Glasnik hemičara i tehnologa Bosne i Hercegovine

Bulletin of the Chemists and Technologists of Bosnia and Herzegovina

2016

47

59-70

Print ISSN: 0367-4444

Online ISSN: 2232-7266

UDC: ________________________

Technical Paper

Nanosensors applications in agriculture and food industry

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Abstract info
Received: 25/10/2016
Accepted: 21/12/2016

Keywords:
Nanotechnology
Nanosensors
Agriculture
Food
Food Industry

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Abstract: Food safety is very important issue in food industry and agriculture because it is directly related to the influence of food on the human health. Recent food safety incidents (such as the melamine affair in 2007 and 2008) and public health concerns about synthetic food additives and chemical residues in food have driven the need to develop rapid, sensitive, and reliable methods to detect those food hazards. An alternative is given in the rapid development of nanosensors which have advantage to detect food components in an easy and quick manner. Linking nanosensors with modern Information and Communication Technologies (ICTs) enables novel and online ways for different components detection accompanied with high accuracy. Various types of nanosensors are being developed to meet the different requirements in food inspection (nanosensors for detection of external and internal conditions in food packaging, carbon nanotubes based electrochemical sensors for detection of cations, anions and organic compounds in food, various aptamers for detection of pesticides, antibiotics, heavy metals, microbial cells and toxins).

The work reviews development and application of the most present nanosensors in agriculture and food industry.

INTRODUCTION

Food safety is a prime concern of human life. With increased globalization of food this implies the importance of food quality assessment in all steps of agri-food supply chain. The chain includes all steps “from the farm to the table” production, distribution, processing, and marketing of agricultural food products to the final consumers (Fig. 1) (Ahumada and Villalobos 2009).

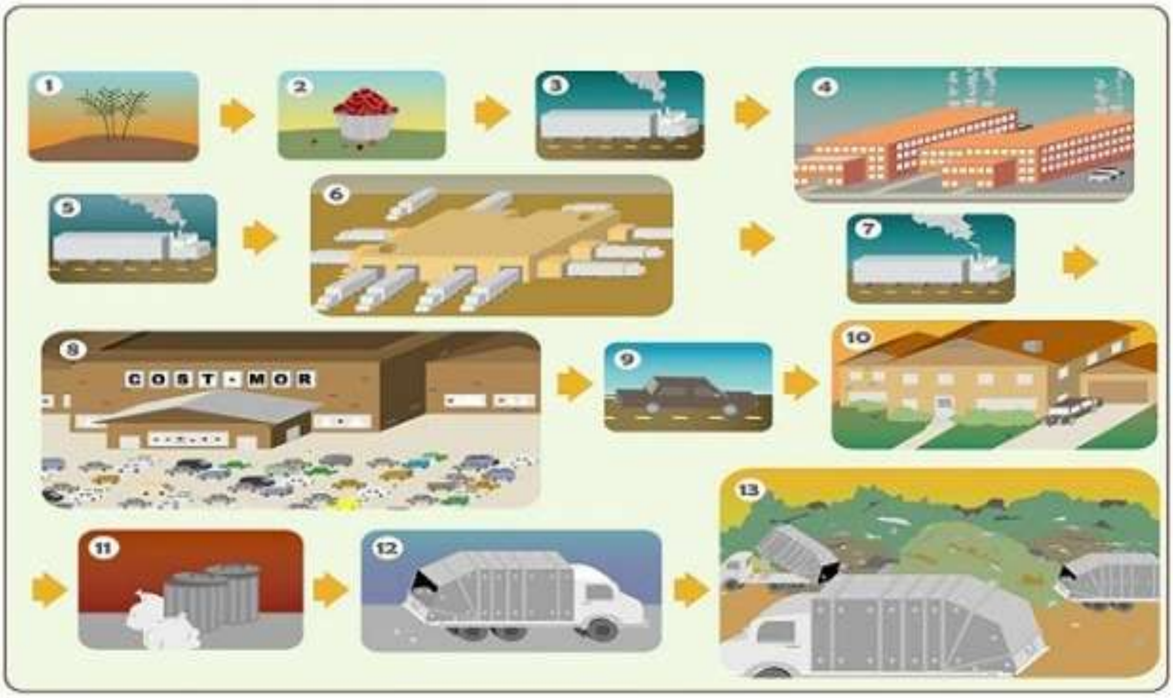

Fig.1 Agri-food supply chain (QS Article 2012)

Globalization of food production along with consumer concerns related to food quality and safety have resulted in interconnected and global systems for the production and distribution of food, followed by significant increase in food standards (Sharma et al. 2015). This approach required a move from the former end-of-line product inspection approach to a new environment in which quality assurance is required at every step of food production chain to ensure safe food and to show compliance with regulatory and customer requirements. As a result, upcoming quality and food safety assessment procedures will require additional essential elements such as low detection limits, high sensitivity and specificity, miniaturization of instrumentation for portable use, simple sample preparation steps (Craig et al. 2013).

At laboratory level, food safety can be quantitatively assessed by various methods, including cell culture and fine instrumental analysis. The main disadvantage of these methods is long analysis time ranging from several hours to days, usually with different pretreatment steps. However, food safety is nowadays threatened by contaminants which cannot be detected with standard analytical methods e.g. formaldehyde, plant pathogens, excessive pesticide residues, (Li and Sheng 2014). The inadequacy of conventional methods to solve new challenges in food safety, leads to the development of new, miniaturized and fast analytical techniques with low detection limits. Nanotechnology aspects integrated with analytical tools present one of the key solutions for development of new devices.

