IJNRD.ORG ISSN : 2456-4184
INTERNATIONAL JOURNAL OF NOVEL RESEARCH AND DEVELOPMENT (IJNRD) | IJNRD.ORG
An International Open Access, Peer-reviewed, Refereed Journal

Nanotechnology in Food Safety: A Review on Adulteration Detection and Quality Preservation

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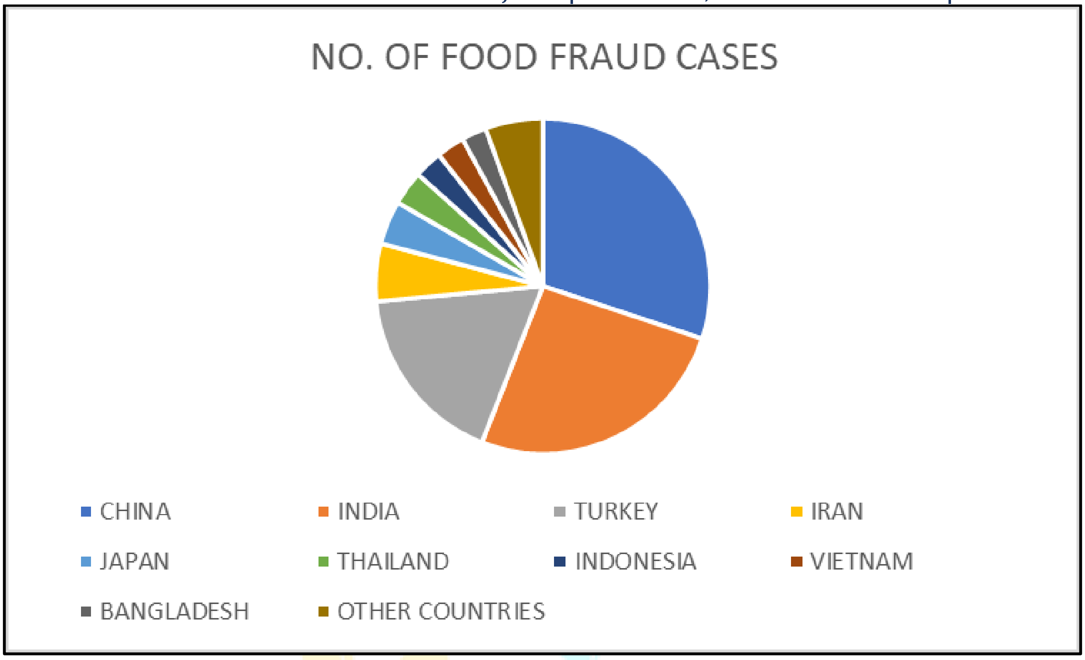
ABSTRACT: Food adulteration is a growing concern since more and more people are exposed to substandard food products. There is a significant risk to people's health when harmful substances are added intentionally or accidentally to food. To ensure food safety, nanotechnology can provide us with innovative ways of detecting food adulteration. Sensitivity and specificity increase by using nanoparticles and nanosensors, which facilitate the detection of even trace amounts of contaminants such as chemical impurities like heavy metals, pesticides, and artificial additives. Furthermore, shelf-life extension in food is achieved by nanomaterials acting as a protective barrier against microbial growth besides oxidation. The review paper focuses on research that integrates these technologies while enhancing the overall quality and life span of the food products. Additionally, this review highlights how nanotechnology has prospects in revolutionizing food safety practices, besides discussing its applications, obstacles, and further developments in combating food adulteration.

Keywords: Food adulteration. Adulterants. Nanotechnology. Nanosensors. Food safety

1. INTRODUCTION

Food is the most basic and vital component of life. However, with the development of food processing sectors, food adulteration has become a serious issue regarding safety and health. Food adulteration refers to the deliberate or accidental adding or replacing of material that has an aim of making profit on foodstuffs which may be poisonous or taking away important nutrient values from the body as well. In the global market, adulterated food products make up almost 10% of all trade, with India alone generating 30% of it. The growing threat to food safety and public health is a worldwide concern. Over 57% of the population suffers health issues due to adulterated food consumption every year (Devrani et al., 2018). The highest impact is in developing countries such as China, India, Turkey, Bangladesh, and Afghanistan.

Economically motivated adulteration (EMA) is a concept of food adulteration that is directly motivated by the purpose of increasing the apparent market value of the product or reducing the production cost (Spink & Moyer, 2011c). From an economic standpoint, adulteration of food dates back to the 18th century in the U.S (*Economic Impacts of Food Fraud*, n.d.). The prevalent adulterants were chalk powder in watered-down milk, lead in coffee, and artificial chemicals in spices. The 2008 Chinese Milk Scandal was a massive economically motivated food fraud, where melamine adulterated infant formula affected more than 300,000 children.



