Plant Archives Vol. 25, Supplement 2, 2025 pp. 806-816 e-ISSN:2581-6063 (online), ISSN:0972-5210

Plant Archives

Journal homepage: http://www.plantarchives.org
DOI Url : https://doi.org/10.51470/PLANTARCHIVES.2025.v25.supplement-2.102

NANOTECHNOLOGY: A SOLUTION FOR MITIGATING AGRICULTURAL POLLUTION

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(Date of Receiving : 11-03-2025; Date of Acceptance : 18-05-2025)

ABSTRACT

Nanotechnology has emerged as a promising tool in agricultural practices, offering solutions to enhance crop productivity, manage nutrients effectively, and mitigate environmental stressors. This abstract provides an overview of recent advancements in applying nanotechnology to agriculture, focusing on its roles in crop improvement, soil remediation, and pest management. One significant application of nanotechnology in agriculture is the development of nano-enabled delivery systems for agrochemicals and nutrients. These systems enable precise and targeted delivery of fertilizers, pesticides, and growth regulators, improving their effectiveness while minimizing environmental impact. Additionally, nanomaterial-based sensors allow real-time monitoring of soil conditions and plant health, enabling precision agriculture practices for optimal resource management. Furthermore, nanomaterials have shown promise in soil remediation by facilitating the removal of heavy metals, pesticides, and other contaminants. Their unique properties, such as high surface area and reactivity, make them efficient adsorbents and catalysts for environmental cleanup, contributing to soil fertility restoration and ecosystem preservation. In crop improvement, nanotechnology enables targeted delivery of nucleic acids and gene editing tools for precision breeding and trait enhancement. Nano-enabled formulations of plant growth regulators promote root development, stress tolerance, and yield optimization, supporting sustainable agricultural practices. Moreover, nanotechnology offers novel approaches to pest management, including the development of eco-friendly nanopesticides and nano formulations of botanical extracts with enhanced bioactivity against agricultural pests.
***Keywords* :** Nano technology, nano products, agricultural pollution.

Introduction

Over the past decade, research on applications of nanotechnology in agriculture have been emerging rapidly. Agriculture has also been evolving since history and was in search of newly growing technology that could serve the purpose of producing while maintaining sustainability. Nanotechnology holds high potential to bring sustainable and precise way of solving problems of agricultural sector that eventually aids in development of smart agricultural practices (Lyons *et al.,* 2011). It has been one of the most promising agents in reducing the number of spread chemicals, minimize nutrient losses in fertilization, and increased yield through pest and nutrient management (Prasad *et al.,* 2017; Neme *et al.,* 2021). In the current scenario of rapidly growing global population, nanotechnology could help us produce food grains in surplus in a sustainable manner, while improving resilience of crops in the face of climate change (Iqbal *et al.,*2019). It has been evident from many literatures that the use of nano-formulations or nanoparticles in agriculture has the potential to facilitate precise and controlled delivery of agricultural inputs including fertilizers and pesticides. This strategy seeks to increase the efficiency of agricultural practices by lowering costs, minimizing input amounts, and optimizing water and nutrient management. The goal is to create a more productive agriculture system while addressing environmental concerns tied to the excessive use of synthetic chemicals (Mukhopadhyay, 2014). The prolonged use of chemicals in agricultural practices has led to the emergence of numerous disorders in growers as well as consumers, while also adversely impacting the health of soil and water, making them hazardous for succeeding generations. Therefore, there is a dire need to transform this situation into a sustainable state through the implementation of nanotechnology. In this study we have reviewed the use of nanotechnological tools, such as nano-fertilizers, nano-pesticides, nano-sensors, etc. as an attempt to reduce agricultural pollution.

Scenario of agricultural pollution

The expected increase in global population and food consumption will escalate the demand on agricultural systems to produce food, heightening the risk of water pollution. Taking decisive actions in agriculture to mitigate the impact of agricultural activities on water quality is essential, particularly in managing non-point source pollution. The issue of water pollution in agriculture is a widespread concern affecting both developed and developing nations. In developed countries, agriculture emerges as a notable contributor to water pollution due to the utilization of fertilizers, pesticides, and other chemicals in farming practices (Zahoor *et al.,* 2023). These pollutants possess the potential to infiltrate nearby rivers and lakes, resulting in eutrophication and causing harm to aquatic life. Furthermore, the runoff from agricultural land poses a risk to groundwater, which serves as a vital source of drinking water for numerous communities (Babu *et al.,* 2022).