In addition, nanotechnology, as one of the exciting new fields of research, has great promise in addressing many of the pressing needs in the food and agriculture sectors by opening new avenues of food production, manufacturing and packaging, plant cropping and animal feeding. In the food sector, this technology has great potential to improve food functionality and quality. Unfortunately, many of the nanotechnological tools for food and agriculture field are still on a research level. Only practical applications of nanotechnology are in food packaging and in nanosensors for detection of food contaminants. Nanotechnology, nanominerals and nanosensors in the agri-food sector, including feed and nutrient components, intelligent packaging and quick-detection systems, can be seen as new source of key improvements in the agrarian sector (Fig. 2).

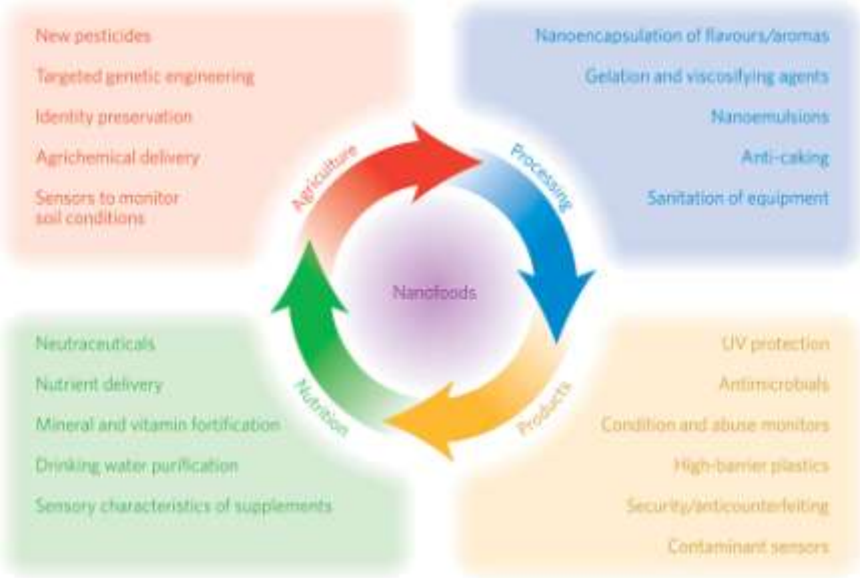

Fig.2 Nanotechnology's potential benefits to many areas of the food industry (Duncan, 2011)

Innovative enhancements for the molecular treatment of diseases, rapid disease detection, successful dealing with viruses and crop pathogens, enhancing the power of plants to absorb nutrients as well as lowering usage doses of pesticides and herbicides proved that nanotechnology has the potential to revolutionize the agricultural and food industry (Joseph and Morrison 2006). To understand and address the importance of nanotechnology in the agri-food sector, this paper represents a review of types and applications of the most present nanosensors in agriculture and food industry. Even there is a belief that nanotechnology will also protect the environment indirectly through the use of renewable energy supplies, and filters or catalysts to reduce pollution and clean-up existing pollutants (Joseph and Morrison 2006), there are still many concerns regarding nanomaterials toxicity and possible negative impact on the surroundings. Alongside the potential advantages of nanotechnology applications in the agri-food supply chain, concerns regarding nanotoxicology and safety will be discussed as well.

Nanosensors

Nanosensors are emerging as a promising tools for the applications in the agriculture and food production. They offer significant improvements in selectivity, speed and sensitivity compared to traditional chemical and biological methods. Nanosensors can be used for determination of microbes, contaminants, pollutants and food freshness (Joyner and Kumar 2015).
The nanosensors used in food analyses combine knowledge of biology, chemistry and nanotechnology and may also be called nanobiosensors.

Need for nanosensors

The part of food production where the need for the nanosensors is the most visible is food packaging and food transport.
Food packaging prevent sensory exposure from the foods thus consumers must rely on expiry dates provided by producers based on a set of idealized assumptions about the way that the food is stored or transported. If the transport or storage conditions are violated for any period of time, the quality of food might be deteriorated which might not be known to the consumer unless the food package is opened, or even consumed (Joyner and Kumar 2015).
Nanosensors can improve the disadvantages of food packaging through their unique chemical and electro-optical properties. They are able to detect the presence of gasses, aromas, chemical contaminants, pathogens, and even changes in environmental conditions. Nanosensors ensure that consumers purchase fresh and tasty products and reduce the frequency of food-borne illnesses which improve food safety.

Development of nanosensors in agri-food sector

Nanosensors have the arrangement like ordinary sensors, but their production is at the nanoscale. Therefore, nanosensor can be defined as an extremely small device than can bind to whatever is wanted to be detected and send back a signal. These tiny sensors are capable of detecting and responding to physicochemical (sensors) and biological signal (biosensors), transferring that response into a signal or output that can be used by humans.

Compared with traditional sensors and their shortcomings, nanosensors have several advantageous properties, such as high sensitivity and selectivity, near real-time detection, low cost and portability and other necessary attributes which are improved by using nanomaterials in their construction (Lu and Bowles 2013). There are many techniques for development of nanosensors which involves top-down lithography, molecular self-assembly and bottom-up assembly approaches. Current nanosensors devices can be divided into (Liu 2003):

- Nanostructured materials - e.g. porous silicon,
- Nanoparticles based sensors,
- Nanoprobes,
- Nanowire nanosensors,
- Nanosystems: cantilevers, Nano-electromechanical systems (NEMS).

