Application of Nanotechnology in Food Processing: A Promising Prospective with Considerable Risk

Sanjib K. Paul[1], Sudipto Sarkar[2], Laxmi Narayan Sethi[3], Sujit K. Ghosh[4]

[1,2,3]*Department of Agricultural Engineering, Assam University, Silchar, Assam*
[4]*Department of Chemistry, Assam University, Silchar, Assam*

Abstract: **Nanotechnology is an emerging field of research for every domain of science and technology including food sector. Application of nanotechnology in food industry though still at juvenile stage but outcomes of recent extensive researches has indicated that it can bring revolutionary changes in various area of food domain including post-harvest management, food packaging and storage, biosensors, medicines, nutrient and nutraceutical delivery, additives and ingredients and also bioprocessing of food and effluent in near future. Technology of active and smart or intelligent packaging has received acceleration in its improvement with the incorporation of nanomaterials. Hazardless and edible packaging or coating with nanomaterials has provided a boon in edible packaging and storage sector for preservation and storage of fresh as well as processed food products. For quick detection of pathogenic microorganisms, contaminations, specific nutrient content, adulteration in food products etc., various nanomaterial based biosensors has already developed and some are under experimental trials. Nano-encapsulation of nutrients and nutraceuticals has shown the effectiveness of nanotechnology in maximum delivery of nutrients with minimum destruction. In addition, application of nanotechnology has made the process of food processing more effective with maximum retention of colour, flavor, and nutrient content including various functional components of food products. Researchers also pointed out about the possibility of risk for consumers health and environment with the nanomaterial incorporated food products. Future researches in proper direction to investigate further applicability, potentiality of hazard and establishment of regulations and guidelines for using nanotechnology in food is expected. In this article, current status of various applications nanotechnology in food industry and their potential risk has been discussed.**

***Keywords:** Nanofood, nutrient delivery, food packaging, nanomaterials*

1. INTRODUCTION

Research and development in new materials technology is attracting the attention of researchers all over the globe. Developments are being made to improve the properties of the materials and to find alternative precursors that can give desirable features on the materials. The term *nano* originates etymologically from the Greek, and it means “dwarf.” It indicates physical dimensions in the scale called colloquially *nanometer scale*, or also *nanoscale.* Nanotechnology, which is one of the new technologies, refers to the development of devices, structures, and systems whose size varies from 1 to 100 nanometers (nm). The advancement of nanotechnology is fostered with the availability of techniques to examine and visualise things at the atomic scales. Nanoscience and technology explores electrical, optical, and magnetic activity as well as structural behavior at the molecular and submolecular level. Nanoscale structures permit the control of fundamental properties of materials without changing the materials’ chemical status. These emergent properties have the potential for great impacts in electronics, medicine, and other fields of science and technology including food processing and preservation.

The last fifteen years has demonstrated advancements in every dimensions of nanotechnology such as nanoparticles and powders, nanolayers and coats, electrical, optical and mechanical nanodevices and nanostructured biological materials [1-5]. This is due to the improvement of mechanical properties, barrier properties, surface biocides, biodegradability and intelligent functionality of nanomaterials [6, 7].

Some nanomaterials occur naturally, but of precise interest are on engineered nanomaterials (EN), which are designed for, and already being used in many products and processes technologies [8]. Engineered nanomaterials are designed at the molecular (nanometer) level to take advantage of their small dimension and novel properties which are generally not observed in their conventional, bulk constituents. The two main reasons why materials at the nano scale can have different properties are increased relative surface area and new quantum effects. Nanomaterials have a much greater surface area to volume ratio than their conventional forms, which can lead to greater chemical reactivity and affect their potentiality. Also at the nano scale, quantum effects can become much more important in determining the materials properties and characteristics leading to novel optical, electrical and magnetic attribute [6, 7]. Nanomaterials are already in commercial use, with some having been available for several years or decades.

Application of nanotechnology in agri-food industry was first pointed out by United States Department of Agriculture (USDA) roadmap published in September 2003 [9]. The main focus of new applications so far appears to be on food packaging and healthfoods, with only a few known examples in the mainstream food and beverage areas. In the present article, a general overview of the state-of-the-art of nanotechnology, its present scenario, future prospective in the food industry and its considerable risk factors for the consumer health and environment has been discussed. It is expected that the paper will be quite useful for developing the knowledge of present and future researchers in the field of food nanotechnology.