The substantial utilization of chemical fertilizers and pesticides represents a major contributor to the contamination of agricultural water. When these substances infiltrate nearby water reservoirs, they can adversely affect aquatic ecosystems and pose a threat to human health when consumed or when used for irrigation. While chemical fertilizers and pesticides are indispensable for boosting crop yields and protecting against pests, their usage must be carried out responsibly and in an environmentally sustainable manner.

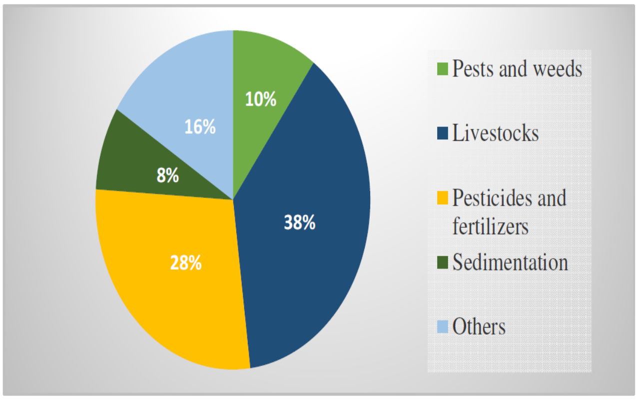

Fig. 1 : Effects of different sources of water contamination (Zahoor *et al.,* 2023)

The excessive usage of chemical fertilizers and pesticides can result in algal blooms, eutrophication, and other detrimental effects on water sources (Wyer *et al.,* 2022). Improper use of fertilizers leads to the migration of excess chemical substances into water bodies such as rivers and lakes, causing eutrophication and negatively impacting the environment, water quality, overall health, and aquatic ecosystems. There are two categories of fertilizers: organic (derived from natural materials like compost and animal waste) and mineral (chemical fertilizers such as nitrates and phosphates) which are considered less sustainable. The research findings of Ndaba *et al.* (2022) reveals that both non-point and point sources of pollution can contribute to eutrophication. Enhancing fertilizer management and storage involves implementing appropriate techniques to prevent runoff and leaching into surface waters. Additionally, insufficient education among farmers contributes to water contamination in agriculture. Lack of awareness about proper pesticide use and irrigation management leads to inefficient practices, causing soil erosion and generation of wastewater. Empowering farmers with knowledge and tools are crucial to promoting sustainable farming practices and reducing the environmental impact of agricultural water pollution (Pravalie *et al.,* 2021). Water pollution can arise from runoff originating in industrial and urban zones. Moreover, incorporation of Genetically Modified Crops (GMOs) could also contribute to water pollution. In developing nations, the absence of regulatory measures and proper infrastructure can lead to increased levels of runoff from industrial and urban areas, while the use of GMOs may result in the leaching of chemical residues into water sources. Recent global research has also focused on assessing nitrate levels in groundwater from wells, boreholes, and springs, with the World Health Organization setting a threshold of 50 ppm for nitrate concentration to ensure water quality. Research findings reveal that Europe has the highest percentage of regions with nitrate levels surpassing 50 ppm, followed by Asia and America (Yadav *et al.,* 2019). There is widespread application of pesticides in agriculture and various industries to manage pests and diseases. While their utilization has transformed agricultural practices and pest control, it has raised apprehensions regarding their fate and potential impacts on the environment and human health. Dating back to the Roman Empire's use of Sulphur as a pesticide, the history of pesticideusage spans thousands of years. The significant expansion in pesticide use during the past century is attributed to technological advancements and the growing consumer demand for food. Organophosphorus pesticides (OPPs) rank among the most commonly employed pesticide, playing a crucial role in reducing pathogen contamination and enhancing production. However, their prolonged use has sparked concerns about adverse effects on animal health and environmental ecosystems. The detrimental impact of organophosphorus pesticides extends to both developed and developing nations, posing a challenge in striking a balance between public health, environmental preservation, and food security. Inadequate water quality not only poses threats to fish and wildlife populations but also diminishes the enjoyment of recreational activities such as fishing and swimming. The presence of sediment pollution stands out as a major environmental concern affecting both water quality and aquatic habitats, with the potential to be mitigated by understanding its origins and consequences and implementing effective best management practices (Sarker *et al.,* 2021). Recent research indicates that light to heavy river pollution reduces GDP growth by 1.4% to 2.5% in 17 countries from 1990 to 2014. This underscores the often-underestimated economic impact of environmental degradation and emphasizing the need for more effective pollution control measures (Russ *et al.,* 2022).