Based on applications in food analysis, nanosensors can be divided on:

- Nanoparticle based nanosensors
- Electrochemical nanosensors
- Optical nanosensors

Aptasensors

Aptasensors are biosensors consisting of aptamers (the target-recognition element) and nanomaterial (the signal transducers and/or signal enhancers). Aptamers are single stranded nucleic acid or peptide molecules of size less than 25 kDa with natural or synthetic origin. They are highly specific and selective towards their target compound (ions, proteins, toxins, microbes, viruses) due to their precise and well defined three-dimensional structures. Aptamers are named as synthetic antibodies due to their selection and generation through an *in vitro* combinatorial molecular technique called SELEX. Dissociation constants of aptamers are in nanomolar or picomolar range. Aptamers are extensively used as recognition elements in the fabrication of aptasensors (Sharma et al. 2015). There are a wide variety of nanomaterials, which can be used in aptasensors (metal nanoparticles and nanoclusters, semiconductor nanoparticles, carbon nanoparticles, magnetic nanoparticles etc) (Sharma et al. 2015). Also, a wide variety of transducing systems have been employed in aptasensors for food quality assessment and safety. The principles of aptasensors are based on the property of the nanoparticle being used. Based on the detection systems, aptamers can be classified into optical and electrochemical systems.

Nanosensors applications

Numerous nanosensors are developed for various applications in agricultural and food industry either to quickly identify threats in the case of suspected food poisoning, or integrated into packaging as nanotracers to show the history of the food product and whether it is of acceptable quality at any given time. For instance, the use of nanosensors in food packaging to detect growth of microorganisms and change color when a threshold level is reached, as well as nanosensors applied in on-line process control, for monitoring of storage conditions are useful for preventing food poisoning (Augustin and Sanguansri 2009). As another example, scientists are making the gold nanoparticles and coat them with molecules that can bind to substances like pesticides. Farmers could spray these nanoparticles on their fields to detect a chemical like a pesticide (Rathbun 2013).

Furthermore, nanosensors employing Raman spectroscopy are ideally suited for food forensic. Food forensics is investigation of food origin, adulteration and contamination. Nanosensors application in this contributes to the specificity of the method and allows application of various analytes which can be probed; ranging from the macro-food, lipids, proteins and carbohydrates, to the minor components, dyes, pigments, preservatives.

More examples of nanosensors and their development for agriculture and food applications are depicted in (Augustin and Sanguansri 2009; Rai et al. 2012; Parisi et al. 2014). According to Fig. 2 and performed surveys of research articles (Joseph and Morrison 2006; Valdes et al. 2009; Lu and Bowles 2013; Prasad et al. 2014; Nanowerk 2014; Sekhon 2014; Berekaa 2015; Rai et al. 2015), the list of potential applications of nanosensors in agri-food supply chain can be summarized, as it is shown in Table 1.

It can be highlighted that nanosensors are useful for sensing and reporting real time information regarding the product from production through to delivery to the consumer. Nanosensors are far from being simply a passive, information-receiving device. They can get information from immediate and remote contexts and can analyze, record and report data. They can be designed to manage this at critical control points in the supply chain - from the point food is produced or packaged, through to the time it is consumed.

The latest developments have resulted innanosensors which are quite near commercialization: nanosensors and nanoscale coatings to replace thicker, more wasteful polymer coatings for preventing corrosion, nanosensors for detection of aquatic toxins, nanoscale biopolymers for improved decontamination and recycling of heavy metals, nanosensors able to provide quality assurance by tracking microbes, toxins and contaminants through the food processing chain by using data capture for automatic control functions and documentation, among others (Prasad et al 2014; Lu and Bowles 2013).

Gold nanoparticles functionalized with cyanuric acid groups selectively bind to melamine, an adulterant used to artificially inflate the measured proteins content of pet foods and infant formulas (Ai et. al, 2009).

A promising photoactivated indicator ink for in-package oxygen detection based upon nanosized TiO_2 or SnO_2 particles and a redox-dye (methylene blue) has been developed (Mills, 2005) (Fig. 3).

Nanosensors based on nanoparticles have also been developed to detect the presence of moisture content inside a food packaging (Luechinger et al., 2007) (Fig. 4).

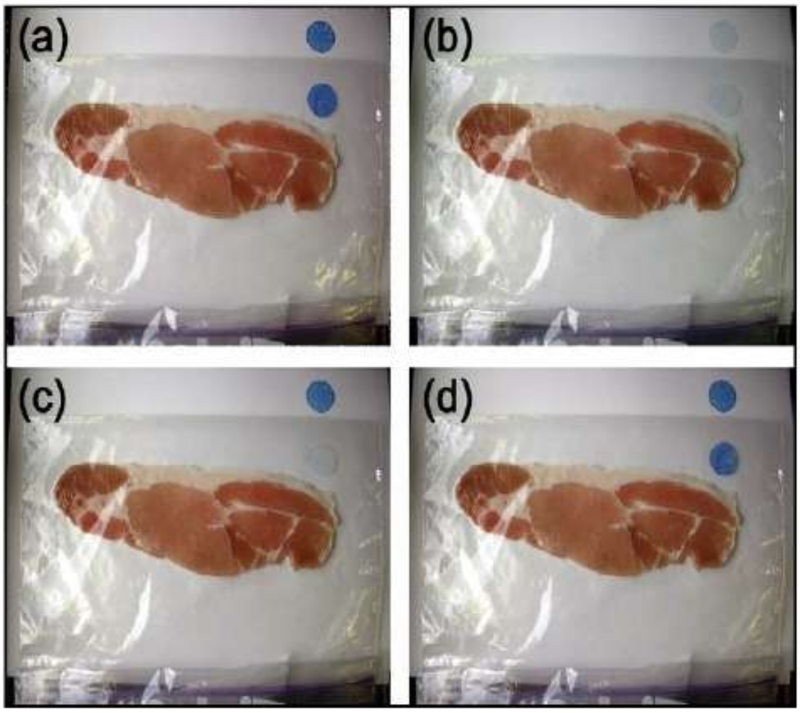

Fig.3 Photographs of O2 sensors which utilize UV-activated TiO2 nanoparticles and methylene blue indicator dye, one placed inside of a food package flushed with CO2 and one placed outside. In (a) the package is freshly sealed and both indicators are blue. The photograph in (b) shows the indicators immediately after activation with UVA light. After a few minutes, the indicator outside of the package returns to a blue color, whereas the indicator in an oxygen-free atmosphere remains white (c) until the package is opened, in which case the influx of oxygen causes it to change back to blue (d). This system could be used to easily and noninvasively detect the presence of leaks in every package immediately after production and at retail sites (Adapted from: Mills, 2005)