Graph 1: Food Adulteration among countries in Asia

Source: Data from RASFF

1.1. **Causes of Food Adulteration**

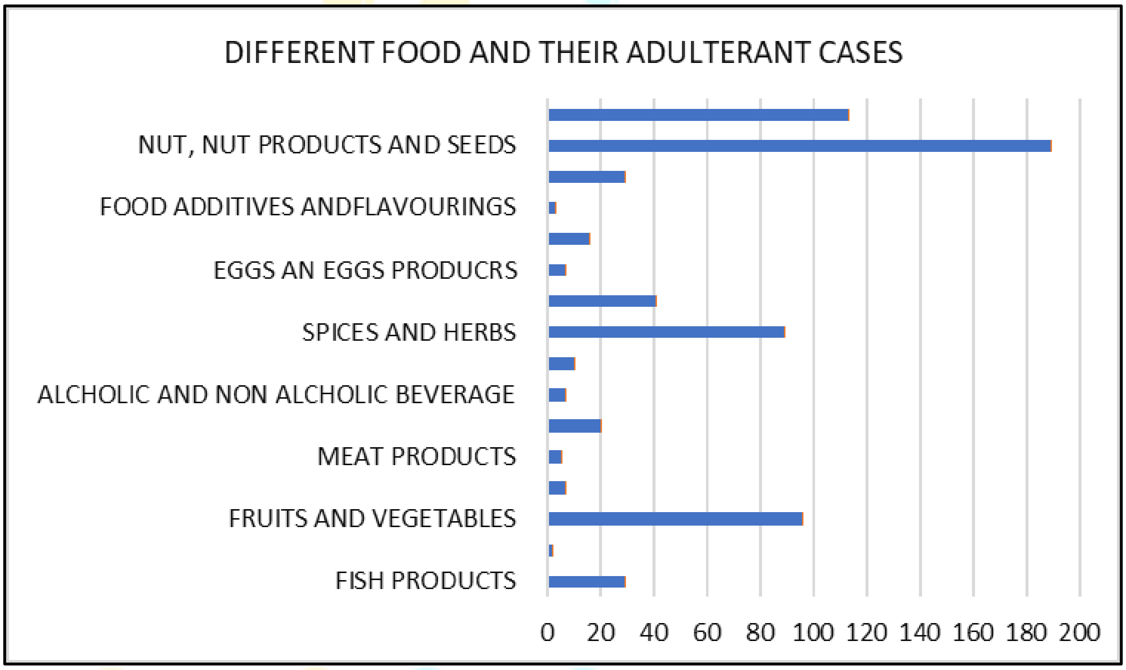
Food adulteration is a menace to health globally, so its detection is imperative (Pal et al., 2020). It increases the population morbidity rate significantly. Some of the health consequences are diarrhoea, nausea, diabetes, cancer, skin diseases, etc. Exposure to higher toxin adulterants can affect internal organs such as the liver, kidney, and heart (Choudhary et al., 2020). The Prevention of Food Adulteration Act (1954) came into effect all over India on June 15th, 1955. This regulated a ban on the distribution and sales of any adulterated food products, including food contaminated with toxins and microbes. In 2011, the Food Safety and Standards Authority of India (FSSAI) established certain standards for the manufacture, processing, storage, distribution, sale, and import of food for consumers' health (*FSSAI*, n.d.). The Food and Agriculture Organization (FAO), under the World Health Organisation (WHO), established the Food Quality and Standards Service to assist developing countries in reinforcing national food control systems. Multiple projects have been initiated by FAO in the past two decades to improve laws and regulations, inspection, certification, monitoring, and training regarding food safety (*FAO Technical Assistance*, n.d.) . Detection of food adulteration is an essential requirement to ensure food standards and consumption safety.

According to the Food Safety and Standards Authority of India (FSSAI) - Food adulteration is when a substance is added or removed from food, which affects the food's quality and natural composition (Food Safety Standards and Authority of India, n.d.-b). This can include:

- Adding substances that make food unsafe, substandard, or misbranded
- Adding substances that reduce the value of nutrients in food
- Adding cheaper or inferior substances in place of valuable or necessary constituents
- Imitating food
- Treating food to improve its appearance
- Adding substances that are harmful to health
- Selling decomposed food
- Using packaging that misleads consumers

The World Health Organization (WHO) defines food adulteration as the "act of intentionally making food lower quality by adding or replacing food substances with undeclared alternatives, or by removing valuable components". Adulteration is not a recent phenomenon. Since ancient times, humans have tampered with food's original form through additions and defilement. But because it was small and had minimal to no effect, it went unnoticed. However, financial adulteration has just come to light as a persistent problem impacting the food industry at its most extreme point. These days, food adulteration is so pervasive that it is hard for consumers to get pure food. The following factors typically contribute to food and beverage contamination (WHO, 2017):

- Maximizing profits: Producers may be able to sell more for less if adulteration occurs.
- Deficits and disparities between supply and demand: To fulfill rising demand, adulteration can be employed to boost food production and sales volumes.
- Loopholes in enforcement: Food adulteration may be caused by ineffective government programs and regulations pertaining to food.
- Consumer illiteracy: Food adulteration can also result from a lack of knowledge about appropriate food consumption.