2. PREPARATION OF ENGINEERED NANOMATERIALS AND THEIR PROCESSING

The synthesis of nanomaterials can be achieved in both the 'bottom up' and the 'top down' approaches i.e. either to assemble few atoms together or dissociate (break or dissemble) bulk solids into finer pieces until they are constituted of only a few atoms. This field of technology is a pure example of interdisciplinary activity comprising physics, chemistry, and engineering upto life science and medicine.

There are several different established methods of creating nanostructures but definite structures such as macromolecules, nanoparticles, rods, buckyballs, nanotubes and so on can be synthesized artificially for certain specific materials to fulfill desired purposes. They can also be arranged by methods based on equilibrium or near-equilibrium thermodynamics such as methods of self-organization and self-assembly (sometimes also called bio-mimetic processes). Using these methods, synthesized materials can be arranged into useful shapes so that finally the material can be applied to a certain application.

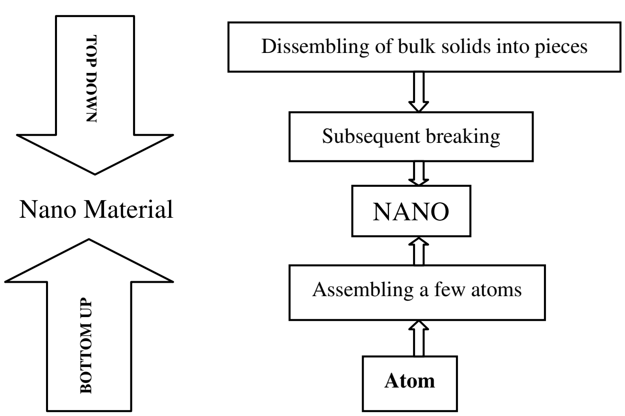

Figure 1. Schematic representation of nano material preparation

3. PRESENT SCENARIO OF APPLICATION OF NANOSYSTEMS IN FOOD TECHNOLOGICAL INNOVATIONS

The term nano-food can be defined as "food which has been cultivated, produced, processed or packaged using nanotechnological techniques or tools or to which manufactured nanomaterials have been added" [10]. In this point of view, it is expected that thousands of food products could emerge based on nanotechnology in the coming decades, though still it is at infancy [11]**.** With realization that nanofood is about the future way of life and is among the most important scientific and technological developments affecting mankind and enterprise, it is important to be better understanding about the applications of nanotechnology in food industry towards economic growth, healthcare and environment which will be eventually determined the priority areas of nanotechnology to be invested. The success in nanofood technology not only can solve the food shortage, but also can improve the health of people by producing healthy foods [11].

Now-a-days, application of nano materials having desired functional characteristics are being analyzing and applying in food processing operations, product development, quality control and analysis such as, post-harvest management and storage, packaging and functional coatings, effective delivery nutrients and nutraceuticals, medicines and therapeutic food, biosensors etc. Nanotechnology is an emerging field, which is expected to have a substantial impact on the modern research and development of science and technology now and in the future. In general, nanotechnology is acknowledged to represent a new frontier area in science and technology of the 21st century. In simple words, nanotechnology is a promising technology seeking to exploit distinct technological advancement of controlling the structure of materials at a reduced dimensional scale approaching individual molecules and their molecular or macromolecular level. In this arena, nanotechnology may provide improved functional and sensory properties to food components. Nano-particles, nano-emulsions, and nano-capsules may be designed to enhance the availability and dispersion of nutrients, antioxidants or nutraceuticals in foods.

3.1 Crop production and post-harvest management of agricultural produce

Drawbacks of the existing techniques like- controlled and modified atmospheric storage (CAP and MAP), cold storage, chemical preservation etc in terms of lacking in desired effectiveness and parallel harmful possessions for health and environment have triggered the researchers towards innovations for the development of alternative packaging and post-harvest management techniques, such as functional edible coatings, disease control of agricultural produce at genetic level with nanotechnology etc. A number of researches have been carrying out their researches to develop coating materials that would coat fruits and vegetables to provide an internal modified atmosphere to them [12]. However, development of an edible coating incorporating nano materials will be an excellent innovation in order to reduce the post-harvest losses of fruits, vegetables and various other food products. Advancement in nanofabrication and characterization tools have enabled studies of physical, chemical and biological interactions between plant cell organelles and various disease causing pathogens, i.e., plant pathology. A better understanding of plant pathogenic mechanisms such as flagella motility and biofilm formation will lead to improved treatment strategies to control the diseases and protect production [13, 14]. The advancement in nanotechnology-enabled gene sequencing is expected to introduce rapid and cost effective capability within a decade [15], hence leading to more effective identification and utilization of plant gene trait resources.