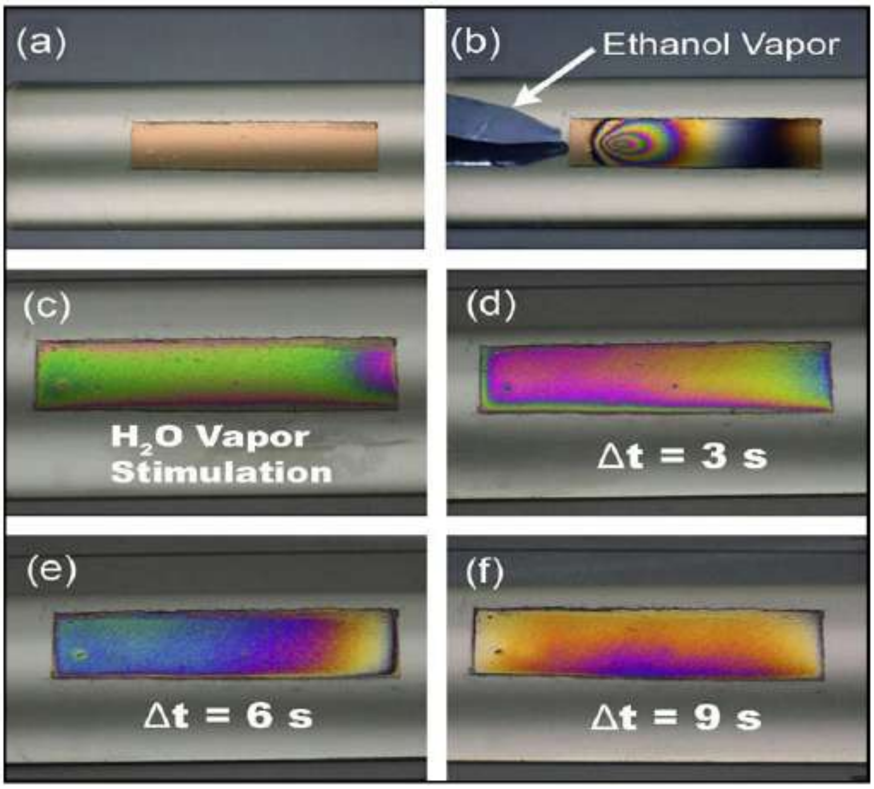

Fig.4 Moisture sensor which utilizes carbon-coated copper nanoparticles dispersed in a polymer matrix (a). Ethanol vapor exposure results in rapid and reversible iridescent coloration (b). Water vapor exposure swells the polymer, which causes the nanoparticles to exhibit larger interparticle separation distances and thus different observable optical behavior (c). As moisture dissipates (d–f), the sensor reverts back to its native state and appearance (Adapted from: Luechinger et al., 2007)

Table 1: Nanosensors potential applications in agri-food sector

Agriculture	Food processing	Food packaging	Food transport	Nutrition
• Nanosensors for monitoring soil conditions (e.g. moisture, soil pH), a wide variety of pesticides, herbicides, fertilizers, insecticides, pathogens and crop growth as well • Nanosensors for detection of food-borne contaminants or for monitoring environmental conditions at the farm • Nanochips for identity preservation and tracking • Nanocapsules for delivery of pesticides, herbicides, fertilizers and vaccines • Nanosensors and nano-based smart delivery systems for efficient use of agricultural natural resources (e.g. water), nutrients and chemicals through precision farming • Nanoparticles to deliver growth hormones or DNA to plants in controlled manner • Nanoparticles used as smart nanosensors for early warning of changing conditions that are able to respond to different conditions • Aptasensors for determination of pesticides and insecticides (e.g. phorate, acetamiprid, isocarbophos) • Aptasensors for determination of antibiotics, drugs and their residues (e.g. cocaine, oxytetracycline, tetracycline, kanamycin). • Aptasensors for determination of heavy metals (e.g. Hg^{2+}, As^{3+}, Cu^{2+})	• Nanoencapsulated flavor enhancers • Nanotubes and nanoparticles as gelation and viscosifying agents • Nanocapsule infusion of plant based steroids to replace a meat's cholesterol • Nanoparticles to selectively bind and remove chemicals or pathogens from food • Aptasensors for determination of microbial toxins (e.g. OTA, Fumonisin B1)	• Portable nanosensors to detect chemicals, pathogens and toxins in food • DNA biochips to detect pathogens and to determine the presence of different kind of harmful bacteria in meat or fish, or fungi affecting fruit • Nanosensors incorporated into packaging materials for detection of chemicals released during food spoilage and serve as electronic tongue (e.g. bitter, sweet, salty, umami, and sour detection), or nose (e.g. wine characterization) • Electromechanical nanosensors to detect ethylene • Nanosensors applied as labels or coating to add an intelligent function to food packaging in terms of ensuring the integrity of the package through detection of leaks, indication of time-temperature variations and microbial safety • Aptasensors for determination of microbial cells (e.g. Salmonella typhimurium, Escherichia Coli, Listeria monocytogenes) • Aptasensors for determination of antibiotics, drugs and their residues (e.g. cocaine, oxytetracycline, tetracycline, kanamycin). • Aptasensors for determination of heavy metals (e.g. Hg^{2+}, A^{s3+}, Cu^{2+})	• Nanosensors for monitoring environmental conditions during distribution and storage • Nanosensors for traceability and monitoring product conditions during transport and storage, what is crucial for products which have a limited shelf-life • Smart-sensor technology for monitoring the quality of grain, dairy products, fruit and vegetables in a storage environment in order to detect the source and the type of spoilage • Aptasensors for determination of microbial cells (e.g. Salmonella typhimurium, Escherichia Coli, Listeria monocytogenes)	• Nanocapsules incorporated into food to deliver nutrients • Nanocochleates (50 nm coiled nanoparticles) for delivering nutrients (e.g. vitamins, lycopene, and omega fatty acids) more efficiently to cells, without affecting the color or taste of food

