Nanotechnology and Sustainable Agriculture

7

Abstract

Nanoparticles interact with plants causing many morphological and physiological changes, depending on their properties. Their chemical composition, size, surface covering, reactivity, and most importantly the dose at which they are effective determine efficacy of Nanoparticles. Though their importance is immense and day-by-day due to the technological advancement their role is marking an impact in every sphere of living. Now a day's every science is served with Nano-techniques from nano-medicine to nano-Agriculture. In this context, the chapter is divided in several sections depending on the need of assessment of the topic particularly with reference to Agriculture sustainability.

Keywords

Nano pesticides · Microencapsulation · Nano fertilizers · Nanotechnology

7.1 Nanoparticles: Role and Functions

Nanoparticles communicate with plants causing frequent morphological and physiological changes, contingent upon their properties. Viability of Nanoparticles, is controlled by their synthetic arrangement, measure, surface covering, reactivity, and above all the portion at which they are compelling (Khodakovskaya et al. 2012). Specialists from their discoveries recommended both positive and negative consequences for plant development and improvement, and the effect of designed nanoparticles (Encapsulated Nanoparticles) on plants relies upon the creation, measure, focus and physical and synthetic properties of Encapsulated Nanoparticles just as plant species (Ma et al. 2008). Adequacy of Nanoparticles relies upon their fixation and shifts from plants to plants (Table 7.1). However, this review covers plausible role of Nanoparticles in seed germination, photosynthesis, roots, and plant development (root and shoot biomass).

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Table 7.1 Beneficiary concentration(s) of nanoparticles for plants

Nanoparticle(s)	Beneficiary concentration(s)	Plant	Part of plant/process
Nano-anatase TiO2	0.25% (foliar spray)	*Spinacia oleracea*	Rubisco activase (rca) mRNA expressions,
	0.25% (foliar spray)	*Spinacia oleracea*	Oxygen evolution, Rubisco carboxylation, Rubisco Activase, rate of photosynthetic carbon reaction
	0.25%	*Spinacia oleracea*	Several enzymes activities induction
Aluminum oxide Nanoparticles	400–4000 mg/L	*Arabidopsis thaliana,*	Root length
Alumina Nanoparticles	10 mg/L	*Lemna minor*	Root length
	0.3 g/L	*Lemna minor*	Biomass accumulation
nZVI (nanoscale Zero- Valent Iron particles) Iron oxide Nanoparticles	0.5 g/L	*Arabidopsis thaliana*	Root elongation
Iron oxide Nanoparticles	0.5–0.75 g/L	*Glycine max*	Yield and quality
	50 ppm (foliar spray)	*Vigna radiata*	Biomass
ZnFeCu-oxide Nanoparticles (suspension)	50 ppm (foliar spray)	*Vigna radiata*	Biomass
CeO_2 Nanoparticles	250 ppm	*Arabidopsis thaliana*	Biomass
CO_3O_4 Nanoparticles	5 g/L	*Raphanus sativus* L.	Root elongation
CuO Nanoparticles	500 mg/kg (sand culture)	*Triticum aestivum*	Biomass
Hydroxyapatite Suspension	100–2000 mg/L	*Lactuca sativa*	Root length
GNanoparticles	10 and 80 µg/mL	*Arabidopsis thaliana*	Germination
	10 and 80 µg/mL	*Arabidopsis thaliana*	Root length
	80 µg/mL	*Arabidopsis thaliana*	Shoot and root system (longer), early flowering, Yield
SilverNanoparticles	10–30 µg/mL	*Boswellia ovaliofoliolata*	Germination and seedling Growth
	60 ppm	*Phaseolus vulgaris* L., *Zea mays* L.	Root length
	60 ppm	*Phaseolus vulgaris* L., *Zea mays* L.	Shoot length
	60 ppm	*Phaseolus vulgaris* L., *Zea mays* L.	Dry weight of root and shoot
	100 µM	*Vigna radiata*	Antagonize inhibition by 2,4-dichlorophenoxyacetic acid (2,4-D) at 500 µM of plant Growth

(continued)

Table 7.1 (continued)

