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Full Length Research Paper

Nano-particles - A recent approach to insect pest control

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Nanotechnology, a promising field of research opens up in the present decade a wide array of opportunities in the present decade and is expected to give major impulses to technical innovations in a variety of industrial sectors in the future. The potential uses and benefits of nanotechnology are enormous. These include agricultural productivity enhancement involving nanoporous zeolites for slow release and efficient dosage of water and fertilizer, nanocapsules for herbicide delivery and vector and pest management and nanosensors for pest detection. The atom by atom arrangement allows the manipulation of nanoparticles thus influencing their size, shape and orientation for reaction with the targeted tissues. It is now known that many insects possess ferromagnetic materials in the head, thorax and abdomen, which act as geomagnetic sensors. In this paper, our discussion is focused on nanoparticles in insects and their potential for use in insect pest management.

Key words: Nanoporous zeolites, nanocapsules, nanosensors, nanoparticles, insect pest management.

INTRODUCTION

Targeted nanoparticles often exhibit novel characteristics like extra ordinary strength, more chemical reactivity and possess a high electrical conductivity. Thus, nano-technology has become one of the most promising new technologies in the recent decade. Nanoparticles possess distinct physical, biological and chemical properties associated with their atomic strength (Leiderer and Dekorsy, 2008). Nanoparticles (which are 1-100 nm in diameter) are agglomerated atom by atom, and their size (and some-times shape) may be maintained by specific experimental procedure (Roy, 2009). Nanoparticles can be arranged or assembled into ordered layers, or mine layers (Ulrich et al., 2006). Such self-assembly is due to forces such as hydrogen bonding, dipolar forces, hydrophilic or hydrophobic interactions, surface tension, gravity and other forces. Many naturally occurring biological structures like membranes, vessicles, and deoxyribonucleic acid (DNA) are formed by self-assembly.

The word "Nano" is developed from the Greek word meaning "dwarf". In more technical terms, the word "nano" means 10^{-9}, or one billionth of something. For example, a virus is roughly 100 nm in size. Naturally, the word nanotechnology evolved due to use of nanometer size particles (size of 1 to 100 nm). Nanotechnology exhibits the top down phenomena, which means reducing the size of the smallest structures to the nanoscale. For example, photonics applications in nanoelectronics and nanoengineering or the bottom up approach, involving individual atom by atom and molecules into nanostructures, which are applicable in several biological processes (Niemeyer and Doz, 2001; Elibol et al., 2003; Wadhwa, 2009). Thus nanotechnology deals with the targeted nanoparticles as and when the particles exhibit

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different physical strength, chemical reactivity, electrical conductance and magnetic properties (Nykypanchuk et al., 2008). Nanotechnology, a promising field of research opens up in the present decade a wide array of opportunities and is expected to give major impulses to technical innovations in a variety of industrial sectors in the future. In particular, in this paper, our discussion is focused on nanoparticles in insects and their potential role in insect pest management.

NANOSCALE MATERIALS AND THEIR APPLICATION

In the present century, the fact that nanoscale particles and other magnetic materials of similar property can be applied in nanotechnology which cannot be overstressed. In nature, living organisms from bacteria to beetles rely on nanometer-shaped protein machines that perform everything from whipping of flagella to flexing of muscles. Nanometer-sized carbon (carbon black) that improves the mechanical properties of tires, nanometer silver particles that initiate photographic film development, and nanometer particles that are the basis of catalysts critical to the petrochemical industry have contributed to commercial products for many years (Huck, 2008; Fiorito, 2008). Nanoparticles and other nanostructured materials are often synthesized using chemical methods. It is very essential to identify the target nanoparticles through the scanning tunneling microscope (STM) and atomic force microscope (AFM). Nanoscale science probably began with the ground breaking invention of the STM, for which Gerd Binnig and Heinrich Rohrer of the International Business Machines (IBM) were awarded the Nobel Prize for Physics in 1986. Nanotechnology has already shown great potential for application in environmental protection (Nowack, 2009; Ying, 2009).