Toxicology and safety aspects of nanosensors utilization in agricultural and food industry

Despite the tremendous benefits of nanosensors in the agriculture and food industry, there is a huge public concern regarding toxicity and environmental effect. There is very limited knowledge about its long term adverse effect on soil, plants and ultimately on human (Dubey and Mailapalli 2016). Preliminary studies on animal have shown potential toxicity of nanomaterials for liver, kidneys, and immune system. Additionally, the effects of exposure to engineered nanoparticles may be dissimilar from the effects induced by naturally occurring nanoparticles (Rai and Ingle 2012). Therefore, risk assessment studies to show adverse effects of nanoparticles on human health and the environment should be standardized and their number should be increased while at the same time the field of nanotoxicology emerges to international level. Obviously, the necessity of awareness of the nanoparticles presence in the environment and their detection, the measurement of nanoparticles emissions, life-cycle, toxicity and impact to human health and environment are crucial in achieving all the benefits nanotechnologies has to offer.
The toxicity of nanoparticles in the environment depends on their size, type, charge, etc. Additionally, the influence of nanoparticles on the environment depends also of the environmental factors (humidity, temperature, wind flow rate, the nature of light, etc). However, properties of nanomaterials, small size and large surface allow easy dispersion and bonding in the environment and with human tissues.
One way in which nanomaterials enter the environment and humans is through agriculture sector (Rico 2015). Nanoparticles strongly interact with soils. Nanomaterials enhanced plant foods and pesticides are able to disperse into soil, water and atmosphere, to bond more strongly with pollutants and carry them through soil and water (Sastry 2012). Exposure to nanofertilizers and pesticides, can contribute to health hazards (Sastry 2012). Migration of nanoparticle incorporated in food material to human is also high risk (Berekaa 2015). In other words, direct exposure of consumers to nanomaterials poses a serious problem to human health. Nanoparticles can enter the human body through the skin, respiratory system or digestive system (Fig. 5). However, as long as the nanoparticles remain bound, exposure is limited or very low. Health impact and safety regarding the application of nanomaterials was reported in detail by Teow et. al (2011).

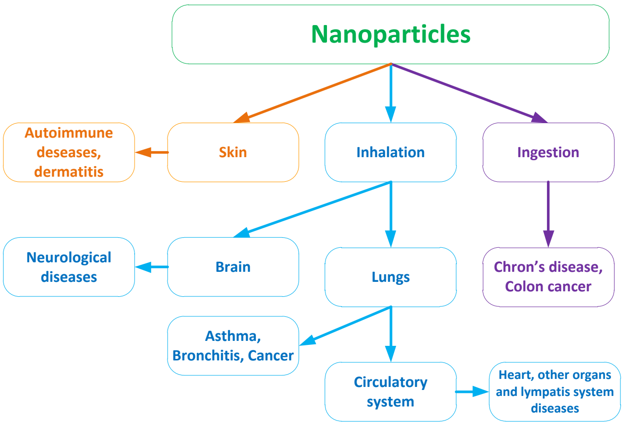

Fig. 5. Potential harmful effects of nanoparticles to human health

Modern techniques revealed that nanomaterials with higher reactivity and ability to cross membrane barriers can lead to different toxico-kinetic and toxico-dynamic properties. Some nanomaterials interact with proteins and enzymes leading to oxidative stress and generation of ROS, which cause destruction of mitochondria and produce apoptosis.
Over the last few years there have been numerous publications reporting a variety of biological and toxicological interactions of nanomaterials in *in vitro* and *in vivo* experimental systems. A wide range of biochemical and toxicological endpoints within each system have been reported. Most have been directed to proinflammatory and inflammatory markers since existing knowledge on the health effects of ambient fine particulates and nanomaterials has identified a central role for oxidative stress and inflammation in the toxicological mode of action of nanoparticles.
Therefore, the understanding of the biological and toxicological effects of nanomaterials has significantly advanced in the last few years. Much of this has been in relation to what type of physical characterization and toxicological data is required for hazard and risk assessment, and how to go about obtaining it. Serious adverse effects have not been observed in limited applications to nanomaterials of "traditional" tests for assessing the acute toxicity of chemicals. The toxicological data sets available for nanomaterials remain rudimentary, for example long term inhalation studies, reproductive or developmental studies are not available. The fact that, if nanoparticles are absorbed into the systemic circulation, they may be retained within cells for long periods, makes it imperative that chronic studies be undertaken for hazard and risk assessment of nanomaterials.
One of the potential solutions to make nanotechnology applications as safe as possible is moving towards green nanotechnology. Safe and energy efficient nanomaterials, nanoproducts and processes, reduced waste, lessen greenhouse gas emissions and usages of renewable materials are the benefits green nanotechnology concept offers. Even this concept is still in the lab/start-up phase, it is anticipated that by greening nanotechnology, environmental, health and societal benefits of nanoparticle production and nanoparticle application in various fields will be maximized (Dahl et al. 2007, OECD 2013, Goel and Bhatnagar 2014).