Nanoparticle(s)	Beneficiary concentration(s)	Plant	Part of plant/process
Sulfur Nanoparticles	500, 1000, 2000 and 4000 ppm	*Vigna radiata*	Dry weight
Silicon dioxideNanoparticles	15 kg/ha	*Zea mays L.*	Growth parameters
TiO2 Nanoparticles	400 mg/L	*Arabidopsis thaliana*	Root length
	60 ppm	*Foenicutum vulgare*	Germination
	Lower than 200 mg/L	*Lemna minor*	Plant growth
	1000 mg/L	*Triticum aestivum*	Chlorophyll content
	0.25%	*Spinacia oleracea*	Hill reaction, non cyclic photophosphorylation, protect chloroplasts from silvering
	0.05–0.2 g/L	*Lycopersicon esculentum Mill*	Net photosynthetic rate, conductance to H_2O, and transpiration rate, regulation of photosystem II (PSII)
Graphene oxide	400 and 800 mg/L	*Vicia faba* L.	Germination
Carbon nanotubes	40 μg/mL	*Lycopersicum esculantum*	Germination and seedling Growth
	75 wt% carbon nanotubes	*Medicsilvero saliva, Triticum aestivum*	Root elongation
	75 wt% carbon nanotubes impurities	*Medicsilvero saliva, Triticum aestivum*	Root elongation
SW carbon nanotubes	9, 56, 315, and 1750 mg/L	*Allium cepa, Cucumis sativus*	Root elongation
MULTI-WALLED carbon nanotubes	25–100 μg/mL	*Hordeum vulgare* L., *Glycine max, Zea mays*	Root elongation
	50 and 200 μg/mL	*Lycopersicon esculentum Mill*	Plant height and number of Flowers
	5 up to 500 μg/mL	*Nicotiana tabacum*	Growth
o-MULTI-WALLED carbon nanotubes	10–160 μg/mL	*Triticum aestivum*	Root growth, vegetative Biomass
ws carbon nanotubes	6.0 μg/mL	*Cicer arietinum*	Growth rate
MULTI-WALLED carbon nanotubes, dMULTI-WALLEDCNT	40 μg/mL	*Lycopersicon esculentum Mill*	Uptake nutrients (K, Ca, Fe, Mn and Zn)

(continued)

Table 7.1 (continued)

Nanoparticle(s)	Beneficiary concentration(s)	Plant	Part of plant/process
Pristine MULTI-WALLED carbon nanotubes	20 mg/L	*Zea Mays*	Nutrient transport, biomass
ZnO Nanoparticles	400 mg/kg	*Cucumis sativus* fruit	Micronutrients (Cu, Mn and Zn)
	1.5 ppm (foliar spray)	*Vigna radiata*	Biomass
	1000 ppm	*Arachis hypogaea*	Germination
	1000 ppm	*Arachis hypogaea*	Stem, root growth and yield
	500, 1000, 2000 and 4000 ppm	*Vigna radiate* L. Wilczek	Dry weight

Source: Siddiqui et al. (2015)

7.1.1 Silicon Dioxide Nanoparticles

Plant development and advancement begins from the germination of seeds pursued by root extension and shoot rise as the most prompt indications of maturity and improvement. Subsequently, it is essential to comprehend the course of plant development and advancement in connection to Nanoparticles. The announced information from different investigations recommended that impact of Nanoparticles on seed germination be also focused on secondary basis. In tomato, the lower concentration of nano-silicon dioxide enhanced seed germination (Siddiqui and Al-Whaibi 2014). As per Suriyaprabha et al. (2012), nano-silicon dioxide extended seed germination by giving better supplements accessibility to maize seeds, and pH and conductivity to the developing medium. Bao-shan et al. (2004) applied exogenous application of nano-SiO2 on Larix olgensis seedlings and found that nano-SiO2 improved seedling growth and quality, including mean height, root collar diameter, main root length, and the number of lateral roots of seedlings and also induced the synthesis of chlorophyll. Haghighi et al. (2012), in tomato and Siddiqui and Al-Whaibi (2014) in squash detailed that nano-silicon dioxide improved seed germination and animated the cell reinforcement framework under NaCl stress. Shah and Belozerova (2009) tried silica, gold, copper and palladium nanoparticles in their investigation and found that every one of these nanoparticles impact lettuce seeds. Exogenous use of nano-silicon dioxide and nano-titanium dioxide (nano-TiO2) enhances seed germination of soybean by expanding nitrate reductase and furthermore by upgrading seeds capacity to retain and use water and supplements (Zheng et al. 2005). Under salinity stress, nano-silicon dioxide enhances fresh and dry weight of leaves, chlorophyll substance and proline collection. An expansion in the collection of free amino acids, proline, substance of supplements, antioxidative enzyme activity due to the nano-silicon dioxide, accordingly enhancing the resilience of plants to abiotic stress (Kalteh et al. 2014; Haghighi et al. 2012). Wang et al. (2014) carried out an investigation on rice plant which were treated with