Nanoproducts to mitigate agricultural pollution

Different types of Nano Fertilizers

Nano-Fertilizers

The new era in fertilizers as a complementary to conventional fertilizers is nano-fertilizers. Many researchers have revealed that application of mineral fertilizers (as nitrogen or phosphorus sources) in excess amounts have adverse effects on both the soil and the ground water, due to leaching down of the remaining minerals into the soil andor through vaporisation into air. Tilman *et al.* (2002) state that overuse of fertilizers reduces nitrogen fixation, increases disease and pest resilience, encourages pesticide bioaccumulation, and disturbs bird habitats, all of which lead to long-term ecological and financial losses. Thus, resulting in negative effects on both productivity of crops and environmental sustainability. Recent studies have revealed that use of nano-fertilizers can prove to be eco-friendly, improving soil fertility as well as yield, reduce soil and water pollution and increase microbial activities (Ahmed *et al.,* 2012). Thus, nanotechnology could be considered as a powerful tool to revolutionise agricultural sector (Baruah and Dutta, 2009).

Preetha and Balakrishnan (2017) conducted a study that highlighted the ineffectiveness of traditional fertilizers at reaching the targeted plant portions at all; only certain concentrations are effective un doing so. The main causes of these phenomena include runoff, evaporation, hydrolysis brought on by soil moisture, chemical leaching, and degradation by soil flora. According to Ombodi and Saigusa (2000) research, 40–70% of nitrogen, 80–90% of phosphorus, and 50–90% of potassium fertilizers are lost in the soil and do not reach the intended plants, which eventually causes financial losses. Baruah and Dutta (2009) have observed that the depletion of fertilizers leads to a heightened application of fertilizers and pesticides to the soil, thereby disturbing the equilibrium of nutrients.

The issue of excessive fertilizer use is addressed through a variety of tactics, one of which is the use of nano-fertilizers. These slow-releasing nano-fertilizers offer a good substitute for soluble mineral fertilizers. According to Huiyuan *et al.* (2018), this is because they release nutrients at a moderate rate during crop development, enabling plants to receive most of their nutritional demands without leaching.

Fertilizer particles are applied to the surface of nanoparticles to provide them strength and a higher surface tension than conventional materials. According to Brady and Weil (1999), this strength gain results in more effective management of fertilizer release. In a previous study, Kottegoda *et al.* (2011) synthesized urea-modified hydroxyapatite (HA) nanoparticles for the intermittent release of nitrogen during crop growth. These nano-fertilizers have a slower rate of nitrogen release and can delay plant development for up to 60 days, in contrast to conventional mineral fertilizers that only last up to 30 days. Conversely, Huiyuan *et al.* (2018) discovered that soluble fertilizers contained in nanomaterials to reduce their exposure to water-soluble substances make up controlled-release nano-fertilizers.

Guru *et al.* (2015) claim that formulations of nano-mineral micronutrients improve the solubility of minerals that were previously insoluble and encourage their dispersion in the soil. As a result, there is less of these nutrients absorbed and fixed in the soil, which eventually increases their bioavailability and boosts their uptake efficiency. According to recent studies by Qureshi *et al.* (2018), using rock phosphate that is nanosized increases the amount of phosphorus that is available to plants. This is explained by the fact that the crop was directly treated with nano-rock phosphate nanoparticles, which may have stopped the crop's soil fixation process. Furthermore, the process of phosphorus absorption does not necessitate iron, silicic acid, or calcium, resulting in enhanced phosphorus availability in the soil. Similarto this, ZnO's solubility and dissolution kinetics in nanoparticle form show a faster rate of dissolution than in bulk form, as documented by Milani *et al.* (2012). The recently discovered property of ZnO nanoparticles being very soluble may increase their efficacy as novel fertilizers.

