat and pathogenic fungus in oilseeds were successfully detected using nanosensor. Real time monitoring of agrochemicals is helpful in saving resources and environmental pollution too. Some of the Nano fertilizers possesses biosensors which liberates fertilizer after it sense the root contact.

When used to detect residue of pesticides, nanobiosensors exhibit improved sensitivity, lower testing limits, and quick response times. Nanosensors has been used successfully to sense phytohormones and agrochemicals like Atrazine, Urea, Nitrate, Glyphosate, Methyl Parathion, Trichoderma with very low detection limits.

Precision farming aims at maximizing the agricultural output with reducing inputs like water, agrochemicals etc. Variable rate technology is the major component of precision agriculture which is based on use of global positioning system (GPS) and geographical information system (GIS) systems. The basic goal is to determine the site specific needs and problems and application of required inputs as per site specific requirements to save resources. This also prevents application of excess agrochemicals in the soil or plants which can later pollute the environment. Nanosensors increases the adoption rate of precision farming to render efficient monitoring of crop and soil which assist farmers in efficient utilization of agricultural inputs such as water, fertilizers, pesticides etc.

Table 3: Some Agriculture based Compounds/Species Detected using Nanosensors

S.No	Compound /Species	Nanoparticle used as Sensor	References
1.	Urea and Urease	Gold (Au)	Deng et al., 2016
2.	Nitrate	Graphene oxide	Ali et al. 2017
3.	Mg ²⁺ , Ca ²⁺ , Sr ²⁺ , Ba ²⁺	Gold (Au)	Ben-Amram et al. 2012
4.	Methyl parathion	Multi walled Carbon-chitosan nano composite	Dong et al. 2013

5.	Trichoderma harzianum	Chitosan nanocomposite	Siddiquee et al. 2014
6.	Organophosphates	Gold (Au)	Kang et al. 2010
7.	Acetamiprid	Gold (Au)	Shi et al. 2013
8.	Atrazine	Titanium oxide (TiO ₂)	Yu et al 2010
9.	Deltamethrin	SiO ₂	Ge et al. 2011
10	Cymbidium mosaic virus	Gold nanorods	Lin et al. 2014
11	Cysteine	Gold (Au)	Yadav et al., 2021
12	Auxins	Carbon nanotubes	McLamore et al. 2010
13	Sclerotinia sclerotiorum	Copper Nanoparticles	Wang et al. 2010
14	Karnal bunt of wheat	Nanogold	Singh et al 2010

VI. NANOSENSOR AND NANOBIOSENSOR APPLICATIONS IN THE FOOD INDUSTRY

Since it directly relates to how food affects the well-being of people, food safety is an essential concern in both the food and agricultural sector. Innovative and online methods for diverse component detection with high accuracy are made possible by combining nanosensors with contemporary Information and Communication Technologies (ICTs). Nanosensors for detecting both internal and external conditions in food packaging, carbon nanotube-based electrochemical detectors for detecting cations, anions, and organic molecules in food, and different aptamers for detecting pesticides, heavy metals, antibiotics, microbial cells, and toxic substances are just a few of the numerous kinds of nanosensors currently being created to meet the various requirements for food analysis.

Numerous nanosensors are currently being researched for use in the agricultural and food industries for a variety of purposes, including the ability to instantly recognize dangers in the event of probable food poisoning and the incorporation of nanotracers into wrapping to demonstrate a food product's history and establish the level of acceptable quality at any particular period. For example, nanosensors employed in on-line process regulation to evaluating the state of storage and nanosensors used in food packaging to identify the proliferation of microorganisms and change colour when a threshold level is attained have applications for averting food poisoning (Augustin and Sanguansri 2009). Another illustration is the production of gold nanoparticles that have molecules on them that are capable of binding to things like insecticides. These nanoparticles might be sprayed on fields by farmers to detect chemicals like pesticides (Rathbun 2013).