3.2 Modern food packaging and coating

Nanotechnology has already immerged into packaging industries throughout the world and various extraordinary outcomes have been revealed by various researchers and manufacturers. Various properties of packaging materials like- UV protection, barrier properties to moisture, gasses and volatile components, mechanical strength, thermal resistant and sealability has significantly improved with the ncorporation of nanomaterials into base matrix of packaging materials. Nanotechnology has also shown its potential future in active and smart packaging technology. Reinforcement of nanomaterials having different desired properties into edible films and coatings has brought the attention of researchers into functional and edible nanocoatings.

Examples include plastic polymers with nano clay as gas barrier, nano-silver and nano-zinc oxide for antimicrobial action, nano-titanium dioxide for UV protection, nano-titanium nitride for mechanical strength and as a processing aid, nano-silica for surface coating etc. The use of nano-composite with biopolymers is expected to rise because they offer possibility for carbon-neutral biodegradable materials for packaging [16].This will offer opportunities for developing countries to utilize their agricultural and forestry resources, by-products and wastages or development of biopolymer nano-composites.

Silver nano-particles can be introduced in polymeric materials such as PVC, PE, PET etc while polymerization occurs. Silver Nano particles kill pathogens, bacteria, viruses and fungus and are used as a good and safe packaging material. Such nano based packaging materials are 100 times more secure than the normal one for the storage of juices, milk and other agri-products [17]. Nanotechnological products in packaging food materials thus offer immense potential. Food packaging films in the name of "hybrid system" films have enormous number of silicate nano particles. They massively reduce the entrance of oxygen and other gases, and the exit of moisture and volatiles, thus preventing food from spoiling or drying [10]. Nanotechnology can provide solutions for modifying the permeation behavior of foils, increasing barrier properties and improving mechanical and heat-resistance properties [17]. Other nano tech devices may include developing active antimicrobial and antifungal surfaces and sensing as well as signaling microbiological and biochemical changes.

Nanocomposites or nanoparticles in packaging materials (e.g. silver, TiO_2, SiO_2, nano-clay) can ensure better protection for food, for example by reducing the permeability of foils, deodorizing, blocking UV light, improving mechanical and heat-resistance properties, and acting against bacteria or fungi. Nanoform TiO_2 is transparent, UV resistant, and is sold by several companies as filler particles in foils and plastic containers. Nano-TiO_2 in packaging materials is classified as safe for food, although most of the safety data refers to the larger form of TiO_2. There is no record of any investigations to discover whether packaging materials containing Nano-TiO_2 are just as inert (not generally reactive) as those containing the larger "bulk" form, i.e. it cannot be ruled out that nano-TiO_2 particles migrate from packaging to the food. Nylon nanocomposites are used for food packaging (e.g. in PET bottles for beer and other alcoholic beverages), because they constitute a barrier to oxygen and CO_2, keeping the product fresh and/or preventing nasty smells [17].

Ecology Coatings, Inc. (Auburn Hills, USA) has developed UV-cured coatings specifically to address opportunities within the paper and packaging industry. These coatings offer significant benefits over existing UV-cured coatings, and replace expensive adhesive-plastic lamination used in many label applications. This reduces the cost of materials and simplifies the manufacturing line [18].

Bayer Polymers has developed the Durethan KU2-2601 packaging film, which is transparent, lighter, stronger and more heat resistant than those currently in the market. The primary purpose of food packaging films is to prevent contents from drying out and to protect them from moisture and oxygen. In a different strategy, Kodak is developing antimicrobial films that have the ability to absorb oxygen from the contents of the package, thus impeding food deterioration [10]. Certain other antimicrobial packaging and container products like- BlueMoonGoods™, Fresh Box Silver Nanoparticle, Antibacterial Kitchenware, Sunriver Industrial nanosilver fresh food bag, FresherLonger™ Plastic Storage Bags, Food Storage Containers etc are developed by using silver nanoparticles are also coming into the market commercially [19-21]. Using Zinc oxide a product viz- Nano Plastic Wrap of SongSing Nano Technology Co. Ltd was developed for the purpose of Anti-UV, reflecting IR, sterilizing, better temperature tolerance and fire-proof. In which ZnO uses light to sterilize the surface of the film and hence the food [21].

With the similar strategy 'Voridan' in association with 'Nanocor' has developed nanocomposite containing clay nanoparticles, called Imperm. The resultant bottle is both lighter and stronger than glass and is less likely to shatter. The nanocomposite structure minimizes loss of carbon dioxide from the beer and the ingress of oxygen to the bottle, keeping the beer fresher and giving it up to a six-month shelf life [10].