Nano-fertilizers, as emphasized by Cui *et al.* (2010), have a crucial role in managing agrochemical release, minimizing soil and plant toxicity, enabling targeted delivery, and optimizing nutrient utilization. Sasson *et al.* (2007) attributed these benefits to the unique characteristics of nano-fertilizers, including a high surface area to volume ratio, specific targeting, small size leading to high solubility, increased mobility, and low toxicity. Baruah and Dutta (2009) additionally noted that these factors are driving the progressive shift of nanotechnology from experimental domains to practical implementation.

The continuous and widespread use of fertilizers and pesticides negatively impacts the balance of nutrients in the soil, resulting in contamination of the environment that negatively impacts the native flora and fauna. By decreasing the loss of fertilizer nutrients, the use of nano-fertilizers lowers the demand for chemical fertilizers and, as a result, soil contamination. Encapsulated nanoparticles, such as nano-clays or zeolites, have been shown in a recent study by Manjunatha *et al.* (2016) to improve the efficiency of applied fertilizers, hence enhancing soil fertility and plant health. Agro-ecological degradation and environmental pollution are also positively impacted. As a result, controlling the application of mineral fertilizers is essential for meeting nutritional requirements and lowering the possibility of environmental pollution. It is possible to accomplish this goal by using nano-fertilizers.

Nano-Pesticides

Nano pesticides refer to pesticides incorporated into nanomaterials, designed for use in agriculture. They can be used as functionalized nanocarriers that respond to external stimuli or enzyme-mediated triggers, or they can be firmly affixed to a hybrid substrate and encased in a matrix (Chaud *et al.,* 2021). Furthermore, the nanopesticide formulations have the potential to enhance the water solubility and bioavailability of agrochemicals while providing protection against environmental degradation. This innovation has the potential to drastically alter current approaches of managing weeds, insects, and agricultural illnesses (Yadav *et al.,* 2020). On the other hand, the irresponsible and unreasonable application of pesticides can upset ecosystem balances and endanger public health. Pesticide residues in food and drinking water can cause both short-term (acute) and long-term (chronic) exposure that can be lethal or result in disability-adjusted life years. Children are particularly susceptible to the harmful effects of pesticide exposure, facing the risk of permanent damage to their tissues and organs. The effects on blood coagulation capabilities and central and peripheral neurotoxicity are noteworthy issues (Kuhlbusch *et al.,* 2017). Pesticides can be nano encapsulated to solve a number of problems, including challenges with efficacy loss from leaching, degradation, and evaporation. It also increases activity by better interacting with insects, weeds, diseases, and other pests. The potential of these encapsulated nanopesticides to increase overall pesticide efficiency, minimize leaching and drift, reduce usage amounts, target delivery, and prolong agrochemical release has been investigated (Zhang *et al.,* 2019; Xiao *et al.,* 2021; Gao *et al.,* 2021).

Fate of nano formulations in the environment

The impact of a nanoformulation on the movement of an active ingredient (AI) might be diverse and dependent on the product under consideration. Many nano formulations, as depicted in available literatures, aim to achieve the gradual release of an organic AI and/or shield it from premature degradation. The information presented in Table 1 illustrates that several products have successfully fulfilled this goal. Consequently, these nano formulations are anticipated to directly affect the longevity of the AIs. However, the potential impacts of a nano formulation on other environmental fate processes have seldom been taken into account. Polymer-based nano pesticides have received the most attention to date and can serve as a useful model with which to illustrate the issues discussed in the sections below. We thus consider a nanocarrier (NC) that is loaded with an AI and releases the free AI over time.