Nanostructured materials are being used in devices for pollution sensing, treatment and remediation. Application of nanoparticles for pollution prevention through environmentally benign synthesis and manufacturing are also being explored (Duebendorf, 2008). In addition, nanostructured materials are being used in many manufactured products, especially in composite materials and fillers. The potential of nanotechnology to revolutionize the health care, textile, information and communication technology and energy sectors has been well documented. In fact several products enabled by nanotechnology are already in the market and they include antibacterial dressings, transparent sunscreen lotions, strain-resistant plants and nano-particles in eco-friendly pesticides (Bhattacharyya, 2009; Sukul et al., 2008; Barik et al., 2008; Gha-Young et al., 2008).

NATURAL NANOPARTICLES IN SEVERAL INSECTS

Although naturally occurring nano-structures are being neglected, they are a potentially rich source of products that meet certain specifications (Watson and Watson, 2004). The emerging industries based on nanotechnology have so far made little use of 'free' technology available in nature (Bhattacharyya and Debnath, 2008; Ehrlich et al., 2008). A good example is the ordered hexagonal packed array of structures in the wings of cicada for instance, *Psaltoda claripennis* Ashton and termite for example, family *Rhinotermitidae* (Zhang and Liu, 2006). Studies have shown that the size of the nanoparticles may vary from 200 to 1000 nm. The structures tend to have a rounded shape at the apex and protrude some 150-350 nm out from the surface plane. These wing nanoparticles help in the aerodynamic efficiency of the insect.

Nowadays, we know that insects possess ferromagnetic resonance which is temperature dependent. The magnetic material is present in the head, thorax and abdomen of insects like *Solenopsis substitute* (Fabricius), an ant. These magnetic nanoparticles in social insects act as geomagnetic sensors (Esquivel, 2007). The magnetic material content is slightly higher in heads with antennae than in abdomen of the ants. It is known that the behaviour of a great variety of higher animals is influenced by changes in the local magnetic field within their environment. More specifically, it has been shown that honey bees use geomagnetic field information for orientation, homing and foraging (Binhi, 2004). However, the process that animals use to detect the geomagnetic field is still not known. Several observations indicate that intracellular biomineralized magnetite could interact with the geomagnetic field monitoring information on its intensity and direction. Identifying the presence of magnetite particles in different species of insects and thus showing that insects' behaviour is influenced by the geomagnetic field is a first step towards demonstrating that biogenic magnetite is involved in geomagnetic field detection (Ishay et al., 2008). It has been shown that the ant *Formica rufa* Linnaeus uses information from the geomagnetic field for orientation during the foraging process. The same observation has been made in respect of the ant *Solenopsis invicta* Buren (Slowik et al., 1998). The presence of ferric iron in the abdomen of *S. invicta* workers was also observed (Abracado et al., 2005).The observation which was made through electron microscope technique clearly demonstrated that several species of ants recognize magnetic signals with the help of magnetite nanoparticles (Abracado et al., 2005). Isolated nanoparticles of insects have diameters of about 12 and 11 nm in abdomen with petiole and head with antennae, respectively. It is noteworthy that magnetite particles were also observed in the stingless bee *Schwarziana quadripunctata* Lepeletier especially in the head, antennae, thorax and abdomen (Lucano et al., 2006; Esquivel et al., 2007). The magneto sensor is present in *Pachycondyla marginata* Roger, a migratory and termitephagous ant, hunting only the termite species *Neocap-*