Researchers in the Netherlands are going further to develop intelligent packaging that will release a preservative if the food is within the begining of spoilage. This "release on command" preservative packaging operates by using a bio-switch developed through nanotechnology. 'Smart' food packaging will warn when oxygen has got inside, or if food is going off. Such packaging is already in use in brewing and dairy production and consists of nanofilters that can filter out micro-organisms and even viruses [22].

3.3 Nano-biosensors and rapid detection devices

In the recent years the advent of nanotechnology applications in food safety (i.e. detection systems, biosensors, etc) is becoming a key focus of research and development, and the potential benefits of this emerging technology are receiving growing attention from both the public and the private sector. The application of nanobiosensors in food industry could lead to immense improvements in quality control, food safety, and traceability. The advantages of nanobiosensors can lead to their use in various food production processes: from raw material preparation, food processing (quality control), monitoring of storage conditions and use of these devices as cost effective tools for quality & process controls as well as to ensure food safety [17].

In recent years, it has aroused great interest in modifying electrode surfaces with novel nanomaterials so as to achieve a faster electron transfer of biomolecules and a higher specificity and accuracy. This advantage has inspired research in coupling nanomaterial based biosensors with biomolecules. These biosensors have been applied in different areas such as food quality, food safety, clinical analysis and environmental control [17].

Kraft foods, along with researchers at Rutgers University in the US, are developing an "electronic tongue" for inclusion in packaging. This consists of an array of nanosensors which are extremely sensitive to gases released by food as it spoils, causing the sensor strip to change colour as a result, giving a clear visible signal of whether the food is fresh or not [10]. AgroMicron has developed the NanoBioluminescence Detection Spray which contains a luminescent protein that has been engineered to bind to the surface of microbes such as Salmonella and *E. coli*. When bound, it emits a visible glow, the more intense the glow is, the higher the bacterial contamination. The company aims to market the product under the name BioMark and is currently designing new spray techniques to apply in ocean freight containerized shipping as well as to fight bioterrorism [23]. In a similar strategy to ensure food safety, EU researchers in the Good Food Project have developed a portable nanosensor to detect chemicals, pathogens and toxins in food [24]. The project is also developing a device using DNA biochips to detect pathogens. It is a technique that could also be applied to determine the presence of different kinds of harmful bacteria in meat or fish, or fungi affecting fruit. The project also has plans to develop microarray sensors that can be used to identify pesticides on fruit and vegetables as well as those which will monitor environmental conditions at the farm. These have been coined "Good Food sensors" [10].

3.4 Nanotechnology in medicine and therapeutic application

Combination of nanotechnology with medical science has already brought a tremendous changes and advancement in prevention, detection and treatment of various diseases and physiological as well as pathological conditions. The German company Aquanova has developed a new technology which combines two active substances for fat reduction and satiety into a single nano-carrier (micelles of average 30 nm diameter), an innovation said to be a new approach to intelligent weight management. The product is named as NovaSOL Sustain. The NovaSol technology has also been used to create a vitamin-E preparation that does not cloud liquids, called SoluE, and a vitamin C preparation called SoluC. The NovaSOL product can be used to introduce other dietary supplements as it protects contents from stomach acids [25]. Megestrol acetate oral suspension (MAOS) is an appetite stimulant indicated for cachexia in patients with AIDS. It is available in its original formulation, Megace® (MAOS), and as a nanocrystal dispersion, Megace® ES (MA-ES) (Bristol-Myers Squibb, New York, USA). Bioavailability and absorption were found to be greater for MA-ES than MAOS in fasting subjects, thereby, suggesting MA-ES a preferred formulation of megestrol acetate when managing cachectic patients whose caloric intake is reduced [26].

3.5 Nutrient bioavailability and utrient delivery

From the results of the researches on nutrient and nutraceutical delivery with the application of nanotechnological principles, several products are already entered into the market domain. Royal BodyCare, a company utilizing nanotechnology in nutritional sciences, has marketed a new product called NanoCeuticals which is a colloid (or emulsion) of particles of less than 5 nm in diameter. The company claims the product will scavenge free radicals, increase hydration and balance the body's pH. The company has also developed NanoClusters™, a nanosize powder combined with nutritional supplements. When consumed, it enhances the absorption of nutrients [27].

3.6 Nanobiotechnology

Interdisciplinary research in the application of nanostructures in the field of biotechnology has started addressing so many global problems. Nanobiomaterials are developed utilizing DNA molecules as the basic building units using nucleic acid engineering. DNA molecules can be modified to develop novel biomaterials such as nanowires and nanomembranes that can be used for nanofiltration processes. It is reported that the expected global production for engineered nanomaterials applied in biotechnology will reach 10 ton per year by 2020 where the present use is 1 ton per year [28, 29].