Table 4: Nanosensors Potential Applications in Agri-Food Sector (Omanović-Miklićanin & Maksimović, 2016)

Agriculture	Food Processing	Food Packaging	Food Transport	Nutrition
<p>1. Nanosensors for monitoring soil conditions (e.g. moisture, soil pH), a wide variety of pesticides, herbicides, fertilizers, insecticides, pathogens and crop growth as well.</p> <p>2. Nanosensors for detection of food-borne contaminants or for monitoring environmental conditions at the farm.</p> <p>3. Nanochips for identity preservation and tracking.</p> <p>4. Nanocapsules for delivery of</p>	<p>1. Nanoencapsulated flavor enhancers.</p> <p>2. Nanotubes and nanoparticles as gelation and viscosifying agents.</p> <p>3. Nanocapsule infusion of plant based steroids to replace a meat's cholesterol.</p> <p>4. Nanoparticles to selectively bind and remove chemicals or pathogens from food.</p> <p>5. Aptasensors for determination of microbial toxins (e.g. OTA, Fumonisin B1).</p>	<p>1. Portable nanosensors to detect chemicals, pathogens and toxins in food.</p> <p>2. DNA biochips to detect pathogens and to determine the presence of different kind of harmful bacteria in meat or fish, or fungi affecting fruit.</p> <p>3. Nanosensors incorporated into packaging materials for detection of chemicals released during food spoilage and serve as electronic tongue (e.g. bitter, sweet, salty, umami, and sour detection), or nose (e.g. wine characterization).</p> <p>4. Electromechanical nanosensors to detect ethylene.</p> <p>5. Nanosensors applied as labels or coating to add an</p>	<p>1. Nanosensors for monitoring environmental conditions during distribution and storage.</p> <p>2. Nanosensors for traceability and monitoring product conditions during transport and storage, what is crucial for products which have a limited shelf-life.</p> <p>3. Smart-sensor technology for monitoring the quality of grain, dairy products, fruit and vegetables in a storage environment in order to detect the source and the type of spoilage.</p> <p>4. Aptasensors for determination of microbial cells (e.g.</p>	<p>1. Nanocapsules incorporated into food to deliver nutrients.</p> <p>2. Nanocochleates (50 nm coiled nanoparticles) for delivering nutrients (e.g. vitamins, lycopene, and omega fatty acids) more efficiently to cells, without affecting the color or taste of food.</p>

<p>pesticides, herbicides, fertilizers and vaccines.</p> <p>5. Nanosensors and nano-based smart delivery systems for efficient use of agricultural natural resources (e.g. water), nutrients and chemicals through precision farming.</p> <p>6. Nanoparticles to deliver growth hormones or DNA to plants in controlled manner.</p> <p>7. Nanoparticles used as smart nanosensors for early warning of changing conditions that are able to respond to different conditions.</p>		<p>intelligent function to food packaging in terms of ensuring the integrity of the package through detection of leaks, indication of time-temperature variations and microbial safety.</p> <p>6. Aptasensors for determination of microbial cells (e.g. Salmonella typhimurium, Escherichia Coli, Listeria monocytogenes).</p> <p>7. Aptasensors for determination of antibiotics, drugs and their residues (e.g. cocaine, oxytetracycline, tetracycline, kanamycin).</p> <p>8. Aptasensors for determination of heavy metals (e.g. Hg^{2+}, As^{3+}, Cu^{2+}).</p>	<p>Salmonella typhimurium, Escherichia Coli, Listeria monocytogenes).</p>	
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<p>8. Aptasensors for determination of pesticides and insecticides (e.g. phorate, acetamiprid, isocarbophos).</p>				
<p>9. Aptasensors for determination of antibiotics, drugs and their residues (e.g. cocaine, oxytetracycline, tetracycline, kanamycin).</p>				
<p>10. Aptasensors for determination of heavy metals (e.g. Hg^{2+}, As^{3+}, Cu^{2+}).</p>				

Forensic applications of food are well-suited for nanosensors using Raman spectroscopy. Food forensics is the study of the source, alteration, and contamination of food. The use of nanosensors in this procedure adds to the technique's accuracy and enables the use of a wide range of analytes that can be probed, from major food elements like carbohydrates, lipids, and protein to minor ones like dyes, colourants, and preservatives. The use of nanosensors for sensing and providing real-time data pertaining to the product from manufacture to delivery to the user might be emphasized. Nanosensors are much more than only passive information receivers. They are able to analyze, record, and report data as well as obtain information from nearby and distant environments. They can be created to control this at key stages in the supply chain, such as when food is manufactured or packed up until the moment of consumption (Lu and Bowles 2013).