Graph 2: Different food products and their adulteration cases

Source: Data from RASFF

According to Narayan (Narayan, n.d., 2014) the reasons for food adulteration are:

- When the demand is more than the supply in the market.
- To come at par with the market competitors by lowering the cost of production.
- The greed for increased profit margins.
- The common man cannot afford food items with their original constituents.
- Lack of trained manpower with outdated food processing techniques
- No idea about the disease outbreaks caused due to adulterated food products.

1.2. **Impact of Food Adulteration on Public**

According to the World Health Organization (WHO), food adulteration can have a significant impact on public health and the economy (WHO, 2019) :

a. Health: Unsafe food can cause more than 200 diseases, including diarrhoea, cancers, and organ disorders. The WHO estimates that 600 million people get sick and 420,000 die from foodborne diseases each year. Children under five are especially vulnerable, with 125,000 deaths annually. Other vulnerable groups include the elderly, pregnant women, infants, and people with medical conditions.
b. Economy: Foodborne diseases can strain healthcare systems and harm national economies, tourism, and trade. The WHO estimates that unsafe food causes $110 billion in lost productivity and medical expenses each year in low- and middle-income countries. Food fraud also costs the global food industry an estimated $40 billion annually.
c. Trade: Countries may impose bans and stricter regulations to prevent the import of adulterated goods, which can impact economies that rely on food exports.

Awareness of food safety events through the media about some chemicals that contain a lot of nitrogen has made melamine popular. Some examples are pet food recalls in North America (2007) and contaminated milk, baby formula and other dairy products in China (2008). These resulted in approximately 300,000 sick infants with a death rate of six. The presence of melamine is a serious concern to public health due to its widespread use in both human and animal food supplies (Food Safety Standards and Authority of India, n.d.-b)

The 2015 Maggi noodles crisis arose when FSSAI found high levels of lead and undisclosed MSG in the product even though the packaging carried the message "No added MSG." This had a huge media blitzkrieg, and the brand was severely dented by this customer trust erosion

Indian spice brands MDH and Everest have been banned in Singapore and Hong Kong for suspected high levels of ethylene oxide. The US FDA is also investigating the brands for suspected use of pesticides. Shipments of MDH to the US had a rejection rate of 14.5% since 2021 due to bacterial contamination.

In 2015, the FDA of Uttar Pradesh found detergent in the milk samples of Mother Dairy supplied from Bah tehsil for which the unit was charged with a revocation of license and a penalty for selling adulterated milk. Mother Dairy contested such results, but the concerned authorities warned that frequent consumption may lead to severe health disorders.

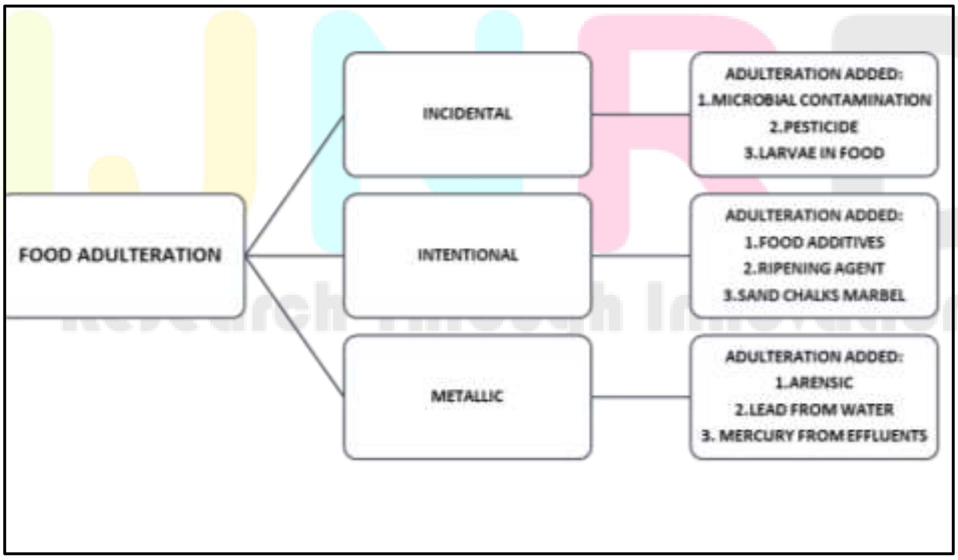


Figure 1: Classification of Food Adulteration

Source: Food Safety Standards and Authority of India, n.d.