3.5 Food additives and ingredients

Various nanomaterials are used as additives and/or ingredients to produce various functional food products to achieve certain goals like-low fat absorption on frying,, to supplement and effective delivery of nutrients, to make the process easier and energy efficient etc. In addition to that present day researchers of this domain are concentrated on proper fabrication of nano-sized food components and additives to reduce processing and biological loss. In this context, US based Oilfresh corporation has marketed a new nanoceramic product which reduces oil use in restaurants and fast food shops by half. As a result of its large surface area, the product prevents the oxidation and agglomeration of fats in deep fat fryers, thus extending the useful life span of the oil. An additional benefit is that oil heats up more quickly, reducing the energy required for cooking [30]. Some other products which are designed and developed by using nano-ingredients that are already exist in the market worldwide includes: Fortified Fruit Juice (High Vive. com, USA), Nanoceuticals Slim Shake (assorted flavors, RBC Lifesciences, Irving, USA), NanoSlim beverage (NanoSlim), Oat Nutritional Drink (assorted flavors, Toddler Health, Los Angeles, USA), 'Daily Vitamin Boost' fortified fruit juice (Jamba Juice Hawaii, USA) and nanocapsules containing tuna fish oil (a source of omega 3 fatty acids) in "Tip-Top" Up bread which will break only when it will reach the stomach and will avoid the unpleasant taste (Enfield, Australia) [31]. Nanoparticles of different materials including Silver, gold, copper, platinum, palladium, iridium, titanium and zinc are also used in the production of various food supplements viz- MesoSilver, Mesogold, Mesocopper, Mesoplatinum, Mesopalladium, Mesoiridium, Mesotitanium and Mesozinc respectively [32].

4. THREAT OF NANOTECHNOLOGY IN FOOD PROCESSING

Nano materials offer lots of potential benefits in almost all sectors of technological developments including food processing, preservation, storage, quality assurance, value addition and also food safety and security. It has also proved that this modern technology can become the accelerator in developments of all sectors of human and social need of coming future. But as most of the good inventions has its opposite side of effects also, so the probable harmful aspects of nanotechnology should also be analysed critically and it is the need of present time to conduct extensive researches so that its benificial effects can be utilised to fulfill the global needs by eliminating its hazards.

It is established that products containing natural food nano-structures that are likely to be digested/degraded in the gastro-intestinal (GI) tract (soft nanomaterials) may not require a detailed evaluation compared to products containing insoluble and biopersistent nanomaterials [16]. On this basis the following broad application categories may be considered:

Areas of least concern include food products that contain processed (natural) food nano-structures, which are either digested or solubilised in the GI tract and are not biopersistent. Areas of some concern arise where food products contain encapsulated food/feed additives in nano-sized carriers which may not be biopersistent, but may carry the encapsulated substances across the GI tract. In such condition, tissue distribution of the materials contained in nano-carriers may be different from that of equivalent bulk materials. Also an increased bioavailability of vitamins and minerals may not always be beneficial for consumer health. A greater uptake of food colors or preservatives could take the application outside of the conditions under which the ADI (acceptable daily intake value) was set for the additive [16]. Areas of major concern include when food products contain insoluble, indigestible by the digestion enzyme system, and potentially biopersistent and even non-degradable nano-additives (e.g., metals or metal oxides) or functionalized nanomaterials. Such applications may impart a risk of consumer exposure to hard nanomaterials [16].

Risks of migration of nanomaterials from the packaging into the food and subsequently to the body system are also being advocated [33-35]. This may impact negatively on the use and progress of such packaging materials. But researches has till now showed that the chance of migration of nano particles is very low. It is found that migration can only happen when the size of incorporated nanomaterial is within the lower nm range, have very high dynamic viscosity and if they are not bounded properly with the polymer matrix [36].

Toxicological risk of nanomaterials is also of a major concern but toxicology research and risk assessments in nanotechnology are practically non-existent, especially in the food sector [37] and few have proved to be valuable in terms of their use in assessing toxicity [38]. Some materials exhibit toxicity at the nanoscale and not at the macroscale. For example, Cui et al., (2005) showed that single-walled carbon nanotubes inhibited human embryo kidney cell proliferation and negatively impacted on cell growth and cell turnover[39]. The nanomaterials involved in this study are unlikely to be used in the food industry, however, such toxic effects must be noted at this early stage of technological development and progress must be cautious. It may substantially affect the human and environmental health.