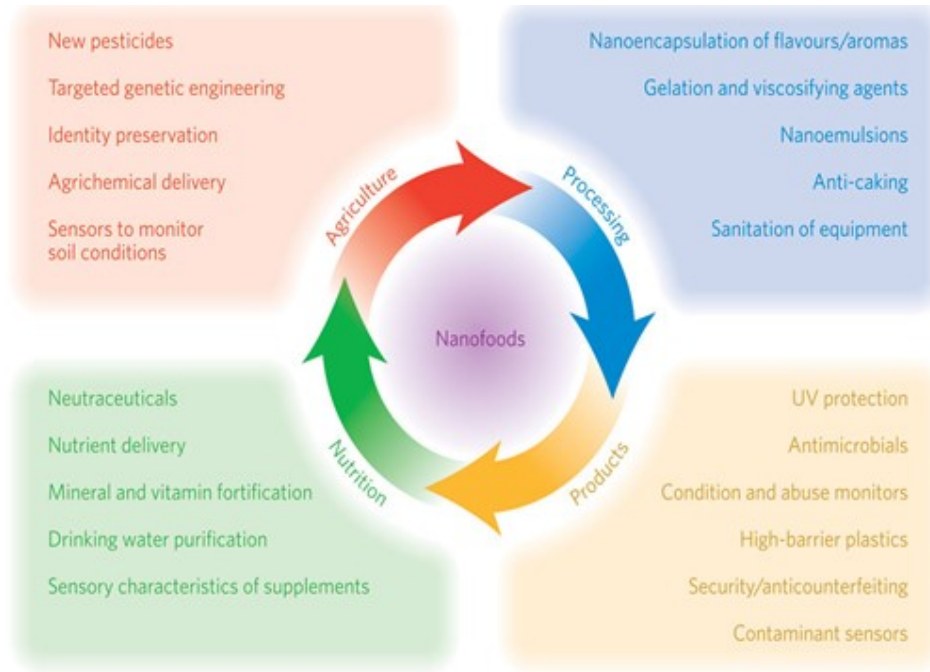


Figure 2: Potential Benefits of Nanotechnology in Many Areas of the Food Industry (Duncan, 2011)

VII. IDENTIFICATION OF FOOD CONTAMINATION OWING TO PRESERVATIVE

Metallic nanoparticles have unique shape- and size-dependent features that have a wide range of potential uses in the field of food processing. Metallic nanoparticles are novel for conjugating with proteins, antibodies, drugs, ligands, fluorimetric and colorimetric substances, and other biomolecules due to their desirable optical, chemical, mechanical, electronic and antimicrobial properties. This opens the door for sensitive diagnostic analyses, radiation therapy, thermal ablation, optical scans, gene and drug delivery, labelling of biological entities, efficient sterilization, and the purification of toxic substances. The ability of metallic nanoparticles to quickly react against infections, pesticides, and other harmful byproducts by means of the identification of microbial degradation of food quality and contaminant also plays a significant role in food manufacturing, packing, and ingestion. Given its wide size spectrum from sub-10 to 250 nm and complex shape-dependent physical properties, gold nanoparticles in colloidal form have been used most frequently for a variety of applications amid metallic nanoparticles (Castro et al. 1990). One of the challenging areas in the food industry is estimating the residual level of antibiotics in milk, dairy products, and meat. A mycotoxin generated by *Aspergillus* and *Penicillium* species that is frequently responsible for agricultural food spoilage, ochratoxin A is detected via surface plasmon resonance augmented by nanoparticles of gold. The approach is applied to assess the antioxidant level in commercial fruit juices and is more accurate compared to current spectroscopic monitoring techniques in terms of quick response time, simplicity of usage, and excellent biocompatibility (Hu et al. 2014). The principle of detection is based on antioxidant's capacity to shield the fluorescence of gold nanoparticles. Food producers are extremely concerned about the contamination of natural honey with

sulfonamide residues since honey containing these antibacterial medicine residues carries toxicological hazards as well as allergic impacts. The method uses a lateral flow immunochromatographic test and a polyclonal anti-serum against sulfathiazole linked with colloidal gold nanoparticles as the detection agent.