2. DISCUSSION

Over the last decade, there have been several qualitative and quantitative tests to detect food adulteration. Several analytical methodologies have been opted for the rapid screening or selective confirmation of adulterants such as liquid chromatography (LC) and gas chromatography (GC), collaterally with mass spectrometry (MS) (Anagaw et al., 2024). A comparatively modern approach based on Raman spectroscopy has been implemented in fat-based analysis (Esmonde-White et al., 2022b). Combining Raman spectroscopy with chemometric data analysis methods showed a promising outcome in an even faster and more accurate detection of food adulterants.

According to the National Nanotechnology Initiative, Nanotechnology is "the understanding and control of matter at the nanoscale, at dimensions between approximately 1 and 100 nanometres, where unique phenomena enable novel applications" (About Nanotechnology | National Nanotechnology Initiative, n.d.). More and more fields are making use of this unconventional science. Nanotechnology can have multifaceted applications in the food industry in processing, storage, preservation, controlled release, and toxin and adulterant detection. In the past ten years, the use of nanotechnology has rapidly increased to ensure food safety. Nanomaterials are applied in the analytical process of physical, chemical, and biological contaminants. Its unique high sensitivity, reactivity, and certain antimicrobial properties have been manipulated for detection processes. Due to the increased surface area of nanomaterials, they can provide a wide range of solutions against the issue of adulteration compared to their macro-scale counterparts.

These materials are created in various forms, including nanoparticles, nanot, nanofibers, nanoemulsions, and nano biosensors. In 2014, a research on the sight detection of melamine adulterants in milk using gold nanoparticles was conducted. Kumar et al. devised a novel colorimetric analysis on the same, using gold nanoparticles (Kumar et al., 2014). It has been tested that coating fish filets with nano-nisin peptide increases their shelf life and protects them from contaminants for up to 12 days. Tripathy et al. developed a sensor paper with nanofibers of nylon that would detect milk adulteration based on pH level and capture the colour changes through a smartphone (Tripathy et al., 2018). Thus, nanotechnology is being used in various forms regarding food safety.

2.1. Different Nanomaterials used in Food Industry

2.1.1. Nanoparticles

Nanoparticles (NP) are solid particulate structures in the size range of 1-100 nm, produced by either a bottom-up or top-down approach. In the former, NPs are created by the aggregation of individual atoms while in the latter, NPs are fabricated by the structural breakdown of bulk material. These NPs are further classified as Inorganic, Organic, and Carbon-based. Inorganic and carbon-based NPs have vast use in detecting food adulterants and pertain greatly against accidental food toxins. AuNPs have great detectability towards intentional chemical adulterants like Sodium dodecyl benzene sulphonate, melamine, and formaldehyde; heavy metals like lead and cadmium; and incidental adulterants like pesticides by acting as an efficient detector in colorimetry analysis (Tseng et al., 2020). AgNPs show significant antimicrobial and disinfectant properties hence used in the detection and decontamination of various adulterants (Bruna et al., 2021). AgNPs assist in determining the presence of antibiotic adulterants like tetracycline residue in poultry products, accidental toxins like aflatoxin, and artificial dyes in food which react with the nanoparticles to give colour changes. Several technical methodologies are being improvised by incorporating nanoparticles such as SERS and molecular assays for effective detection of trace adulterants.

2.1.2. Nanotubes

Sheets of nanoparticles are rolled to form cylindrical structured nanotubes (NT). However, due to the high length-to-diameter ratio, nanotubes are regarded as one-dimensional composition. If a single sheet is rolled, it is called a Single-walled Nanotube (SWNT) and if multiple sheets are rolled, it is called a Multi-walled

Nanotube (MWNT). In the field of food technology, carbon nanotubes are widely utilized. Carbon nanotubes are thermally stable and electrically conductive, two requisites of a sensor. CNTs are used to detect incidental adulterants such as pesticide residues in fruits and vegetables. Due to the versatile nature of carbon, CNTs can recognize a wide range of chemical contaminants through modified electrochemical analysis. Different nanotubes are used in food processing and packaging methods for real-time tracking of accidental adulterations (R. Singh et al., 2020c).

2.1.3. **Nanofibers**

Nanofibers are one-dimensional fibrous materials within a size range of <100 nm. These are produced by electrospinning. The process uses electrostatic force to guide the charged polymer solution across the field to the collector. Nanofibers have varying structures and thicknesses, depending on the manipulation and function. Nanofibers can be implemented to make active food packaging which prevents degradation and adulteration of food by its antioxidant properties. Nanofiber-based optic sensor, along with AuNP pertains to the sensitivity needed to analyse the adulteration level in coconut oil (Jadhav et al., 2017).

