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NANOTECHNOLOGY FOR AGRICULTURE AND FOOD SYSTEMS – A VIEW

H. C. Warad and J. Dutta

Microelectronics, School of Advanced Technologies, Asian Institute of Technology, P.O. Box 4, Klong Luang, Pathumthani 12120, Thailand. E-mail: joy@ait.ac.th

ABSTRACT

Nanotechnology applications in food and agriculture is in its nascent stage and over the next decade we will see increasing uses of tools and techniques developed by nanotechnology to detect carcinogenic pathogens and biosensors for improved and contamination free food and agricultural products. Here we discuss some of these applications that has a potential for wider acceptance in the field of food and agricultural technologies.

Keywords: nanoparticle, Q-dot, colloid, nanotechnology

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INTRODUCTION

The word 'nano' meaning 'dwarf' in Greek language refers to dimensions on the order of magnitude of 10^{-9}. Nanotechnology, focusing on special properties of materials emerging from nanometer size, for e.g. In biological systems, the first level of organization occurs at the nanoscale structure where all the fundamental properties and functions are systematically defined.

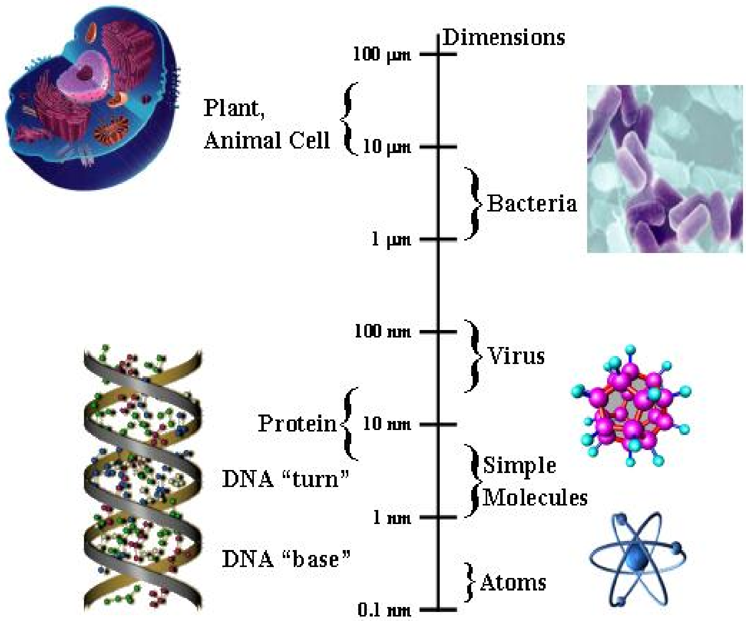

Fig. 1: Logarithmic Length, A matter of scale, and the level of structure

Nanotechnology has the potential to revolutionize the scientific world by allowing scientists to manipulate matter at the atomic or molecular scale using physics, engineering, chemistry and biology [1]. Nanotechnology is a broad and interdisciplinary area of research and development activity that has been growing at a raipd pace worldwide in the past few years. It enables researchers to understand the relationship between macroscopic properties and molecular structure in biological materials of plants and animal origin [2]. It is already having a significant commercial impact, which will certainly increase in the future. Using nanotechnology, scientists are able to self assemble atoms into structures with highly controlled properties e.g. nanowires [3, 4], self assembled molecules and particles [5], 3-D architecture [6] etc.

There are two basic forms of attaining nanomaterials “top-down” and “bottom-up”. The Greeks coined the term ‘atom’, defined as the unbreakable, implying that they believed that it was possible to break down matter down to the level of individual atoms or molecules. This old age approach is termed as ‘top-down’ approach. This approach usually involves breaking of big chunks of materials (physically or chemically) into smaller objects of desired shapes and sizes by either cutting or grinding. e.g. mechanical milling, ion implantation etc. Complementary to ‘top-down’ approach is the ‘bottom-up” approach or ‘self-assembly”, which involves building up of macro-sized complex systems by combining simple atomic level components material. By this approach of arranging molecules one at a time, we can design complex systems by incorporating specific features which requires a good understanding of individual molecular structures and various molecular forces.