Nanosensors in the realization of smart agri-food sector

Nanotechnology is recognized by the European Commission as one of its six “Key Enabling Technologies” that have potential to significantly improve various industrial sectors. Even nanotechnology application to the agriculture and food sectors is at the nascent stage compared with some other sectors, like drug delivery and pharmaceuticals, the current challenges of sustainability, food security and climate change implicate enhanced researchers' interest in exploring the role and significance of nanotechnology in the improvement processes of the agrarian sector (Parisi et al. 2015). Nanotechnology holds the potential to revolutionize the global food system, and there are a lot more applications in agriculture and food system that can be expected in the years to come (Prasad et al. 2014). Novel agricultural and food safety systems, disease-treatment delivery methods, tools for molecular and cellular biology, sensors for detecting pathogens and pesticides, intelligent packaging materials, environmental protection, and education of the public and future workforce are some of examples of the important impact that nanotechnology could have in agrarian sector (Garcia et al. 2010).

Inexpensive sensors, cloud computing and intelligent software together can revolutionize the whole agri-food sector. Thanks to the computers, global satellite positioning systems and remote sensing devices, precise farming becomes reality. Monitoring and measuring of environmental variables, and making appropriate and on-time decisions and performing targeted action according to collected data in order to maximize output (i.e. crop yields) with optimal use of resources (i.e. fertilizers, pesticides, herbicides, etc.) are the main characteristics of precise farming vision (Rai and Ingle 2012).

It is important to highlight various micro-nano bio systems, developed as projects of European Commission (2015) and used to realize smart agri-food systems. Technology development, particularly Internet of Things (IoT), as an emerging reality where more and more devices are connected to users and other devices via the Internet, significantly contribute to the realization of the smart agriculture by increasing the quality, quantity, sustainability and cost effectiveness of agricultural production. The innovative application of nanotechnology in IoT creates a new paradigm, namely the Internet of Nano Things (IoNT). Nanosensors, because of their small dimensions, can collect information from numerous different points. Nanosensors made from non-biological materials, such as carbon nanotubes, have ability to sense and signal, acting as wireless nanoantennas (Garcia-Martinez 2016). External devices can then integrate the data to automatically generate incredibly detailed report and respond to potentially devastating changes in their environment. There are numerous intelligent nanosystems, used in the smart agriculture for the crop monitoring, immobilization of nutrients and their release in soil, analysis of pesticides, moisture and soil pH. Networks of connected nanosensors for monitoring soil or plant conditions have ability to alert automatically according to conditions detected by sensors and therefore influence more efficient usage of the water, fertilizers, herbicide, pesticide, insecticide, etc. In this way, a real time and comprehensive monitoring of the crop growth, lead to accurate and on-time decisions, reduced costs and waste, improved quality of production and above all, to sustainable agriculture.

As food safety is a main concern nowadays, it is essential to have manners and systems which enable foodstuffs traceability and monitoring during the whole food chain process (Maksimovic et al. 2015). Nanosensors can be applied along the entire food supply chain, in order to detect different targets in quickly, sensitive, and cost-effective manners. This is necessary in the process of ensuring food quality, safety, freshness, authenticity, and traceability (Fraceto et al. 2016). For instance, involving nanosensors in the design of smart or intelligent packaging, spoilage or harmful contaminants during distribution or storage can be detected alongside enabled transfer of information regarding product conditions. In this way food producers, transportation and hospitality/retail companies become connected as never before.

The response generated due to changes related to internal or external environmental factor, are recorded through specific sensors (Berekaa 2015), stored in the database and via Internet 24/7 available insight into soil and crop health, food contaminations, quality, etc (Fig. 6). In this way, rapid response and reactions to detections of abnormally parameters’ values, are enabled and lead to more quality and safe food, what direct influence to human health. However, to achieve the full potential IoNT has to offer in agriculture and food industry, many concerns, regarding data security and privacy as well as nanomaterial’s toxicity and impact to the environment and human must be considered.