2.1.4. **Nanoemulsion**

Nanoemulsions are emulsions made of two dispersion phases, hydrophilic and lipophilic, ranging from 20-500 nm. NEs protect from the active reaction of food components with external factors such as heat, heat, and oxidation, due to their nano size. NEs have a transparent or cloudy appearance and are extremely stable when surfactants are added (Almoselhy, 2023). In food processing, NEs enhance the bioavailability of nutrients and increase the shelf life, preventing accidental adulteration. Nanoemulsion of essential oil chemicals such as thymol, carvacrol, and eugenol acts against food toxins (Maurya et al., 2021). Hence, they are used as natural preservatives, instead of harmful additives.

2.1.5 Nanosensors

Nanosensors help to detect adulterants or spoilage in food by color changes with the production of gases such as hydrogen, hydrogen sulfide, nitrogen oxides, sulfur dioxide, and ammonia. These are more sensitive and selective than conventional sensors. The sensors are usually made from nanosized metallic particles of palladium, platinum, and gold. Gold nanosensors can be used in toxin detection such as aflatoxin B1 in milk (Guo et al., 2020). Recent research shows that nanosensors can be directly installed in food packaging to provide real-time analysis of contaminants. This would reduce the need for laboratory sampling of processed food. The nanosensors would directly indicate the standard and quality of the food product to the consumers. There are several types of nanosensors under research such as biosensors, nanoparticles in solution, nanoparticle-based sensors, nano test strips, electronic noses etc.

2.2. **Common methods of Food Adulteration Detection using Nanotechnology**

2.2.1. Surface Enhanced Raman Spectroscopy

Surface-enhanced Raman scattering (SERS), developed by Sir C.V. Raman in 1928, is an ultrasensitive and non destructive methodology that can be utilised for food adulteration detection (Zhou et al., 2021). The principle is based on the inelastic scattering of photons from a sample, when an incoming excited wavelength of light incident and interacts with it. These scattered photons scan the rotation and vibration of the sample's molecules, providing unique molecular fingerprints. These unique spectral prints can help to identify even trace amounts of adulterants . SERS modified with gold, silver or copper nanoparticles enhances the Raman signals. Adjusting the size, shape and material of the nanoparticles allows ultrasensitive detection of adulterants (Nam et al., 2019). SERS technique is especially effective in metallic adulterants detection. Lead and mercury are both accidental metal adulterants that might be found in traces in agricultural products, and water. A SERS model has been developed using AuNPs and AgNPs for the detection of mercury. Coupled with colorimetric analysis, nanoenhanced SERS signals can detect as low concentration of mercury as 0.28nm (Song et al., 2020).

In lead detection, AgNPs and AuNps were deposited on the SERS substrate, along with a monolayer of graphene on a porous gallium nitride substrate. A thiolated probe (Cy3-DNAzyme) was used for hybridization of single-stranded DNA. In the presence of lead adulterants, the single-stranded DNA and Cy3-DNAzyme splits, enhancing the SERS signals and detecting the adulterants as low as 4.32pM concentration (He et al., 2021).

SERS also helps in detection of pesticide adulterants. Pesticides are a major toxin in both water and food sources. It can contaminate food both by incidental or intentional adulterations. SERS, modified with nanoparticles, can detect pesticide even at a low concentration. Acetamiprid, a common pesticide used against aphids, and methyl parathion has been detected up to a low concentration of 0.9 nM (Pang et al., 2016). Other pesticides such as deltamethrin in strawberries, tea, and wheat have been traced by SERS (Dong et al., 2018) (Jiao et al., 2020). Fipronil insecticide in chicken eggs has been detected by AuNPs (Ly et al., 2019). Recently, portable SERS models with nanoparticles have been developed for in-situ analysis of pesticide traces in fruits and vegetables (Liu et al., 2022). Thiram and carbaryl at trace levels on apple skins have been detected on site using similar methodology to a limit of detection of 2.5 and ~0.012 µg/mL (Nowicka et al., 2019).

2.2.2. Molecular Assays

Molecular assays such as Polymerase Chain Reaction (PCR) can be enhanced with nanotechnology for highly sensitive and efficient detection of adulterants in food (Nam et al., 2022). In PCR technique, specific DNA/RNA sequences are extracted, amplified and analysed for adulterations. Nanoparticles are used in the extraction process such as amino-modified silica-coated magnetic nanoparticles in DNA extraction from raw milk to detect *Salmonella enteritidis* and *L. monocytogenes*, which are considered as adulterants in raw meat and milk by US Department of Agriculture (Bai et al., 2013). Research found the detection limit as low as 15 and 25 CFU/mL respectively. Real time PCR detection of milk adulterants and pathogens has been conducted utilizing immunomagnetic separation with magnetic nanoparticles (Yang et al., 2007). Apart from these, AuNPs combined with loop-mediated isothermal amplification (LAMP) helps in the detection of *Salmonella sp.* in chicken, turkey, and egg products (Teixeira et al., 2020) (Garrido-Maestu et al., 2017) .