Nano-additives incorporated in foods are readily reactive with the other food compounds, stomach acids as well as enzymes of the GI track, thus will change the internal environment of the digestive system of the individual. This phenomenon may also loss the nano property of the incorporated materials due to agglomeration or aggregation.

Though the risk potentiality of the nanomaterials are under research stage, but another important issue concern to risk is that nanomaterials are extending their range of application in a unexpected progression, but still there are not a single regulation specifically for the application and analysis of nanomaterials in food. General regulatory rules like European Union, Codex Alimentarious, USDA, USFDA, PFA etc. are still following for the purpose, but these regulations concern with general food safety, food contact surface, food hazard, general food adulteration etc. But nanomaterials have certain extraordinary properties than the general bulk materials, so specific regulations are in emergency need for the proper welfare of the society by nano-food technology [40].

The concern aspect regarding nanomaterials differs from country to country. In Taiwan, authority have introduced a quality assurance system viz-'Nano Mark System' for consumers which certifies that a product uses a genuine nanotechnology [41] but food is not included as a category to which this symbol is assigned. In Australia, like Europe, nanotechnologies are regulated by horizontal legislation of European Commission [42]. NICNAS, which regulates chemicals for the protection of human health and the environment, has recently introduced new administrative processes to address nanotechnology [43]. NICNAS monitors changes in industrial usage and can legislate accordingly to ensure legislation remains at the forefront of developments and to ensure emerging challenges in industrial chemical regulation, including the challenge of nanotechnology, are under control [44]. In the United States, multiple federal agencies regulate products associated with nanotechnologies and nanomaterials, but there is no regulatory framework that provides consistent and comprehensive screening and protections for consumers [45]. So, it is transparent that a regulatory gap exists between commercial developments and public expectations about regulatory protections for nanotechnologies [46].

Thus, at present along with the regulatory aspects, a concrete definition of nanomaterials, proper detection and characterization technique, its reactivity with food components, toxicological features, long term effects on human and biological system and risk assessment procedures are the major area of concern issue for utilizing the benefits of nanoscience in a viable way [16]. A number of novel research projects are carrying out worldwide to establish some solution of the above problems.

5. FUTURE EXPECTATIONS AND CONCLUSION

Science and technology of nanomaterials though is at a juvenile stage, but it is already showing a great potentiality in every areas of application**.** Efforts to facilitate international collaboration and information exchange are underway to ensure acceptance and utilization of the many benefits of nanotechnology. All ideas about future applications of nanotechnology in food do not closely resemble with the currently available food and processing technologies. Even though such futuristic speculations are probably not the aim of present-day research, the fact that they are suggested in public media influences the public awareness about food based on nanotechnology. Some of these are that our grandchildren will eat vegetarian "meat" tasting the same as animal meat to guarantee a sustainable food supply for the whole world population or that we need food produced with nanotechnology as a form of preventive medicine. Incorporating many kinds of artificial ingredients in novel chocolate bars with some unforeseen effects for the unsuspecting consumer. This imaginative yet not totally impossible idea keeps popping up in the futuristic speculation about food produced with nanotechnology. Thus, future of nanotechnology in food is expected to be extra-ordinary, which will change the entire scenario of food production, packaging, chemical framework, processing, analysis technique, marketing including consumer safety, but extensive research in this field can only bring the speculations into reality. Continous R&D work is again the only way for the establishment of concrete regulations for the applications of nanotechnology in food industry to ensure the quality, human health and environmental safety thus enhancing the perception of consumers towards nanofoods.

REFERENCES

[1] ObservatoryNANO, "Nanotechnology for Biodegradable and Edible Food Packaging", Working Paper Version, April 2010, available at: *www.observatorynano.eu.* (accessed June, 2011).

[2] deMoura, R.M., Aouada, F.A., Avena-Bustillos, R.J., McHugh, T.J., Krochta, J.M., and Mattoso, L.H.C., "Improved barrier and mechanical properties of novel hydroxypropyl methylcellulose edible films with chitosan/tripolyphosphate nanoparticles", *Journal of Food Engineering,* 92, 2009, pp. 448–453.

[3] Torres-Giner, S., Gimenez, E., and Lagaron, J.M., "Characterization of the morphology and thermal properties of Zein Prolamine nanostructures obtained by electrospinning", *Food Hydrocolloids*, 22, 2008, pp. 601-614.

[4] Yao, C., Li, X., and Song, T., "Electrospinning and crosslinking of zein nanofiber mats", *Journal of Applied Polymer Science*, 103, 2007, pp. 380-385.