From the moment of the creation of the universe, to the first signs of life on this earth, self-organization has existed. Nature has evolved many bioorganic molecules that form complex structures with very complex dynamic behavior, called living cells. These cells, self assemble and form further complex structures culminating in intelligent life forms like humans and other animals. Even when a damage is done to the living cells, nature has an amazing ability to heal itself by self-organization. e.g. when a living cell is wounded, the body reacts by sending white blood cells to ward off the infections killing the germs, red blood cells and proteins form a seal cover over the wound and also nutrients to the cells, so that they can produce new cells to replace the damaged cells. Such biomaterials are custom made for specific applications inspiring us to design materials that are ideal for a specific application rather than to cut and trim natural materials to suit our needs. When materials are built by the bottom-up process , one molecule at a time, it is possible to incorporate specific features at will. The concept of self-assembly with nanotechnology has the potential to impact diverse fields ranging from biology to materials science [7].

Nanotechnology will enable making high-quality products at a very low cost and at a very fast pace. It is commonly referred to as a generic technology that offers better-built, safer, long lasting, cheap and smart products that will find wide applications in household, communications, medicine as also agriculture and food industry amongst others. Currently the main thrust of research in nanotechnology focuses on applications like electronics, automation, medicine and life sciences [8]. The experience gained from this could be used to revolutionize the food and agriculture systems. Novel agricultural and food security systems, cellular biology, environmental protections, disease treatment delivery methods etc. are just a few examples where nanotechnology could have important impact.

Agriculture forms the backbone of third world economies. Research in agriculture has always dealt with improving the efficiency of crop production, food processing, food safety and environmental consequences of food production, storage and distribution. Nanotechnology provides a new tool to pursue these historically relevant goals. A reappraisal of attitudes towards food security, increasing emphasis on environmental compliance and alterations to the Common Agricultural Policy all combine to make farming and rural land-owning far less profitable than in previous times.

In agriculture and food systems, the fundamental life processes are explored through research in molecular and cellular biology. New tools for molecular and cellular biology are needed that are specifically designed for separation, identification and quantification of individual molecules. This is possible with nanotechnology and could permit rapid advances in agricultural research, such as reproductive science and technology, conversion of agricultural and food wastes to energy and other useful by-products through enzymatic nanobioprocessing, disease prevention and treatment in plants and animals. To excel in these and other areas of agriculture, are required novel tools that allow us to work and explore living cells and biomolecules at the molecule scale. Nanotechnology holds such a promise.

Applications

Photocatalysisis one such application using nanoparticles [9]. Photocatalysis is a reaction in which chemical compounds react in the presence of light and itself not being completely consumed in the reaction. In the presence of UV light the valance electrons in the nanoparticles are excited to form electron-hole pairs. These negative electrons and positive holes are strong oxidizers. When harmful substances (pesticides) stick to the positive holes, they are disintegrated into harmless compounds. The excited electrons are also injected in bacteria in contact of nanoparticles and hence act as a disinfectant (could find applications in fruit packaging and Food Engineering).

Photocatalysis degradation process has gained popularity in the area of wastewater treatment process [10]. Peral et al [11] explained the use of photocatalysis for purification, decontamination and deodorization of air. Mills et al [12] also explained semiconductor sensitized photosynthetic and photocatalytic processes for the removal of organics, destruction of cancer cells, bacteria and viruses.

Metal oxides like TiO_2 [13], ZnO [14], SnO_2 [15] etc. as well as sulphides like ZnS [16] have been used for photocatalysis. These nanoparticles have efficient disinfectant rate due to another important property of nanoparticles in general, which is increased surface to volume ratio (Fig. 1). The principle of photocatalysis could be used in the decomposition of toxic pesticides, which take a long time to degrade under normal conditions [17].