2.2.3. Photothermal Assays

Photothermal Assays are mostly used for biological adulterations. It is based on the principle that samples absorb light energy photons and convert it to heat energy to detect biomolecules. This analytical method has been further enhanced by incorporating nanoparticles in the photothermal conversion. Immuno filtration strips, modified with photothermally active AuNPs, helps in the quantification of biological contaminants in food products (Zheng et al., 2022b). The photothermal conversion by AuNPs is directly proportional to the contaminant's concentration (Jia et al., 2018b). These strips are both portable and sensitive. Nickel oxide nanoparticles can both detect and destruct *Salmonella typhimurium* in milk at as low as 10 CFU/mL concentration (Pandian et al., 2017).

2.2.4. Electrochemical analysis

Carbon nanotubes are often used as electrode modifiers due to their high conductivity, stability and biocompatibility. These CNTs have an unique hollow one dimensional structure that helps to increase the surface area of the electrode and helps in increasing electron transfer. CNT based electrochemical analysis has detected pesticides like carbofuran at a minimum concentration of 0.1 ppb (Chen et al., 2008) and heavy metals such as cadmium and lead at concentration limits of 1.06 ppb and 0.72 ppb, respectively (Palisoc et al., 2019). Modified electrodes can also be used to detect food additives and harmful colorants. Nano-ZnO based electrodes and poly (p-aminobenzenesulfonic acid) can detect tartrazine, a lemon yellow azo dye colorant adulteration in foods, at a concentration as low as 80 nM (Karim-Nezhad et al., 2016).

The electrochemical signal generated can be further enhanced by incorporating Signal Tags. Signal tags are labeled components combined to the surface of the electrodes to improve the electrochemical signal generation during the analysis of the analyte (Yu et al., 2019). The signal tags can produce catalytic signals through catalyzing biochemical reactions. For instance, thymine-functionalized silver nanoparticles (Ag-T) have been used as the signal tags for mercury detection (Wei et al., 2015).

2.2.5. Colorimetric sensor

Colorimetric analysis is the detection of concentration of any component in a given product by determining the color change of any dye. In the food industry, colorimetric analysis can be used to detect heavy metal adulterations. Combining with nanomaterials increases the sensitivity and specificity of colorimetric detection. The change to a particular color can be controlled by the size and type of nanoparticles as well. AuNPs, AgNPs and CuNPs are commonly used in colorimetry due to their plasmonic properties (Shrivastava et al., 2022). Plasmonic property is the unique behavior of metal nanoparticles in interacting with light due to the phenomenon of surface plasmon resonance (SPR). This happens when the electric field of incidenting light causes free electrons on the surface of metal nanoparticles to vibrate collectively. This enables the nanoparticles to give the vibrant color on any changes. For instance, AuNPs normally give red color in aqueous solutions at a diameter of less than 30 nm. However, in presence of heavy metal adulterants the particles aggregate and the surface plasmon resonance shifts the red to another color (Hyder et al., 2021b). Similarly, AgNPs and CuNPs, having yellow and red appearance in aqueous solutions respectively, aggregates and shifts in color to indicate presence of metals (González et al., 2014) (Markin & Markina, 2019).

2.2.6. Chromatographic analysis

Chromatographic separation methods can be polarity or boiling-point based. Such methods allow elution of analytes through both stationary and mobile phases, with the weaker-retained components eluting first. Some examples of such methods are gas chromatography (GC), though such methods are often needed to be derivatized, such as in the conversion of tocopherols into the lower-boiling TMS forms. HPLC, on the other hand, allows for direct analysis and thus is useful for food quality and classification. Tocopherols are sensitive with UV or fluorescence detection in HPLC. This method allows for specificity with little interference. UHPLC could increase resolution and decrease the demand of the mobile phase (Derewiaka et al., 2011). HPLC is also capable of distinguishing animal-derived substances such as collagen and food adulteration, such as with milk or gelatin. LC-MS and HPLC are widely applied for the accurate analysis of complex matrices in honey, milk, and other foods (Czerwenka et al., 2010). Specific techniques, like HPLC-MS and HPLC-Q-TOF-MS, identify critical fatty acids or detect adulteration in cocoa powder but are each limited in scope to only partially cover the complex interactions or unknown adulterants. GC-MS permits analysis of the origin of cocoa and detection of lard in chocolate, but this technique has a 4% detection limit for lard and less sensitivity for processing nuances (Suparman et al., n.d.). GC-FID, using helium gas, characterizes fatty acids very effectively and detects minor adulterations in cocoa butter but requires time-intensive steps and may miss low trans fat levels (Oliva-Cruz et al., 2021). Therefore, each technique helps quality control by balancing sensitivity, preparation requirements, and time demands.