ritermes opacus Hagen (Acosta-Avalos et al., 1999; Wajnberg et al., 2004; de Oliveira et al., 2008). Also, ferromagnetic material has been detected in *Apis mellifer*a Linnaeus abdomens and identified as suitable for magnetic reception (Desoil et al., 2005). Magnetic nanoparticles in the *A. mellifera* abdomens are well accepted as involved in their magnetoreception mechanism (El-Jaick et al., 2001). The biogenic magnetic properties of the honeybee *A. mellifera* were investigated with a view to understanding the bee's physiological response to a magnetic field (Chambarelli et al., 2008; Hsu et al., 2007; Billen, 2006). The magnetizations of bee abdomens on one hand, and heads and thoraxes on the other hand, were measured separately as functions of temperature and field (Esquivel et al., 2002; Desoil et al., 2005). Both the antiferromagnetic responses of the ferrihydrite cores of the iron storage protein ferritin, and the ferrimagnetic responses of nanoscale magnetite (Fe_3O_4) particles, were observed (Dawson, 2008; Tai Kai, 2008). Relatively large magnetite particles (ca. 30 nm or more), capable of retaining remanence magnetization at room temperature were found in the abdomens, but were absent in the heads and thoraxes. Fire ant (*S. invicta)* workers, queens and alates were analyzed by magnetic resonance imaging (MRI) for the detection of natural magnetism. All ferromagnetic materials are magnetic nanoparticles, which are solely responsible for localization of specific direction for food and host of insects. Recently, cicada wings have been investigated by atomic force microscopy (AFM) used for observing nanoparticles. The structures consist of hexagonal close-packed protrusions with a lateral spacing of 200 nm and may have multiple functionalities. Nanostructure components are also present in compound eyes of insects. Wings of butterflies possess bright colour components and these colour components are nothing but nanoparticles. Recently, a novel photodegradable insecticide involving nano particles has been prepared (Guan et al., 2008). Naturally, volatile phytochemicals and nanoparticles of insects are solely responsible for plant-insect interaction (Gorb and Gorb, 2009). Moreover, in the case of silkworm, electrospun silk fibroin-based fibers with average diameter of 700 nm were prepared from aqueous regenerated silkworm silk solutions (Jin et al., 2004; Zhang et al., 2007). The electrospun nanocomposite of silkworm silk helps in producing single wall carbon nanotubes (SWNT) for drug delivery system (Ayutsede et al., 2008).

NANOPARTICLES - A GREEN REVOLUTION IN FUTURE

The potential uses and benefits of nanotechnology are enormous. These include agricultural productivity enhancement involving nanoporous zeolites for slow release and efficient dosage of water and fertilizer, nanocapsules for herbicide delivery and vector and pest management and nanosensors for pest detection (Scrinis and Lyons, 2007; Scott, 2007; Joseph and Morrison, 2006; Liu and Du, 2004). Nanoparticles help to produce new pesticides, insecticides and insect repellants (Owolade et al., 2008). Nanoencapsulation is a process through which a chemical such as an insecticide is slowly but efficiently released to a particular host plant for insect pest control. Nanoencapsulation with nanoparticles in form of pesticides allows for proper absorption of the chemical into the plants unlike the case of larger particles (Scrinis and Lyons, 2007). This process can also deliver DNA and other desired chemicals into plant tissues for protection of host plants against insect pests (Torney, 2009). Release mechanisms of nanoencapsulation include diffusion, dissolution, biodegradation and osmotic pressure with specific pH (Vidhyalakshmi et al., 2009; Ding and Shah, 2009). It has been observed that nanoparticles loaded with garlic essential oil is efficacious against *Tribolium castaneum* Herbst (Yang et al., 2009). Also, it is known that aluminosilicate filled nanotube can stick to plant surfaces while nano ingredients of nanotube have the ability to stick to the surface hair of insect pests and ultimately enters the body and influences certain physiological functions (Patil, 2009).

Sukul et al. (2009) have reported that potentized drugs significantly increased plant growth, chlorophyll, protein and water content in the leaves as compared to the control. *CCC* 30 (nano) was found to be more effective than *CCC* 30. Potentized drugs are thought to initiate their action on the integral membrane proteins of leaves and modulate cell physiology towards growth. Barik et al. (2008) opined that more ambitious uses of nanoparticles are bio-remediation of contaminated environments, biocides and antifungals on textiles. Surface-modified hydrophobic as well as lipophilic nanosilica could be effectively used as novel drugs for treatment of nuclear polyhedrosis virus (BmNPV), a scourge in the silkworm industry. Also, research on silkworm, *Bombyx mori* L. race Nistari clearly demonstrates that nano particle could stimulate more production of fibroin protein which can help in producing carbon nano tube in future (Bhattacharyya et al., 2008; Bhattacharyya, 2009). The above highlights the putative effects of nanoparticles on insects, as these small particles are present in their entire body parts. Research on nanoparticles and insect control should be geared toward introduction of faster and eco-friendly pesticides in future (Bhattacharyya et al., 2007). It is high time therefore that leading chemical companies to focus on formulation of nano scale pesticides for delivery into the target host tissue through nanoencapsulation. At present, the toxicological and ecotoxicological risks linked to this expanding technology ("emerging technology") cannot be assessed yet. While nanotechnology is increasingly moving into the centre of public attention, it is currently not yet linked to any great degree to concerns about health and the environment.