[5] Corradini, E.A., Souto, E., Carvalho, A.J.F., Curvelo, A.A.S., and Mattoso, L.H.C., "Mechanical and morphological characterization of starch/zein blends plasticized with glycerol", *Journal of Applied Polymer Science*, 101, 2006, pp. 4133-4139.

[6] Bradley, E.L., Castle, L., and Chaudhry, Q., "Applications of nanomaterials in food packaging with a consideration of

opportunities for developing countries", *Trends in Food Science & Technology*, 22, 2011, pp. 604-610.

[7] Lagaron, J.M., and Lopez-Rubio, A., "Nanotechnology for bioplastics: opportunities, challenges and strategies", *Trends in Food Science & Technology*, 22, 2011, pp. 611-617.

[8] Morris, V.J., and Parker, R., "Natural and designed self-assembled nanostructures in foods", *The World of Food Science: Food Nanotechnology,* 4, 2008, available at: *http:// www. worldfoodscience. org /cms/?pid=1004050* (accessed February, 2010).

[9] Nanoscale Science and Engineering for Agriculture and Food Systems – a report from the USDA workshop, 2003, available at: *www.nseafs.cornell.edu/web.roadmap.pdf* (accessed June, 2012).

[10] Joseph, T., and Morrison, M., "Nanotechnology in Agriculture and Food", 2006, available at. http://www.nanoforum.org/ dateien/temp/nanotechnology%20in%20agricult ure%20and%20 food.pdf?08122006200524 (accessed January, 2008).

[11] Chaudhry Q., Scotter M., Blackburn J., Ross B., Boxall A., and Castle L., "Application and implications of nanotechnologies for the food sector", *Food Additives & Contaminants*, 25(3), 2008, pp. 241-258.

[12] Park, H.J., Chinnan, M.S., and Shewfelt, R.L., "Edible coating effects onstorage life and quality of tomatoes", *Journal of Food Science,* 59(3), 1994, pp. 568-570.

[13] Cursino, L., Li, Y., Zaini, P.A., De La Fuente, L., Hoch, H.C., and Burr, T.J., "Twitching motility and biofilm formation are associated with tonB1 in ***Xylella fastidiosa***", *FEMS Microbiology Letters*, 299, 2009, pp. 193-199.

[14] Zaini, P.A., De La Fuente, L., Hoch, H.C., and Burr, T.J., "Grapevine xylem sap enhances biofilm development by ***Xylella fastidiosa***", *FEMS Microbiology Letters*, 295, 2009, pp. 129-134.

[15] Branton, D., Deamer, D.W., Marziali, A., Bayley, H., Benner, S.A., Butler, T., et al., "The potential and challenges of nanopores sequencing", *Nature Biotechnology*, 26(10), 2008, pp. 1146-1153.

[16] Chaudhry, Q., and Castle, L., "Food applications of nanotechnologies: An overview of opportunities and challenges for developing countries", *Trends in Food Science & Technology,* 22, 2011, pp. 595-603

[17] **Paul, S.K,** Sahu, J.K**.** *Nanotechnology in Food Processing. In: Introduction to Advanced food processing technologies.* Sahu, J.K. (ed.), *CRC press*, ISBN 9781439880715, 2014.

[18] *http://www.nanoid.co.uk/nanofoods.html*, (accessed February, 2010).

[19] Alfadul, S. M., and Elneshwy, A. A., "Use of nanotechnology in food processing, packaging and safety: review", *African Journal of Food, Agriculture, Nutrition and Development*, 10(6), 2010, pp. 2719-2739.

[20] Huang, Y., Chen, S., Bing, X., Gao, C., Wang, T., and Yuan, B., "Nanosilver migrated into food-simulating solutions from commercially available food fresh containers", *Packaging Technology and Science*, 24 (5), 2011, pp. 291-297.

[21] Bouwmeester, H., Dekkers, S., Noordam, M., Hagens,W., Bulder, A., de Heer, C., et al., "Health impact of nanotechnologies in food production", *RIKILT/RIVM Report,* 2007.014, available at: *http://www.rikilt.wur.nl/NR/rdonlyres/BDEEDD31-F58C-47EBA0AA23CB9956CE18/54352/ R20 07014 .pdf* (accessed March 2008).

[22] Bhupinder S.S., "Food nanotechnology-an overview*", Nanotechnology, Science and Applications*, 3, 2010, pp. 1-15.

[23] *http://www.agromicron.com/BTP.htm,* (accessed on 22 September 2012).