Facilitated Transport

Sorption is a crucial process that influences the movement of pesticide AIs after they are applied. The only test for sorption in soil that has been presented was for a nano formulation of paraquat, whose release in water happened in 8 hours (Silva *et al.,* 2011). Batch tests were conducted on very small quantities of soil (0.01–0.05 g) over a period of 3 hours. Even after increasing the amount of soil or the organic matter content, the sorption of the nano formulated paraquat remained low in comparison to that of the pure AI. By reducing sorption and degradation processes, the researchers speculated that the nano formulation may considerably improve the herbicide's efficacy during application. This idea, meanwhile, is predicated on the direct adoption of NC-AI, a phenomenon that has not yet been demonstrated. A careful assessment of the possibility of enhanced movement into groundwater and surface water is also necessary.

The Damkohler number (Da) computation can be used to compare the release of the AI from the nanocarrier, which is equal to the desorption kinetics of the contaminant from the colloid, to the travel time scales. $Da = \lambda\tau$, where τ (s) is the system's mean residence time and λ is the reaction's first-order rate constant (s^{-1}) (Jennings and Kirkner, 1984). The prevailing agreement by Bold *et al.* (2003) states that:

Da>100: Desorption (or release) occurs quickly relative to the transit time scale. This indicates circumstances of equilibrium, and one can ignore enhanced transit (Kretzschmar *et al.,* 1999; Roy and Dzombak, 1998). Conventional solute transport models should accurately reflect the transport of nanopesticides that fall under this group.

Da<0.01: Desorption occurs at such a slow rate. This indicates the transport of the contaminant (in this case, the active ingredient, or AI) and the colloid (the nanocarrier, or NC) is referred to as "decoupled." This suggests that two different pools, the dissolved pool (affected by the AI properties and solute transport) and the attached pool (influenced by the NC properties and colloid transport), need to be taken into account, each with its own set of fate properties. The differences between colloid and solute modelling techniques and their regulatory applications were discussed before in relation to nanopesticides (Kah *et al.,* 2013).

0.01<Da<100: it signifies kinetic conditions where the assessment of desorption (or release) kinetics becomes essential to understand the transition from the attached to the dissolved pools and subsequent alterations in behaviour over the transport time scale.

The initial determination of whether equilibrium, decoupled, or kinetic conditions are applicable serves as a crucial step in identifying scenarios where the facilitated transport of the AI by the nanocarrier can be disregarded (under equilibrium conditions). It also aids in choosing the appropriate modelling approach for other situations. Consequently, when evaluating the transport of nano-pesticides post-application, the primary step involves characterizing the expected release profiles under field conditions.

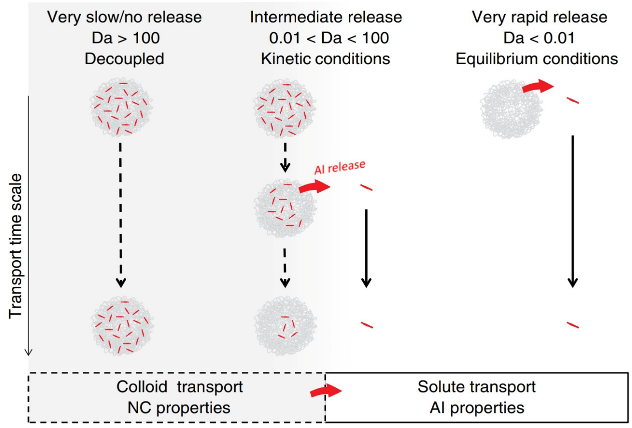

Fig. 2 : Three transport scenarios for the active ingredients (AI) can be distinguished, depending on the release rate from the nanocarrier (NC, represented as grey spheres) relative to the transport time scale.

Bioavailability of nano pesticides

The ability of polymer formulations to increase an active ingredient's (AI) bioavailability has been widely investigated in the context of pharmaceutical medications (Vrignaud *et al.,* 2011). Improved skin penetration, as seen in chitosan-based formulations, could be one aspect of this improvement (Ammala, 2013). Different nanoformulations have proven to be more effective than commercial formulations and pure AI (Kumar *et al.,* 2013; Qing *et al.,* 2013; Kah *et al.,* 2014). When compared to the AI alone, the nanocarrier-active ingredient (NC-AI) may have a higher bioavailability and greater absorption, which would explain its improved efficacy. Although increasing target organism uptake is a desirable goal, it must be accomplished without increasing the risk to non-target organisms, such as handlers and bystanders.