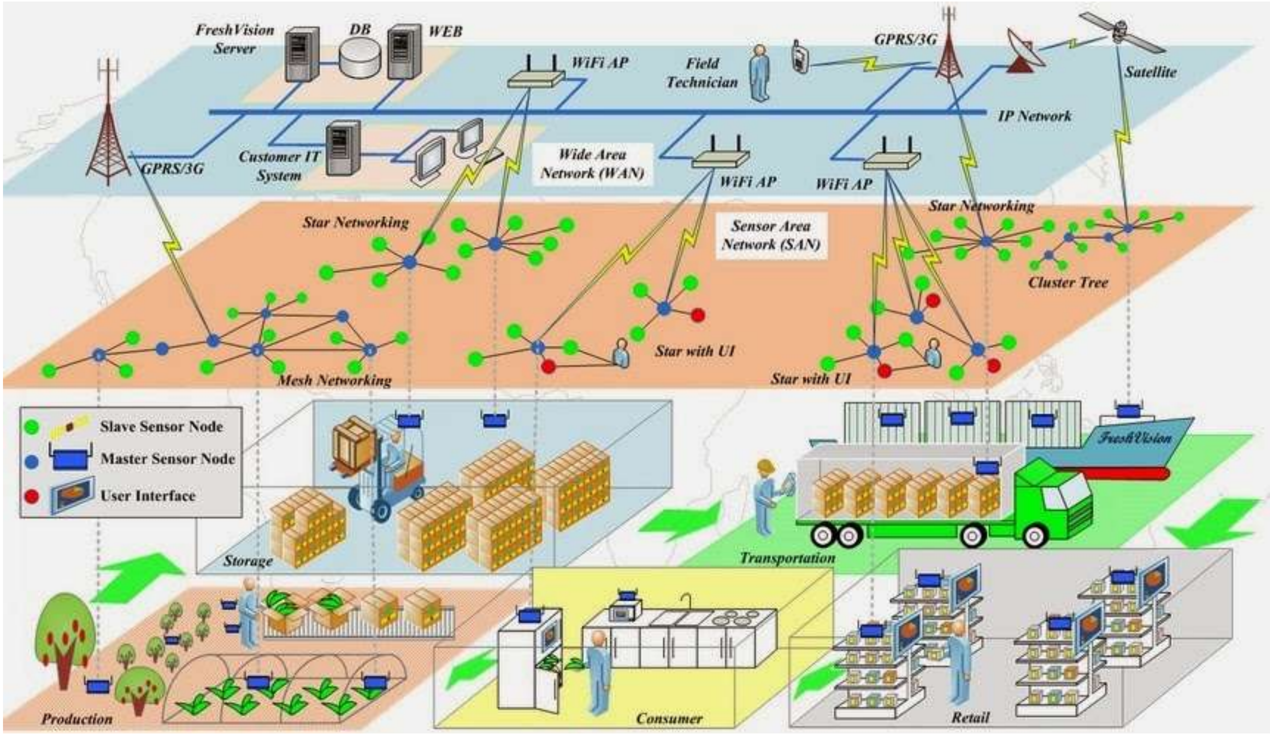

Fig.6 IoT architecture for the agri-food sector (Gannon 2016)

CONCLUSION

Recent advancements in nanotechnology, embraced with intense research at both academic and industrial levels and advancements in ICTs, show its potential to positively influence the agri-food sector. Improved quality of the soil, increased productivity, stimulation of plant growth, the use of precise farming, monitoring food quality and freshness during production, processing, distribution and storage, are just some of the many benefits nanotechnology, nanomaterials and nanosensors have to offer in agricultural and food industry. The excellent specificity of the nanosensors and aptamers allows an analysis of wide variety analytes, including heavy metal ions, toxins, pathogens, small molecules, nucleic acids and proteins. Nanoparticles add on to the selectivity and convenience of the diagnostics, by the providing larger surface area for aptamer immobilization as well as by conferring their own opto-physical and electrochemical properties to the sensor. Some obstacles still exist in the development of field-applicable nanosensor techniques (sample pretreatment technique, specificity, expenses). It can be hoped that further insight into the probable solutions to these problems and in the development of novel nanomaterials will boost designing of affordable and easily operable nanomaterial based sensing system. However, the full potential of nanotechnology in agriculture and food sector is yet to be realized and can be achieved only with improved awareness and knowledge of the potential harm from nano-enabled products, and the long-term impacts of nanomaterials to the environment and human health. The future researches will be focused in the development of novel reliable material, methods and smart devices on the nano-scale, to the realization of IoNT vision, as well as to the evaluation of their impact on the human and environment. Moving towards green nanotechnology and green IoT will lead to a whole new world of safe nanoproducts and their widespread applications with little or no hazards to human health and the environment.

REFERENCES

Ahumada, O., Villalobos, J.R. (2009). Application of planning models in the agri-food supply chain: A review, *European Journal of Operational Research* 195:1–20

Ai, K., Liu, Y., Lu, L. (2009). Hydrogen bonding recognition-induced color change of gold nanoparticles for visual detection of melamine in raw milk and infant formula, *Journal of the American Chemical Society*, Vol. 131 (27), 9496-9497

Augustin, M.A., Sanguansri, P. (2009). Nanostructured Materials in the Food Industry, *Advances in Food and Nutrition Research*, Vol. 58, pp.183-213

Berekaa, M. (2015). Nanotechnology in Food Industry; Advances in Food processing, Packaging and Food Safety, *Int.J.Curr.Microbiol.App.Sci* 4(5): 345-357

Craig, A.P., Franca, A.S., Irudayaraj, J. (2013). Surface-enhanced Raman spectroscopy applied to food safety, *Annu Rev Food Sci Technol*. 2013; 4: 369-380

Dahl, J. A. et al. (2007). Toward Greener Nanosynthesis, *Chem. Rev.*, 107, 2228−2269

Dubey, A., Mailapalli, D.R. (2016). Nanofertilisers, Nanopesticides, Nanosensors of Pest and Nanotoxicity in Agriculture, E. Lichtfouse (ed.), Sustainable Agriculture Reviews 19, Sustainable Agriculture Reviews, Springer International Publishing Switzerland 2016

Duncan, T.V. (2011). The communication challenges presented by nanofoods, *Nature Nanotechnology*, Vol. 6, pp. 683-688

European Comission (2015). Projects on Smart Agri-Food systems. e*c.europa.eu/newsroom/horizon2020/document.cfm?doc_id=18158* (4/12/2016).

Fraceto et al. (2016). Nanotechnology in Agriculture: Which Innovation Potential Does It Have?. *Front. Environ. Sci*.

Gannon, M. (2016). Personal website, http://mark_gannon_cdsr.workfolio.com/

García, M., Forbe, T., Gonzalez, E. (2010) Potential applications of nanotechnology in the agro-food sector. *Food Science and Technology* (Campinas) ISSN 0101-2061 Ciênc. Tecnol. Aliment. Vol.30 no.3.

Garcia-Martinez, J. (2016) The Internet of Things Goes Nano, http://www.scientificamerican.com/article/the-internet-of-things-goes-nano/, (4/10/2016).