Table 1: Different Nanomaterials used in Detection of Food Adulterations

TECHNIQUE	NANOMATERIAL USED	PRINCIPLE	TARGET FOOD	DETECTION SENSITIVITY	DETECTION LIMIT	REF.
NANOSENSORS	GOLD PARTICLE	COLORIMETRIC DETECTION	DAIRY BEVERAGES	HIGH	10^{-9}M	Anh et al., 2022
ELECTROCHEMICAL BIOSENSORS	SILVER NANOPARTICLES	ELECTROCHEMICAL SIGNAL TRANSDUCTION	MEAT, FISH	VERY HIGH	10^{-12}M	Bandyopadhyay et al., 2020
ENHANCED RAMAN SPECTROSCOPY (SERS)	GOLD/SILVER NANOPARTICLES	RAMAN SCATTERING ENHANCEMENT	HONEY, SPICES	VERY HIGH	10^{-11} M	Fá et al., 2019
MOLECULARLY IMPRINTED POLYMERS (MIP)	POLYMERS NANOPARTICLES	SPECIFIC MOLECULAR RECOGNITION	MILK, HONEY	HIGH	10^{-9}M	Y. He et al., 2019
PHOTOTHERMAL ASSAYS	GOLD NANOMATERIAL	HEAT BASED DETECTION DUE TO INTERACTION WITH TARGET MOLECULES	DAIRY, BEVERAGES	HIGH	10^{-10}M	Jia et al., 2018b
BIOSENSORS	GOLD /SILVER NANOPARTICLES CARBON NANOTUBES	BIOLOGICAL RECOGNITION (e.g ENZYME, ANTIBODY, DNA) BINDING WITH NANO MATERIALS TRANSDUCTION	DAIRY, MEAT PRODUCTS, FISH	VERY HIGH	10^{-12}M	Inbaraj & Chen, 2015

2.3. Risk Assessment and Public Perception

There is a significant query among people regarding the safety and risk of implementing nanotechnology in the food industry. A survey was conducted by the Federal Institute for Risk Assessment (BfR) in 2008 and among 1000 German respondents, 66% believed that the benefits of nanotechnology outweighed the risk, while only 9% opposed it. However, when it came to food production, the numbers dropped significantly. 84% of the consumers were against the change in food appearance due to nanoparticles, while only 4% supported the cause (*The Majority of Consumers View the Development of Nanotechnology Favourably - BfR*, n.d.). This shows the public's scepticism towards the application of nanotechnology in food products. The main reason is the yet existing knowledge regarding the characteristics and biological effects of these nano substances. The Inter-Organization Programme for the Sound Management of Chemicals (IOMC) and the Organization for Economic Cooperation and Development (OECD) have listed the top-priority nanoparticles for the determination of their biological characters and affirm their safety (OECD, 2013). This includes some of the extensively used nanomaterials in the food industry such as nanotubes, nano clays, nanoparticles of silver, gold, iron, titanium dioxide, aluminium oxide, silicon dioxide, and zinc oxide.

Thus, the active implementation of nanotechnology in food products requires a comprehensive understanding of the possible hazards and adverse consequences linked to the usage of nanomaterials. Some of the main risk concerns associated are as follows:

a. Health Risk

Nanoparticles, because of their minute size range, can easily penetrate organs, cells, and tissue. They can disseminate into the body through the blood circulatory system, respiratory system, and gastrointestinal tracts. They can translocate through skin contact, irrespective of damaged or undamaged tissues. Thus, they can disperse to the brain, liver, heart, kidneys, spleen, bone marrow, nervous and lymphatic systems (Gorbunova & Tunieva, 2016). If the biological actions are not checked, these nanomaterials may compromise organ functions. Nanoparticles have the capability to pass the blood-brain barrier which, while it might be useful for treatment purposes, can also cause permanent damage to the body if harmful (Hersh et al., 2022). Bioaccumulation is another imperative concern as nanomaterials tend to aggregate if highly concentrated on a specific organ, without any scope of expulsion from the body. AuNPs, AgNPs, and CNTs have shown chances of bioaccumulation (Dash & Kundu, 2020). So extensive research is being conducted to analyze the safe dosage and administrable size of these nanomaterials.

b. Environmental Risk

With the growing concern about ecological safety and future sustainability, it is essential to assess the environmental risks related to the use of nanomaterials in the food industry. Nanoparticles have unforeseen effects not only on humans and animals but on the environment as well. Nanoparticles of silver, iron, and carbon can dissolve in water bodies and penetrate soil layers. This can potentially disrupt the microorganism and microflora balance (Khanna et al., 2021). If the toxic particle enters the food chain, it can impact organisms at different trophic levels (Dang et al., 2021).