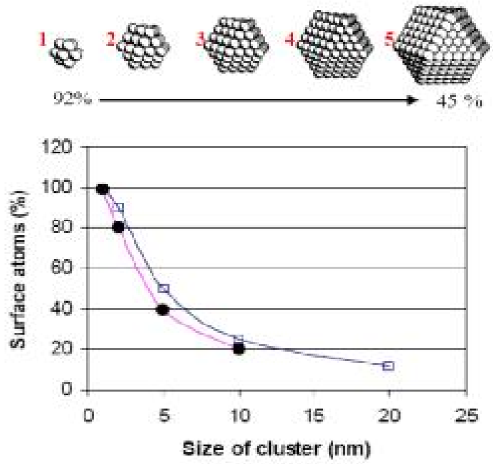

Fig. 2: Number of surface atoms increases when particle sizes decrease. This result in increased reactivity and other physical and chemical properties related to exposure to specific conditions, like photocatalysis, photoluminescence, etc[18]

Identification tags are a part of our daily life today, right from application in wholesale agriculture and live stock products to consumer products. Ultra miniaturized identification tags have applications in the field ranging from advanced biotechnology to agricultural encoding. The possibility of large number of combinations of these nanobarcodes (> 1 million) makes them attractive also for use in multiplexed bioassays and general encoding. Matthew et al [19], describes micrometer sized glass barcodes doped with rare earth containing a specific type of pattern of different fluorescent materials that are identified by using UV lamp and optical microscope. For application in DNA hybridization assays.

Nanobarcode [20] particles are encodeable, machine-readable, durable, sub-micron sized taggants as shown in (Fig. 3a). They are freestanding, cylindrically shaped metal nanoparticles having dimensions of 20 - 500 nm in diameter and 0.04 - 15 mm in length. The particles are manufactured in a semi-automated, highly scalable process by electroplating inert metals (Gold, Silver etc.) into templates defining particle diameter, and then releasing the resulting striped nano-rods from the templates (Fig. 3b).

Applications for these nanobarcodes are as ID tags for multiplexed analysis of gene expression and intracellular histopathology. The Nanobarcodes particles technology also holds great promise in non-biological applications, especially for robust, uniquely identifiable nanoscale tagging of small items for authentication or tracking in agricultural food and husbandary products. The technology will allow tagging of items previously not practical to tag with conventional barcodes, as well as aiding in the development of new Auto-ID technologies.

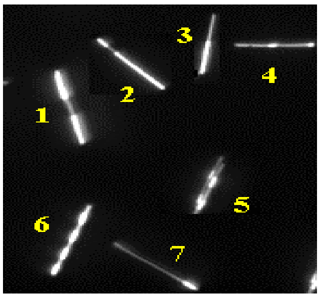

Fig. 3a: Optical micrograph of a mixture of 7 flavors of Nanobarcodes

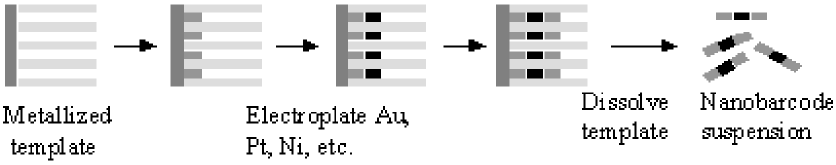

Fig. 3b: Template-directed synthesis of Nanobarcodes particles (http://www.nanoplextech.com/technology/nanobarcodes.htm)

Bacteria are the most primitive life forms found almost in all places. We come into contact with millions of bacteria every day. They are in the air we breathe, in the food we eat and on the surfaces of most things we touch. Along with some useful bacteria there are numerous other disease causing bacteria. Organic dyes are the most commonly used biolabels to stain bacteria for detection. Organic dyes are expensive and also their fluorescence degrades with time. So there is a need for a better alternative. Recent advances in the field of luminescent nanocrystals have led to a new area of research in fluorescent labeling by quantum dots (QDs) with bio-recognition molecules. QDs have several prominent advantages over conventional organic fluorophores (dyes) as they are more efficient in luminescence compared to the organic dyes, their emission spectra are narrow, symmetric and tunable according to the particle sizes and material composition of the QDs and they show excellent photostability [21]. Due to their broad absorption spectra, they can be excited to all colors of the QDs by a single excitation light source. Fig. 4 shows bacteria bacillus bio-labeled by $ZnS:Mn^{2+}$ nanoparticles capped with bio compatible 'chitosan' [22].