[24] *http://www.goodfood-project.org/*, (accessed on 22 September 2012).

[25] *http://www.aquanova.de/product-micelle.htm*,(accessed on 22nd September, 2012).

[26] Deschamps, B., Musaji, N., and Gillespie, J.A., "Food effect on the bioavailability of two distinct formulations of megestrol acetate oral suspension", *International Journal of Nanomed*, 4, 2009.

[27] *http://www.smartwoman.royalbodycare.com/ Nanotechnology_ Revolution.aspx* (accessed September, 2012)

[28] Li, X., Zhou, Y., Zheng, Z., Yue, X., Dai, Z., Liu, S., et al., "Glucose biosensor based on nanocomposite films of CdTe quantum dots and glucose oxidase", *Langmuir*, 25(11), 2009, pp. 6580-6586.

[29] Chen, H., and Yada, R., "Nanotechnologies in agriculture: New tools for sustainable development", *Trends in Food Science & Technology*, 22, 2011, pp. 585 – 594.

[30] http://www.oilfresh.com/of1000.html, (accessed September, 2012).

[31] Sabine, G., André, G., Myrtill, S., Michael, N., and Ulrich, F. "Nanoparticles and nanostructured materials in the food industry", *Nano-trust dossiers*, 004, 2010, pp. 1-5.

[32] Food safety authority of Ireland, *The relevance for food safety of applications of nanotechnology in the food and feed industries*, 2008, ISBN 1-904465-59-5, available at. www.fsai.ie (accessed September 2012).

[33] Avella, M., DeVlieger, J.J., Errico, M.E., Fischer, S., Vacca, P., and Volpe, M.G., "Biodegradable starch/clay nanocomposite films for food packaging applications", *Food Chemistry*, 93, 2005, pp. 467-474.

[34] Bradley, E.L., Castle, L., and Chaudhry, Q., "Applications of nanomaterials in food packaging with a consideration of opportunities for developing countries", *Trends in Food Science & Technology*, 22, 2011, pp. 604-610.

[35] EFSA, "21st list of substances for food contact materials, scientific opinion of the panel on food contact materials, enzymes, flavourings and processing aids (CEF) (question No EFSA-Q-2005- 151, EFSA-Q-2006-324, EFSA-Q-2006-323), adopted on 27 November 2008", *The EFSA Journal,* 888-890, 2008, pp. 1-14.

[36] Simon, P., Chaudhry, Q., and Bakos, D., "Migration of engineered nanoparticles from polymer packaging to food e a physicochemical view", *Journal of Food & Nutrition Research*, 47(3), 2008, pp. 105-113.

[37] Tiede, K., Boxall, A. B. A., Tear, S. P., Lewis, J., David, H., and Hassellov, M., "Detection and characterization of engineered nanoparticles in food and the environment", *Food Additives & Contaminants*, 25, 2008, pp. 795-821.

[38] Card, J. W., and Magnuson, B. A., "A method to assess the quality of studies that examine the toxicity of engineered nanomaterials", *International Journal of Toxicology*, 29(4), 2010, pp. 402-410.

[39] Cui, D., Tian, F., Ozkan, C. S., Wang, M., and Gao, H., "Effect of single wall carbon nanotubes on human HEK293 cells", *Toxicology Letters*, 155(1), 2005, pp. 73-85.

[40] Chun, A.L., "Will the public swallow nanofood?" *Natural Nanotechnology*, 4, 2009, pp. 790–791.

[41] Chau, C. F., Wu, S. H., and Yen, G. C., "The development of regulations for food nanotechnology", *Trends in Food Science & Technology*, 18(5), 2007, pp. 269-280.

[42] Lyons, K., and Whelan, J., "Community engagement to facilitate,legitimize and accelerate the advancement of nanotechnologies in Australia", *NanoEthics*, 4(1), 2010, pp. 53-66.

[43] NICNAS, "National industrial chemicals notification and assessment scheme", *Australian Government Gazette*, 2010.

[44] Mittal, A., "Nanotechnology: Nanomaterials are widely used in commerce, but EPA faces challenges in regulating risk", *Washington: United States Government Accountability Office*, 2010.

[45] Corley, E., Scheufele, D., and Hu, Q., "Of risks and regulations: how leading US nanoscientists form policy stances about nanotechnology", *Journal of Nanoparticle Research*, 11(7), 2009, pp. 1573-1585.

[46] Bowman, D. M., and Hodge, G. A., "Nanotechnology: mapping the wild regulatory frontier", *Futures*, 38(9), 2006, pp. 1060-1073.