Nanoencapsulation is currently the most promising technology for protection of host plants against insect pests. Thus nanotechnology will revolutionize agriculture including pest management in the near future. Over the next two decades, the Green Revolution would be accelerated by means of nanotechnology.

REFERENCES

Abracado LG, Esquivel DMS, Alves OC, Wajnbergo E (2005). Magnetic material in head, thorax, and abdomen of *Solenopsis substituta* ants: A ferromagnetic resonance study. J. Magn. Reson. 175(2): 309-316.

Acosta-Avalos D, Wajnberg E, Oliveira P, Leal I, Farina M, Esquivel DS (1999). Isolation of magnetic nanoparticles from *Pachycondyla marginata.* J. Exp. Biol. 202: 2687-2692.

Ayutsede J, Gandhi M, Sukigara S, Ko F (2008). Carbon Nanotube Reinforced *Bombyx mori* Nanofibers By The Electrospinning Process. In Materials Research Society 506, Keystone Drive, Warrendale, PA, 15086-7573, USA.

Barik TK, Sahu B, Swain V (2008). Nanosilica-from medicine to pest control. Parasitol. Res.103(2): 253-258.

Bhattacharyya A (2009). Nanoparticles-From Drug Delivery To Insect Pest Control. Akshar. 1(1): 1-7.

Bhattacharyya A, Barik B, Kundu P, Mandal DN, Das A, Sen P, Rao CV, Mandal S (2007). Bioactivity of nanoparticles and allelochemicals on stored grain pest-*Sitophilus oryzae* (L) (Coleoptera:Curculionidae). Accepted in 27th Annual Session of The Academy of Environmental Biology and National Symposium of Biomarkers of Environmental Problems, October 26-28, 2007, Jointly organized by Department of Zoology and Department of Environmental Sciences, Charan Singh University, Meerut, U. P., Indian.

Bhattacharyya A, Debnath N (2008). Nano Particles-A Futuristic Approach in Insect Population. In Proceedings on UGC Sponsored National Seminar On Recent Advances In Genetics and Molecular Biology, Biotechnology and Bioinformatics, 21st and 22nd November, 2008. Jointly Organized by Department of Zoology and Botany, Vidyasagar College, Kolkata-700006.West Bengal, Indian.

Bhattacharyya A, Gosh M, Chinnaswamy KP, Sen P, Barik B, Kundu P, Mandal S (2008). Nano-particle (allelochemicals) and Silkworm Physiology. In Recent Trends in Seribiotechnology. Edited by Chinnaswamy KP and Vijaya Bhaskar Rao A. Bangalore. Indian. pp. 58-63.

Billen J (2006). Signal variety and communication in social Insects. Proc. Neth. Entomol. Soc. Meet. 17: 9-17.

Binhi VN (2004). Stochastic dynamics of magnetic nanoparticles and a mechanism of biological orientation in the geomagnetic field. arXiv: physics/0412158v1 [physics biol-ph] 27 Dec.

Chambarelli LL, Pinho MA, Abracado LG, Esquivel DMS, Wajnberg E (2008). Temporal and preparation effects in the magnetic nanoparticles of *Apis mellifera* body parts. J. Magn. Magn. Mater. 320(14): 207-210.

Dawson K (2008). Bionano interactions- a rational approach to the interaction between nanoscale materials and living matter? Nanobioeurope, 8: 1-2.

de Oliveira JF, Alves OC, Esquivel DMS, Wajnberg E (2008). Ingested and biomineralized magnetic material in the prey *Neocapritermes opacus* termite: FMR characterization. J. Magn. Reson. 191: 112-119.

Desoil M, Gillis P, Gossuin Y, Pankhurst QA, Hautot D (2005). Definitive identification of magnetite nanoparticles in the abdomen of the honeybee *Apis mellifera.* J. Phys. Conf. Ser. 17: 45-49.

Ding WK, Shah NP (2009). Effect of Various Encapsulating Materials on the Stability of Probiotic Bacteria. J. Food Sci. 74(2): M100-M107.