Su et al [23] demonstrated a sensitive and rapid method for the detection of E. Coli O157:H7 using quantum dots (QDs) as a fluorescence marker coupled with immunomagnetic separation. They used magnetic beads coated with anti-E. coli O157 antibodies to selectively attach target bacteria, and biotin-conjugated anti-E. coli antibodies to form sandwich immuno complexes. After magnetic separation, the immuno complexes were labeled with QDs via biotin-streptavidin conjugation.

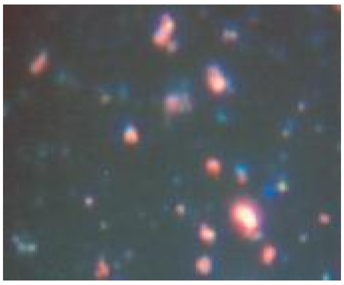

Fig. 4: Bacillus as seen under a Fluorescence Microscope. The orange glow is from bio-functionalized $ZnS:Mn^{2+}$ [24]

Pathogen detection market encompasses medical, military, food and environmental industries along with the food pathogen testing markets are close to 1 billion UD $ [25]. Microorganisms produce a range of characteristic volatile compounds that may be useful as well as harmful to human beings. e.g. Yeasts are beneficial for fermentation, bacteria eat sugar thereby producing alcohol as a by-product. Dairy products, bakery products and other food products are ideal media for rapid growth for a wide range of microorganisms. Bacterias are the most common cause of food rotting. The presence of foul odor is an indication for food rotting. Human nose can literally detect and distinguish thousands of odors which is sometimes impractical and could also be a further cause for poisoning. Sometimes it is more practical to use instruments to detect these odors with what we popularly known as Rapid detection biosensors can minimize the need for food processors to perform lengthy microbial testing and immunoassays on materials suspected of carrying food-borne pathogens.

Applications include detecting contaminations in water supplies, raw food materials and food products as well as the processing lines – all of which require food producers to either hold on to inventory to complete the tests or simply release products which might be harmful. Enzymes can be used as a sensing element, since they are known to be very specific in attachment to certain biomolecules. The general classifications and working of enzymic biosensors is described in fig. 5

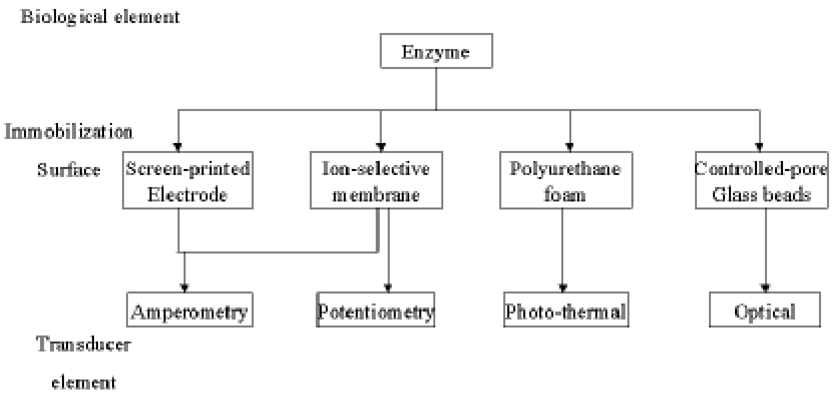

Fig. 5: Presence of the biological element is determined through electrical means (Amperometry or Potentiometry) or through optical means[26]

Electronic Nose (E-Nose) is a device mimicking the operation of the human nose, which uses a pattern of response across an array of gas sensors to identify different types of odors. The main purpose of the E-nose is to identify the odorant, estimate the concentration of the odorant and find characteristic properties of the odor as might be perceived by the human nose.