It is indisputable that the properties of the carrier and the particular cells or organisms being studied affect the bioavailability of the nanocarrier-active ingredient (NC-AI). Since several of the observed NC-AIs have quite large sizes, direct uptake is generally regarded as unlikely. Research pointing to increased toxicity or efficacy after AI release has suggested that NC-AI has a restricted bioavailability. However, at present, no data is accessible concerning studies conducted on the bioavailability of nanopesticides. It may be oversimplified to view the AI that was loaded onto the NC as completely unavailable because there may be more complex processes involved. For example, research has demonstrated that chitosan, a commonly utilized polysaccharide as a polymer carrier for nanopesticides, can alter the enantioselective bioavailability of the chiral herbicide dichlorprop (Wen *et al.,* 2010). Additionally, Qing *et al.* (2013) have proposed that the safeguarding of the active ingredient against photodegradation is significantly influenced by its position or distribution within the polymeric matrix. The bioavailability might also be contingent on the location of the active ingredients within the polymer matrix. It is plausible, for instance, that soil microorganisms could have access to the active ingredient molecules situated at the surface of the nanocarrier but not to those located in the core. Gaining insights into how bioavailability relies on the characteristics of nanoformulations and the organisms engaged becomes highly valuable in elucidating observed variations in efficacy or toxicity across diverse nanoformulations and organisms (such as target and non-target organisms, as seen in studies by Kumar *et al.,* 2013, and Pradhan *et al.,* 2013). Enhanced understanding of the distribution and release of the active ingredient under various conditions is imperative for addressing the remaining crucial inquiries regarding bioavailability.

Mechanisms of Release

The degradation processes of polymers are anticipated to significantly impact the patterns of release. There are two types of polymer carriers: surface-eroding polymer spheres and bulk-eroding polymer spheres. Surface-eroding polymers are typically hydrophobic, resisting water penetration into the polymer bulk, and undergo rapid degradation at the polymer/water interface through hydrolysis. Consequently, the release of the active ingredient predominantly takes place at the polymer's surface as it undergoes breakdown. When the active ingredient is uniformly dispersed throughout the matrix, the highest release rate occurs initially, and over time, both the surface area of the spheres and the release rates diminish. Furthermore, if the AIs are not evenly dispersed throughout the polymer matrix, quick desorption and diffusion from the surface could cause an AI release burst. Many nanopesticides have been shown to have this unfavorable effect, which prompted the creation of substitutes (such as nanogels or nanofibers) later on (Kah and Hofman, 2014).

Factors affecting release

Various attributes of polymers have been demonstrated to affect the release profiles, encompassing factors such as the length of polymer chains (Loha *et al.,* 2012; Sarkar *et al.,* 2012), the gum to chitosan ratio (Abreu *et al.,* 2012), and the content of cellulose nanocrystals (as evidenced by Xiang *et al.,* 2013). As the particle size diminishes, there is an increase in the surface area to volume ratio, consequently leading to an anticipated rise in flux. Numerous nanopesticide formulations have exhibited a swifter release with decreasing size, exemplified by Mingming *et al.* (2013) in the case of a nanosilica–naphthylacetic acid formulation. This raises questions about the practicality of designing exceedingly small carriers, especially when the objective of the formulation is to achieve prolonged activity over weeks or months, given their faster release rates compared to larger carriers. The chemistry of the soil solution, the presence of soil particles, and microorganisms are examples of environmental factors that can affect release profiles. According to Brunel *et al.* (2013), the pH was shown to have a significant impact on the nanoformulation; however, data about other parameters are currently unavailable.