Duebendorf St. GT (2008). How do nanoparticles behave in the environment? NanoEco-Empa organized international meeting on nanoparticles in the environment. Published by Bernd Nowack and Nicole Mueller. In Environ. Sci. Technol. http://pubs.acs.org/cgi-bin/asap.cgi/esthag/asap/html/es7029637.html

Ehrlich H, Janussen D, Simon P, Bazhenov VV, Shapkin NP, Erler C, Mertig M, Born RE, Heinemann S, Hanke T, Worch H, Vournakis JN (2008). Nanostructural Organization of Naturally Occurring Composites-Part II: Silica-Chitin-Based Biocomposites. J. Nanomater. 2008: 1- 8.

Elibol OH, Morisette DD, Denton JP, Bashir R (2003). Integrated nanoscale silicon sensors using top-down fabrication. Appl. Phys. Lett. 83: p. 4613.

El-Jaick LJ, Acosta-Avalos D, Esquivel DM, de S, Wajnberg E, Linhares MP (2001). Electron paramagnetic resonance study of honeybee *Apis mellifera* abdomens. Eur. Biophys. J. 29(8): 579-586.

Esquivel DMS (2007). Magnetic nanoparticles in social insects: Are they the geomagnetic sensors? Entomological Society of America. Annual Meeting. Monday, December 10, 2007 NO-0574.

Esquivel DMS, Wajnberg E, Cernicchiaro GR, Acosta-Avalos D, Garcia BE (2002). Magnetic Material Arrangement In *Apis mellifera* Abdomen http://handle.dtic.mil/100.2/ADP014406.

Esquivel DMS, Wajnberg E, Nascimento FS, de Pinho MB, Lins de Barros GP, Eizemberg R (2007). Do geomagnetic storms change the behaviour of the stingless bee guirucu (*Schwarziana qadripunctata*) Naturwissenschaften. 94(2): 139-142.

Fiorito S (2008). Carbon Nanotubes: Angels or Demons? University La Sapienza Institute of Neurobiology and Molecular Medicine, CNR-Rome, Italy.

Gha-Young K, Joonmok S, Min-Su K, Seung-Hyeon M (2008). Preparation of a highly sensitive enzyme electrode using gold nanoparticles for measurement of pesticides at the ppt level. J. Environ. Monit. 10: 632-637.

Gorb EV, Gorb SN (2009). Contact Mechanics at the Insect-Plant Interface: How Do Insects Stick and How Do Plants Prevent This? Borodich FM (ed.), IUTAM Symposium on Scaling in Solid Mechanics*,* IUTAM Bookseries, Springer Science and Business Media B.V. p. 243.

Guan H, Chi D, Yu J, Li X (2008). A novel photodegradable insecticide: Preparation, characterization and properties evaluation of nano-Imidacloprid. Pestic. Biochem. Physiol. 92(2): 83-91.

Hsu CY, Ko FY, Li CW, Fann K, Lue JT (2007). Magnetoreception System in Honeybees (*Apis mellifera*). PLoS ONE. 2(4): p. 395.

Huck WTS (2008). Responsive polymers for nanoscale actuation. Mater. Today. Volume 11, Issues 7-8, pp. 24-32.

Ishay JS, Barkay Z, Eliaz N, Plotkin M, Stanislav Volynchik S, Bergman DJ (2008). Gravity orientation in social wasp comb cells (Vespinae) and the possible role of embedded minerals. Naturwissenschaften, 95: 333-342.

Jin HJ, Chen J, Karageorgiou V, Altman GH, Kaplan DL (2004). Human bone marrow stromal cell responses on electrospun silk fibroin mats. Biomaterials, 25(6): 1039-1047.

Joseph T, Morrison M (2006). Nanotechnology in Agriculture and Food A Nanoforum report. www.nanoforum.org .

Leiderer P, Dekorsy T (2008). Interactions of nanoparticles and surfaces Tag der mÃundlichen PrÃufung*:* 25. April. URL: http://www.ub.unikonstanz.de/kops/ volltexte/2008/5387/; URN: http://nbn-resolving.de/urn:nbn:de:bsz:352-opus-53877.

Liu XY, Du N (2004). Zero-sized Effect of Nano-particles and Inverse Homogeneous Nucleation. J. Biol. Chem. Vol. 279(7): 6124-6131.

Lucano MJ, Cernicchiaro G, Wajnberg E, Esquivel DMS (2006). Stingless Bee Antennae: A Magnetic Sensory Organ? Biol. Metals, 19(3): 225-343.