The main components in an E-Nose are its gas sensors that identify odors. One such gas sensor functional diagram is shown in Fig. 6a. These gas sensors are composed of nanoparticles (E. g. Zinc oxide nanowires [4, 27]) whose resistance changes when a certain gas is made to pass over it. This change in resistance generates a change in electrical signal that forms the fingerprint for gas detection. This finger print pattern derived from the sensor is used to determing the type, quality and quantity of the odor being detected. The advantage of using nanoparticles is that they have improved surface area for better gas adsorption (fig. 2). Fig. 6b shows Scanning Electron microscope (SEM) image of ZnO nanowires.

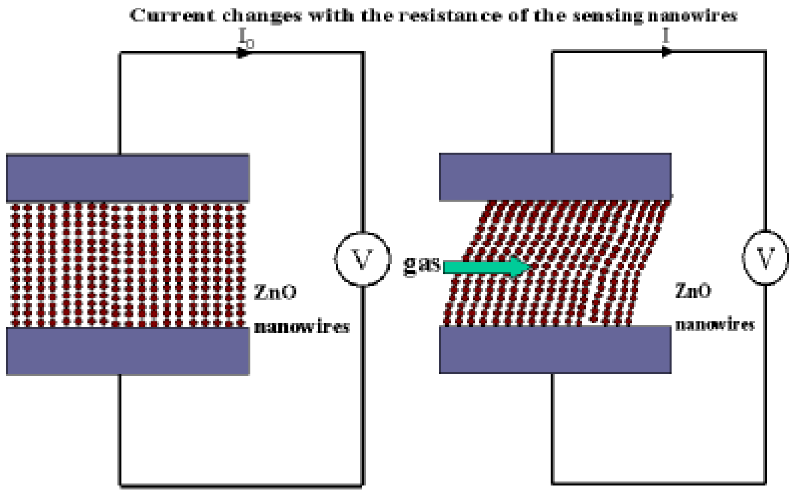

Fig.6a: Functional diagram of gas sensors whose current is a measure of change in resistivity of ZnO nanowires on gas adsorption [27].

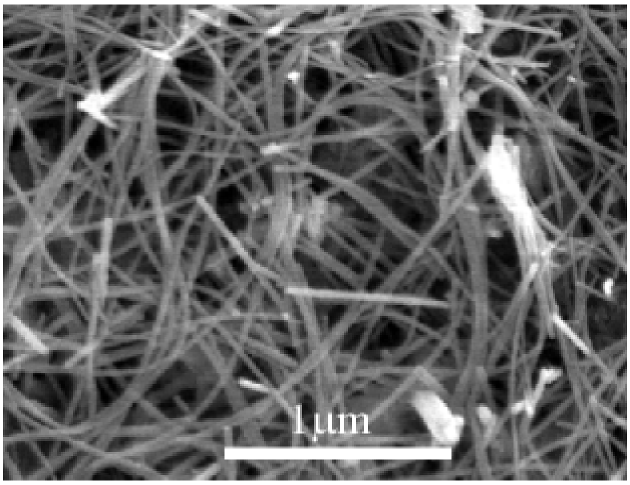

Fig.6b: SEM Image of homogenous ZnO nanowires.

Gold has fascinated man for centuries. Its several qualities have made it valuable throughout history, both as a medium of exchange and for decorative use as jewelry. Like bulk gold, it is most widely studied and abundantly used nanoparticles. Currently rapid testing arrays like pregnancy tests and bio-molecule detectors are a few commercial applications of gold nanoparticles. These applications are based on the fact that the color of these colloids depends on the particle size, shape, Refractive Index (RI) of the surrounding media and separation between the nanoparticles. Any change in any of these parameters results in a quantifiable shift in the Surface Plasmon Response (SPR) absorption peak [28].