quantum spots (QDs), without QDs and with silica covered with QDs, and discovered silica covered with QDs advanced especially rice root development. Nanosilicon dioxide improves the plant development and advancement by increasing chlorophyll fluorescence parameters like transpiration rate, net photosynthetic rate, stomatal conductance, potential movement of PSII, electron transport rate, compelling photochemical productivity, legitimate photochemical effectiveness, and photochemical extinguish (Xie et al. 2011).

7.1.2 Zinc Oxide Nanoparticles

In various, investigations it has been found that these Nanoparticles impact lettuce seeds. As in soybean the exogenous utilization of nano-silicon dioxide and nanotitanium dioxide (nano-TiO2) enhances seed germination by expanding nitrate reductase and furthermore by upgrading seeds capacity to retain and use water and supplements (Zheng et al. 2005). Prasad et al. (2012) in peanut; Sedghi et al. (2013) in soybean; Ramesh et al. (2014) in wheat and Raskar and Laware (2014) in onion, reported that at lower concentration of Zinc oxide nanoparticles which exhibited beneficial effect on seed germination. However, at the higher doses of Zinc oxide nanoparticles impaired the process of seed germination. The effect of nanoparticles on germination depends on concentrations of these nanoparticles and significantly differs from plants to plants. de la Rosa et al. (2013) applied different concentrations of Zinc oxide nanoparticles on cucumber, alfalfa and tomato, and found that only cucumber seed germination was enhanced. Raliya and Tarafdar (2013) reported that Zinc oxide nanoparticles induced a significant improvement in *Cyamopsis tetrsilveronoloba* plant biomass, root area, chlorophyll and protein synthesis, shoot and root growth, rhizospheric microbial population, acid phosphatase, alkaline phosphatase and phytase activity in cluster bean rhizosphere. It is evident from the correlative light and scanning microscope, and inductive coupled plasma/atomic emission spectroscopy that seedling roots of Vigna radiata and Cicer arietinum absorbed Zinc oxide nanoparticles and promoted the root and shoot length, and root and shoot biomass (Mahajan et al. 2011). Nano Zinc Oxide along with MS media promoted somatic embryogenesis, shooting, regeneration of plantlets, and also induced proline synthesis, activity of superoxide dismutase, catalase, and peroxidase thereby improving tolerance to biotic stress (Helaly et al. 2014).

7.1.3 Carbon Nanotubes

The carbon nanotubes have gained a critical position because of their interesting mechanical, electrical, thermal properties among the available Nanoparticles. The accessible information uncovers that reviews on carbon nanotubes have chiefly centered on creatures and people (Ke et al. 2011; Tiwari et al. 2014). Relatively, there has been inadequate data accessible on carbon nanotubes and their connection with plants cells and plant digestion. The important property of carbon