Nanosensors

Detection of harmful contaminants in soil and wastewater is a crucial step before their removal, and researchers are actively exploring methods to identify these toxic chemicals. To achieve highly sensitive detection, they are developing sensors that leverage the unique properties of nanostructured materials. Environmental monitoring focuses on detecting pollutants present in the atmosphere and wastewater, employing various sensor categories that operate based on distinct principles. Biosensors, for instance, have shown efficacy in identifying compounds like phenols/phenoxy acids (e.g., phenol and catechol), polyaromatic compounds (e.g., benzo[a]pyrene), halogenated pesticides (e.g., triazines), volatile organic compounds (VOCs) such as benzene, and inorganic substances. Biosensors have been documented as effective in identifying various compounds, such as phenols/phenoxy acids (e.g., phenol and catechol, Munteanu *et al*. 1998), polyaromatic compounds (e.g., benzo [a]pyrene, Alarie *et al*. 1990), halogenated pesticides (e.g., triazines, Orozlan *et al*. 1993), volatile organic compounds (VOCs) like benzene (Ikariyama *et al*. 1993), and inorganic substances, for example, mercury (Pirvutoiu *et al*. 2001). Solid-state electrochemical sensors are considered ideal for chemical gas sensing due to their sensitivity, reproducibility, and low power consumption. Research into semiconductor use for gas sensing gained prominence after the pivotal report by Brattain and Bardeen in 1953. The gas detection technique primarily relies on changes in the electrical resistance of semiconducting metal oxide films (Jonda *et al*. 1996). The key detection process involves alterations in the oxygen concentration at the surface of these metal oxides, induced by the adsorption and heterogeneous catalytic reaction of oxidizing and reducing gaseous species. The electrical conductivity is influenced by the gas atmosphere and the temperature of the sensing material exposed to the test gas (Eranna *et al*. 2004). One significant drawback of solid-state gas sensors is their limited selectivity. Various approaches, including doping with metal impurities (Nanto *et al*. 1986), impedance measurement (Faglia *et al*. 1994), modulating operating temperature (Heilig *et al*. 1997), surface coating (Pengfei *et al*. 2003), and others, have been reported to enhance sensor selectivity. Additionally, studies have explored the application of metal oxide-based gas sensors for monitoring air pollution (Pummakarnchanaa *et al*. 2005).

Biosensors

Biosensors are being used extensively in environmental monitoring, industrial and food processing, and healthcare. Devices known as biosensors take advantage of biological reactions' capacity to identify particular target analytes. The first description of a biological sensor was published in 1962 by Clark and Lyons. At that time, the sensor was created based on the particular catalytic interaction between glucose and the glucose oxidase enzyme. The Pt electrodes that Clark utilized are referred to as "Clark electrodes" since he is widely acknowledged as the biosensor's founder. The "enzyme electrode," a tiny chemical transducer that likewise uses glucose oxidase immobilized on a gel to monitor the concentration of glucose in biological fluids, was first described in another study that was published in Nature in 1967 (Updike and Hicks 1967). Since then, the science of biosensors has advanced quickly in creating sensors that can characterize biomolecules in a variety of settings, including agriculture, medicine, and the environment. With the integration of novel technologies in the fields of molecular biology, microfluidics, and nanomaterials, biosensors find extensive uses in food processing, agricultural production, and environmental monitoring. These applications include in-field, real-time, online, and in-field detection of pesticides, pathogens, toxic materials, proteins, antibiotics, and bacteria that cause Odors in soil, water, food, and animals. The National Institute of Advanced Industrial Science and Technology (AIST) in Japan's Research Center of Advanced Bionics (RCAB) created the first biosensor in history in 2004 to assess the activity of soil microorganisms. The biosensor has the ability to predict when soil illnesses may manifest. Estimating the relative activity of favourable and unfavourable bacteria in the soil based on differences in oxygen consumption during their respiration is the fundamental idea behind soil diagnosis using a biosensor. Therefore, it is possible to forecast in advance whether or not the examined soil will experience a soil disease epidemic. Thus, the biosensor presents a novel method of determining soil condition based on numerical data. Based on the surface plasmon resonance (SPR) that metal nanoparticles show, certain research groups are creating biosensors (Haes and Van Duyne 2002; Malinsky *et al*. 2001). According to Taton *et al*. (2001), metal nanoparticles can be engineered to scatter light at various wavelengths based on their unique surface plasmon resonance (SPR). According to Cao *et al*. (2001), biomolecules including proteins and oligonucleotides can be utilized to modify the surface of nanoparticles, giving them useful biorecognition capabilities. Due to inter-particle electromagnetic interaction, short segments of deoxyribonucleic acid (DNA) attached to colloidal gold nanoparticles show a color shift from red to blue after hybridization. Currently offered for sale, DNA microarrays rely on optical methods for detection. Nevertheless, the implementation of these technologies in portable devices is challenging and costly.