VIII. SCREENING OF FOOD-BORNE PATHOGENS AND ASSESSING THE MICROBIAL BURDEN

The food sector is extremely concerned about the potential existence of infectious microbes in food products. The food spoils and serious health problems arise when contaminating pathogens are not detected or are detected with only a slight delay. For managing food safety and quality, the pathogen must be detected in real time. The most recent developments in the field of sensor technology gave us a platform to more precisely, quickly, and sensitively identify some microbial contaminants, poisons and chemicals. The majority of instances of food-borne illness have been linked to certain food-borne pathogen species, including, *Salmonella* spp., *Campylobacter* spp., *Listeria monocytogenes*, and *Escherichia coli* O157:H7 (Velusamy et al. 2010). The contagious zoonotic disease Brucellosis, which affects cattle, is disseminated either through encounters with infected animals or through the ingestion of unprocessed dairy goods. Infected milk samples from animals are tested for the presence of Brucella IgG antibodies using antigen-tagged fluorescent silica nano-probes. With significant specificity and sensitivity, the sensing is precise and reproducible and only needs a little volume of sample—50 μ L—over a brief period of time (10 min) (Vyas et al. 2015).

IX. EMPLOYING NANOSENSORS FOR SMART FOOD PACKAGING

One of the most potential uses of nanotechnology is in food packaging, where polymer and nanoparticle materials are employed to stop moisture and gas leakage and avert rotting. The use of nanosensors and nanobiosensors in packaging that remains with the food product and detects its condition, vitality, and aroma has undergone significant innovation. By measuring physical factors including humidity, temperature, pH, oxygen concentration, infectious agents, poisons, and its freshness by evaluating the fermented end-product in the preserved food, nanosensors are currently embedded in packaging to detect the preservation condition. The commercialized nanosensor OxyDot® is used to measure the amount of dissolved oxygen in packaged meals and sealed beverage products. The metallic-organic fluorescent dye immobilized on the gas permeable hydrophobic polymer dot exhibits fluorescence intensity and lifespan quenching, which forms the basis of the oxygen assessment approach. The dye's wavelength of stimulation is in the blue light spectrum and it emits in the red spectrum. The close proximity of oxygen and its strong collision dynamics pull away the dye molecule's excited electron, which in turn reduces the dye's luminescence and fluorescence lifespan. The OxyDot is a trustworthy, sensitive (up to 5% of reading), noninvasive, swift (less than 0.1 s) oxygen sensing technology that can test the oxygen content in actual time. In a similar vein, the intelligent ripeness indicator RipeSense® labels, another patented product, was created to identify the volatile component emitted by the ripened fruit. The label's simple colour transition from red to orange to yellow serves as the sole basis for the detection outcome.

X. CONCLUSION

Over the past decade, the fields of nanosensor and nanobiosensor research and innovation have shown phenomenal growth. This chapter made a concerted effort to provide the most recent innovations and trends in nanobiosensor and nanosensor design, fabrication, and possible applications in the food and agricultural industries. Due to their distinct chemical, thermal, mechanical and optical capabilities, single-walled and multiwalled carbon nanotubes, graphene oxide, gold and silver nanoparticles, quantum dots and magnetic iron oxide nanoparticles have been utilized most frequently among other types of nanomaterials. By synthesising and incorporating these nanoparticles into the sensing component, the sensors' grades of specificity and sensitivity have been enhanced.

The use of nanotechnologies alongside the incorporation of nanomaterials in agriculture could possibly make a significant contribution to addressing the problem of sustainability, especially in light of the significant challenges we will be facing, particularly as a result of an increasing world population and warming temperatures. As a matter of fact, the employment of nanoscale transporters and chemicals can enhance the efficient administration of fertilisers and pesticides, reducing the quantity that needs to be sprinkled while preserving output. Whilst precise farming can be expanded thanks to nanosensor technologies, for the effective handling of resources, which comprises energy; nanotechnologies can also have a beneficial effect on waste reduction, both contributing to a more efficient production and to the reutilization of waste. However, as with the deployment of any novel innovation, a trustworthy risk-benefit analysis as well as a thorough cost accounting study are required. This calls for the creation of credible methodologies for the characterization and quantitation of nanomaterials in various contexts as well as for the assessment of their effects on human well-being and the environment in the realm of nanotechnologies. All parties, especially non-governmental organisations and consumer organisations, must be included in an open dialogue if this technological innovation is to receive consumer consent and support.

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