Niemeyer CM, Doz P (2001). Nanoparticles, Proteins, and Nucleic Acids: Biotechnology Meets Materials Science. Angewandte Chemie International Edition. 40(22): 4128-4158.

Nowack B (2009). Is anything out there? What life cycle perspectives of nano-products can tell us about nanoparticles in the environment. Nano Today, 4: 11-12.

Nykypanchuk D, Maye MM, van der Lelie D, Gang O (2008). DNA-guided crystallization of colloidal nanoparticles. Nature, 451: 549-552.

Owolade OF, Ogunleti DO, Adenekan MO (2008). Titanium Dioxide affects disease development and yield of edible cowpea. EJEAF Chem. 7(50): 2942-2947.

Patil SA (2009). Economics of agri poverty: Nano-bio solutions. Indian Agricultural Research Institute, New Delhi, Indian.

Roy SC (2009).There's plenty of holes at the bottom: The other side of Nano. Sci. Cult. 75(1-2): 1-3.

Scott NR (2007). Nanotechnology Opportunities in Agriculture and Food Systems. Biological & Environmental Engineering, Cornell University

NSF Nanoscale Science & Engineering Grantees Conference December 5, 2007, Arlington, VA.

Scrinis G, Lyons K (2007). The emerging nano-corporateparadigm nanotechnology and the transformation of nature, food and agri-food systems. Int. J. Sociol. Food Agric. 15(2): 22-44.

Scrinis G, Lyons K (2007). The emerging nano-corporate paradigm: Nanotechnology and the transformation of nature, food and Agrifood systems. Int. J. Sociol. Food Agric. 15(2): 1-23.

Slowik TJ, Green BL, Thorvilson HG (1998). Detection of magnetism in the red imported fire ant (*Solenopsis invicta*) using magnetic resonance imaging. Bioelectromagnetics, 18(5): 396-399.

Sukul NC, Singh RK, Sukul (Chunari) S, Sen P, Bhattacharyya A, Sukul A, Chakrabarty R (2009). Potentized Drugs Enhance Growth of Pigeon pea. Environ. Ecol. 26(3): 1115-1118.

Tai Kai NG (2008). Structural Analysis of Crystalline and Nanocrystalline Materials. In Proceedings of the Department of Physics, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong.

Torney F (2009). Nanoparticle mediated plant transformation. Emerging technologies in plant science research. Interdepartmental Plant Physiology Major Fall Seminar Series. Phys. p. 696.

Ulrich C, Mewis I, Goswami A, Chatterjee SD, Banerjee SP, Adhikary S, Bhattacharyya, A (2006). Biodiversity-Macro and Micro: To be Nano or Not to be!. Everyman's Science 11(6): 433-443.

Vidhyalakshmi R, Bhakyaraj R, Subhasree RS (2009). Encapsulation The Future of Probiotics-A Review. Adv. Biol. Res. 3(3-4): 96-103.

Wadhwa S (2009) Nanotechnology and its Future Applications. In Chillibreeze*,* 25th April. Indian Talent, Global Content.

Wajnberg E, Cernicchiaro G, Souza DM de Esquivel DMS (2004). Antennae: the strongest magnetic part of the migratory ant. Bio Metals, 17(4): 467-470.

Watson GS, Watson JA (2004). Natural nano-structures in insects-possible functions of ordered arrays characterized by atomic force microscopy. Appl. Surface Sci. 235 (1-2): 139-144.

Yang FL, Li XG, Zhu F, Lei CL (2009). Structural Characterization of Nanoparticles Loaded with Garlic Essential Oil and Their Insecticidal Activity against *Tribolium castaneum* (Herbst) (Coleoptera: Tenebrionidae). J. Agric. Food Chem. 57(21): 10156-10162.

Ying JY (2009). Nanobiomaterials. Nano Today, 4: 1-2.

Zhang J, Liu Z (2006). Cicada Wings: A Stamp from Nature for Nanoimprint. Lithography 2(12): 1440-1443.

Zhang YQ, Shen WD, Xiang RL, Lan-Jian Zhuge LJ, Gao WJ, Wang WB (2007). Formation of silk fibroin nanoparticles in water-miscible organic solvent and their characterization. J. Nanoparticle Res. 9(5): 885-900.