Microorganisms generate a variety of identifiable volatile compounds that can have both beneficial and harmful effects on humans. Food items, particularly those in the dairy and bakery categories, provide an ideal environment for the rapid proliferation of various microorganisms. Bacteria play a significant role in the spoilage of food, often manifesting through unpleasant odors. The use of rapid detection biosensors, capable of identifying foul odors, can reduce the necessity for food processing units to conduct extensive microbial tests and immunoassays on materials suspected of harboring food-borne pathogens. Biosensor applications extend to detecting contamination in treated water, raw food materials, finished food products, and production lines. These applications force food producers to either hold inventory for testing or release potentially harmful products. Enzymes are employed as sensing elements due to their specificity in binding to biomolecules, as illustrated in Fig. 3 for enzymic biosensors.

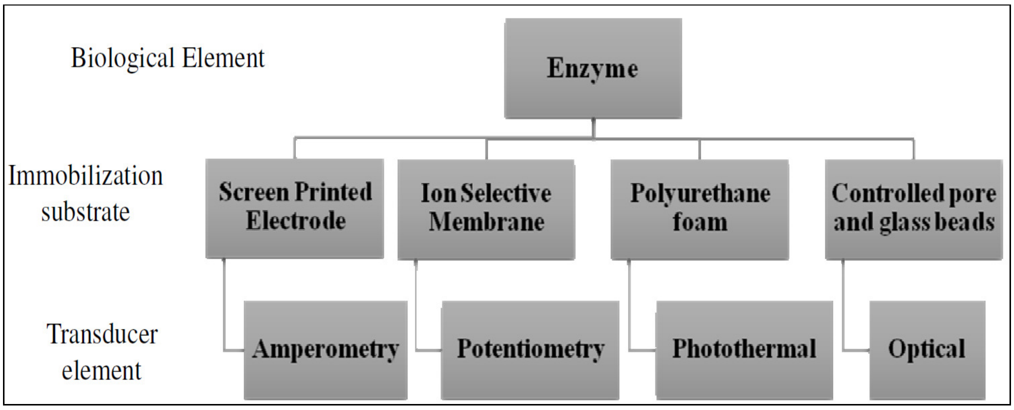

Fig. 3 : The flowchart of enzymic biosensors. Presence of the biological element is done through electrical or optical signals (Baruah and Dutta, 2009).

In the realm of electromechanical sensors, soil temperature and moisture are crucial parameters for regulating the exchange of heat energy and water between the earth's surface and the atmosphere through processes like evaporation and plant transportation (Jackson *et al*. 2007). As water plays a vital role in agriculture, accurate updates on soil moisture at the root level of plants are essential for irrigation management systems. Traditional methods for soil moisture and temperature detection lack precision in providing accurate profiles and are both bulky and expensive. To address this, researchers have devised cost-effective sensors using wireless nanotechnology, comprising micromachined microelectromechanical system (MEMS) cantilever beams coated with a water-sensitive nanopolymer for moisture detection. Additionally, an on-chip piezo-resistive temperature sensor detects temperature changes. Nanotechnology-based MEMS sensors not only sense but also respond to environmental changes through microelectronic circuits, such as, for temperature and moisture sensing.

Conclusion

Nanotechnology is becoming more feasible in the agricultural sector. Promising results and applications are already being developed for pesticide, biopesticide, fertilizer, and genetic material for plant transformation. The use of nanoparticles to deliver insecticides and fertilizers is predicted to lower dosage while maintaining regulated gradual distribution. The use of nanoparticles to stabilize biocontrol preparations is expected to make a significant contribution to lowering environmental hazards. Nanotechnology, by leveraging the unique features of nanoparticles, has created nano sensors capable of detecting viruses at levels as low as parts per billion. Aside from detection, nanotechnology offers ways for decomposing persistent compounds into harmless and occasionally helpful components. Agricultural technology should use nanotechnology's tremendous tools to detect toxins in soil for the sake of humanity. Nanotechnology tools can be used to address urgent environmental challenges such as pollution.

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