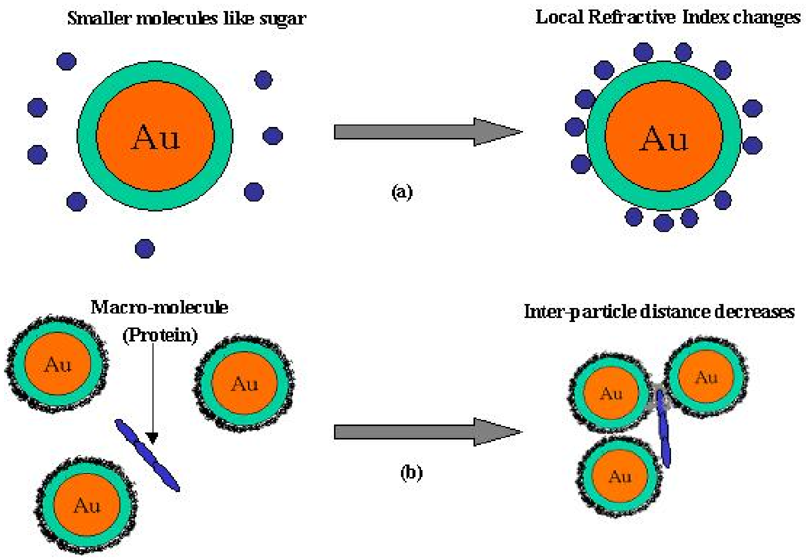

Fig. 7: Plasmon resonance sensors: **(a)** The changes in local RI caused by adsorption of amine molecules, causes a detectable shift in the SPR peak; **(b)** Agglomeration of gold nanoparticles causes a red shift in the SPR peak, agglomeration can be induced with a macro-molecule [29].

By carefully choosing the capping agent for stabilizing gold nanoparticles, we can make these nanoparticles attach to specific molecules, which get adsorbed on the surface of these nanoparticles changes the effective RI of the immediate surrounding of the nanoparticles [30] (Fig. 7a). If the detecting molecules (bio-macromolecules) are larger than the gold nanoparticles, they will adsorb a few nanoparticles making them agglomerate into lumps [31]. This reduces the particle spacing, resulting in shift of SPR, and hence changing the color of gold nanoparticles (Fig. 7b).

CONCLUSIONS AND PERSPECTIVES

Nanotechnology is a part of any nation's future. Research in nanotechnology has extremely high potential to benefit society through applications in agriculture and food systems. Any new technology carries an ethical responsibility for wise application and the recognition that there are potential unforeseen risks that may come with the tremendous positive potential. As a part of the Nation's future, it is critical that the future workforce be trained in nanotechnology. The first step is informing the public at large about the advantages and challenges of nanotechnology. As public awareness increases, so will interest in the understanding of nanotechnology and new applications in all the domains will be found. Rapid testing technologies and biosensor related to the control of pests and cross contamination of agricultural and food products will be certainly see applications of nanotechnology in the very near future.

As in the case of almost every nonconventional technology, e.g., genetic engineering, some fear that nanotechnology can give people too much control. We believe that this control can be wisely used, and that the huge contributions that nanotechnology can make are very strong arguments in favor of using this revolutionary science to its fullest potential. Food and agriculture technology should take advantage of the powerful tools of nanotechnology, for the benefit of humankind.

Richard Feynman, an eminent physicist said in a famous lecture in 1959 [32] said that '*The biological example of writing information on a small scale has inspired me to think of something that should be possible. Biology is not simply writing information; it is doing something about it. A biological system can be exceedingly small. Many of the cells are very tiny, but they are very active; they manufacture various substances; they walk around; they wiggle; and they do all kinds of marvelous things---all on a very small scale. Also, they store information. Consider the possibility that we too can make a thing very small which does what we want---that we can manufacture an object that maneuvers at that level!*'. And that was 45 years ago! Of course it isn't yet possible to realize all that he predicted, or dreamt but the future will definitely show new applications of nanotechnology in the field of food and agriculture.

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