In food packaging and preservatives, nanoparticles sometimes show migratory properties. An experiment on the migratory nature of AgNPs showed that silver migration is more in a finished food product (a model medium of 1% acetic acid solution in water experimented) than in chilled meat or fish (a model medium of 0.3% lactic acid solution in water experimented). Thus, it was determined that AgNPs are more optimum and safer in chilled raw animal products (Gallocchio et al., 2016).

c. Toxicity Concern

The toxicity of a nanomaterial depends greatly on its dosage. Some elements are toxic at the macroscopic level but not as much in the nano range. An example is selenite nanoparticles that are not as toxic as selenite in bulk. However, the opposite is also true. High doses of nano gold, silver, or carbon can pose risks such as cytotoxicity, DNA damage, and even brain impairment (Xuan et al., 2023). Nanozinc affects kidney function and induces anemia (Yan et al., 2012). Nanosilver toxicity is associated with oxidative stress, abnormalities in mitochondrial activity, and an increase in membrane permeability (Zhang et al., 2022). However, a 28-day experiment on rats exposed to 1.73 ±104 — 1.23 ±106 particles/cm3 of silver nanoparticles did not exhibit any appreciable symptoms of deviation from the controlled groups (Ji et al., 2007).

d. Insufficient data and unpredictability

Nanotechnology is yet a novel and expanding field of science. Research on its utilization in the food industry is being conducted in the developmental process. The issue of proper risk prediction and the ensuing damage persists despite the abundance of work on the topic. Authors frequently dwell on the difficulty in predicting the effects of ingesting technogenic nanoparticles by living organisms as well as the difficulty in determining the toxic dose of a nanoparticle. These factors depend on a variety of variables like the physical makeup, production process, sizes, and structures of nanoparticles and nanoclusters, as well as the biological model used in the experiments (SCENIHR, 2006). There is also insufficient data due to a lack of experiments on human models. Most of the research is done in vitro or through rat models, due to ethical issues (Schulte & Salamanca-Buentello, 2006).

To ascertain the rapid enhancement of nanotechnology and create a positive perception among the public, different nations have taken up approaches of risk assurance and strong regulations. Several nanotechnological initiatives have been launched by both government and nongovernmental commissions. The Chinese and Taiwanese governments are the pioneers in validating a certification system on the standard of nano products called "nanoMark" (*NanoMark | NanoTechnology Certificate | NPD, n.d.*). The purpose of the nanoMark is to encourage businesses to work on nanotechnology and consumers to purchase such products. This initiative began in 2004 as the public perception of nanotechnology in the food industry is very restricted. Most surveys indicate that the concept of nanotechnology and its benefits are still somewhat abstract to the general public at varying degrees. The United States shows the most optimistic outlook towards nanotechnology (Cobb & Macoubrie, 2004). However, with the growing concern of food adulteration and no alternatives, people are accepting and inclining more toward nanotechnological assistance. Studies show that among all the fields where nanotechnology is implemented, the food industry is the most successful and in demand (Frewer et al., 2004).

3. CONCLUSION

Currently, with growing health issues and sustainability concerns, procuring and consuming safe and adulterant-free food is a basic need. Most food products manufactured and supplied in underdeveloped or developing countries are substandard. To increase the profit margin and meet the exponentially growing food demand, more novel adulterants are being used. Traditional analysis methods are insufficient, thus more researchers are opting for nanotechnological approaches. Nanotechnology provides innovative processes to detect and purify food contaminants efficiently within moments. Nanotechnology provides new opportunities in terms of sensitivity, specificity, and speed in the process of identifying food adulteration or contaminants. Nanostructured devices that are composed of particles can detect other contaminants, pesticides, pathogens and heavy metals ions in real time or at very low concentrations. This is possible since these sensors employ fluorescence, electrochemical detection mechanisms and colorimetric sensing mechanisms to test the food materials and provide results in real short time aimed at preventing foodborne diseases and promoting food security. Also by employing nanostructures in smart packaging materials, for instance, it is possible to make packaging able to effectively communicate the presence of a certain level of spoilage or other changes in the product that may be detrimental to its quality.

On the other hand, nanotechnology assists in enhancing the traceability of products within the food supply chain. Specialized nanomaterials as biosensors or nano labels (activated even by biosimulated light) can be used also in the smart packaging and shelf initialization, monitoring possible factors such as temperature or even pH and the time when a product is no longer fresh and can be consumed. These technologies are expected to get even more developed and commonly used at the point of food preparation or serving. However, more attention needs to be given to evaluating the effects of nanomaterials on health and the environment in order to allow their possibilities and use at large in society. Most studies indicate that the benefits of these nanoproducts extend much further than the possibility of any harm caused. The use of nanotechnology in food safety, though not sanctioned publically to all, is gaining fast popularity due to its specificity and effectiveness. More and more nano products in the future, along with proper regulatory laws, might enable us to completely eradicate adulterations in the food industry.

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