Goel, A. and Bhatnagar, S. (2014). Green Nanotechnology, *BioEvolution*, pp. 3-4

Joyner, J.R., Kumar, D.V. (2015). Nanosensors and their applications in food analysis: a review, Vol. 1, Issue 4, 80-90

Joseph, T., Morrison, M. (2006). Nanotechnology in Agriculture and Food, ftp://ftp.cordis.europa.eu/pub/nanotechnology/docs/nanotechnology_in_agriculture_and_food.pdf (1/10/2016).

Li, Z., Sheng, C. (2014). Nanosensors for food safety, *J Nanosci Nanotechnol*. Jan;14(1):905-12.

Liu, Y. (2003) Nanosensors, http://www.slideserve.com/kim-johnston/nanosensors, (3/10/2016).

Lu, J. and Bowles, M. (2013) How Will Nanotechnology Affect Agricultural Supply Chains?, *International Food and Agribusiness Management Review*, Vol. 16, Issue 2.

Luechinger, N.A., Loher, S., Athanassiou, E.K., Grass, R.N., Stark, W.J. (2007). Highly sensitive optical detection of humidity on polymer/metal nanoparticle hybrid films. Langmuir, 23(6), 3473-3477

Maksimovic, M. et al. (2015). Application of Internet of Things in food packaging and transportation. *Int. J. Sustainable Agricultural Management and Informatics*, Vol. 1, No. 4, pp. 333-350

Mills, A. (2005). Oxygen indicators and intelligent inks for packaging food. *Chemical Society Reviews*, 34(12), 1003-1011

Nanowerk, (2014). Nanotechnology in agriculture, http://www.nanowerk.com/spotlight/spotid=37064.php (1/10/2016).

OECD (2013). Nanotechnology for Green Innovation, OECD Science, Technology and Industry Policy Papers, No. 5, OECD Publishing.

QS Article (2012). Agri-Food Supply Chain (ASC) affects the Cost Price for Customers, http://www.qsarticle.com/agri-food-supply-chain-asc-affects-the-cost-price-for-customers/, (18/9/2016).

Parisi, C., Vigani, M., Rodríguez-Cerezo, E. (2014). Proceedings of a workshop on “Nanotechnology for the agricultural sector: from research to the field”, Joint Research Centre

Parisi, C., Vigani, M., Rodríguez-Cerezo, E. (2015). Agricultural Nanotechnologies: What are the current possibilities? *Nanotoday*, Science Direct, Volume 10, Issue 2, Pages 124–127

Prasad, R., Kumar, V., Prasad, K. S. (2014). Nanotechnology in sustainable agriculture: Present concerns and future aspects. African Journal of Biotechnology. Vol. 13(6), pp. 705-713

Rai, M., Ingle, A. (2012). Role of nanotechnology in agriculture with special reference to management of insect pests. *Appl Microbiol Biotechnol* 94:287–293

Rai, M., Ribeiro, C., Mattoso, L., Duran, N. (2015). *Nanotechnologies in Agriculture and Food*, Springer International Publishing Switzerland

Rai, V., Acharya., S., Dey, N. (2012). Implications of Nanobiosensors in Agriculture, *Journal of Biomaterials and Nanobiotechnology*, 3, 315-324

Rico, C. (2015). Nanomaterial Implications for Agricultural Productivity and Food Safety. http://www.azonano.com/article.aspx?ArticleID=4076, (20/12/2016).

Rathbun, L. C. (2013). Nanosensors and the Food Supply, http://www.nanooze.org/nanosensors-and-the-food-supply-2/, (2/10/2016).

Sastry, R.K. (2012). Potential Economic Impacts of Agri-Nanotechnology. “International Symposium on Assessing the Economic Impact of Nanotechnology”, Washington DC

Sekhon, B. S. (2014). Nanotechnology in agri-food production: an overview, *Nanotechnol Sci Appl.* 7: 31–53.

Sharma, R., Ragavan, K.V., Thakur, M.S. Raghavaro, K.S.M.S. (2015). Recent advances in nanoparticle based aptasensors for food contaminants, *Biosensors and Bioelectronics* 74, 612-627

Teow, Y., Asharani, P.V., Hand, M.P., Valiyaveettil, S. (2011). Health impact and safety of engineered nanomaterials. *Chem Commun.* 47, 7025-7038

Valdes, M.G. et al. (2009). Analytical nanotechnology for food analysis, *Microchim Acta* 166:1–19

Summary/Sažetak

Sigurnost hrane je vrlo važan aspekt u prehrambenoj industriji i poljoprivredi, jer je u direktnoj vezi sa uticajem hrane na zdravlje ljudi. Nedavni incidenti povezani sa sigurnošću hrane (kao što su afere melamina u 2007. i 2008.) i zabrinutost javnosti zbog sintetičkih aditiva i hemijskih ostataka u hrani istakli su važnost razvoja brzih, osjetljivih i pouzdanih metoda za otkrivanje kontaminanata u hrani. Značajan doprinos sigurnosti hrane daju nanosenzori koji određuju komponente i kontaminante hrane na brz i jednostavan način i u malim koncentracijama. Povezivanje nanosenzora sa modernim informacijskim i komunikacijskim tehnologijama (IKT) omogućava nove i online načine za detekciju različitih komponenti uz visok procenat tačnosti. Postoje različite vrste nanosenzora koji odgovaraju na zahtjeve u inspekciji hrane (nanosenzori integrisani u pakovanju za detekciju vanjskih i unutrašnjih parametara, elektrohemijski senzori na bazi ugljeničnih nanocijevi za detekciju kationa, aniona i organskih spojeva u hrani, razni aptameri za detekciju pesticida, antibiotika, teških metala, ćelijskih mikroba i toksina). Ovaj rad predstavlja pregled razvoja i aplikacija najprisutnijih nanosenzora u poljoprivredi i prehrambenoj industriji.