nanotubes, that they can enter the cell divider and film of cells and furthermore give a reasonable conveyance arrangement of synthetic concoctions to cells. The single-walled- carbon nanotubes (SW carbon nanotubes) penetrate as nanotransporters for conveyance of DNA and color particles into plants cells (Srinivasan and Saraswathi 2010). As in various investigations researchers has revealed that multi-walled- carbon nanotubes have an enchantment capacity to impact the seed germination and plant development, and work as a conveyance arrangement of DNA and synthetic compounds to plants cells. Tiwari et al. (2014) reported that multi-walled-carbon nanotubes incite the water and basic Ca and Fe supplements take-up effectiveness that could upgrade the seed germination and plant development and advancement. Multi-walled carbon nanotubes added to sterile silvere medium invigorated seed germination of three imperative yields (grain, soybean, corn) because of the capacity of multi-walled carbon nanotubes to infiltrate the seed coats as the nanotube agglomerates were identified inside the seed coats utilizing Raman Spectroscopy and Transmission Electron Microscopy (Lahiani et al. 2013). Additionally, they detailed that multi-walled carbon nanotubes directed qualities articulation encoding a few kinds of water divert proteins in soybean, corn and grain seeds coat. The most extreme germination rate in tomato, half and half Bt cotton, Brassica juncea, Phaseolus mungo and rice was seen with multi-walled carbon nanotubes (Morla et al. 2011; Nalwade and Neharkar 2013). Likewise, numerous analysts affirmed the positive job of carbon nanotubes in seed germination and plant development and improvement. Khodakovskaya et al. (2012) announced that multi-walled carbon nanotubes go about as controllers for seed germination and development, and they exhibited that multi-walled carbon nanotubes can enlarge the development of tobacco cell culture by upregulating the marker qualities for cell divisions (CycB), cell divider arrangement (NtLRX1) and water transport (aquaporin, NNtPIP1). Wang et al. (2012) revealed oxidized multi-walled carbon nanotubes altogether improved cell stressing in the root framework and advanced dehydrogenase action. Regardless, a couple of researchers nitty gritty that multi-walled carbon nanotubes don't demonstrate a constructive outcome on seed germination in numerous plants notwithstanding when they got high centralization of multi-walled carbon nanotubes (Lin and Xing 2007). Multi-walled carbon nanotubes enhance the root and stem development and peroxidase and dehydrogenase movement might be because of essential take-up and accretion of multi-walled carbon nanotubes by roots pursued by the translocation from roots to leaves that could incite qualities articulation (Khodakovskaya et al. 2012; Lahiani et al. 2013). Tripathi and Sarkar (2014) affirmed the nearness of water dissolvable carbon nanotubes inside the wheat plants utilizing Scanning Electron and Fluorescence Microscope, and they revealed that carbon nanotubes instigated the root and shoot development in light and diffuse conditions. Additionally, multi-walled carbon nanotubes enhance water maintenance limit and biomass, blooming and organic product yield and increment restorative properties of plants (Husen and Siddiqi 2014). Notwithstanding, inhibitory impact of multi-walled carbon nanotubes on plants development has been accounted for by numerous specialists (Tiwari et al. 2014; Ikhtiar et al. 2013; Begum and Fugetsu 2012; Begum et al.

2014). In this way, the impact of Nanoparticles on plants differs from plant to plant, their development stages, and the idea of nanoparticles.

7.1.4 Gold Nanoparticles

Least efforts have been done on the association of Gold nanoparticle (Au Nanoparticles) with plants. A few researchers discovered Au Nanoparticles prompt harmfulness in plants by repressing aquaporin work, a gathering of proteins that assistance in the transportation of wide scope of atoms including water (Shah and Belozerova 2009). While as, Barrena et al. (2009) in lettuce and cucumber, Arora et al. (2012) in Brassica juncea; Savithramma et al. (2012) in Boswellia ovalifoliolata and Gopinath et al. (2014) in Gloriosa superba revealed that Au Nanoparticles enhance seed germination. Au Nanoparticles enhance the quantity of leaves, leaf zone, plant stature, chlorophyll substance, and sugar content that lead to the better harvest yield (Arora et al. 2012; Gopinath et al. 2014). Christou et al. (1988) brought neomycin phosphotransferase II quality into soybean genome through DNA-covered au particles. The beneficial outcome of AuNanoparticles in this manner needs further examination to investigate the physiological and atomic system. Kumar et al. (2013) detailed AuNanoparticles have a noteworthy job on seed germination and cell reinforcement framework in Arabidopsis thaliana and modified dimensions of microRNAs articulation that directs different morphological, physiological, and metabolic procedures in plants.

7.1.5 Silver Nanoparticles

As indicated by accessible information a substantial number of concentrates on silver nanoparticles (SilverNanoparticles) have been recorded on microbial and creature cells; be that as it may, just a couple of studies were done on plants (Krishnaraj et al. 2012). As we probably are aware about that Nanoparticle have both positive and negative consequences for plant development and improvement. As overdue, Krishnaraj et al. (2012) considered the impact of organically orchestrated Silver Nanoparticles on hydroponically developed Bacopa monnieri development digestion, and found that biosynthesized Silver Nanoparticles demonstrated a noteworthy impact on seed germination and incited the union of protein and sugar and diminished the all out phenol substance and catalase and peroxidase exercises. Additionally, organically blended SilverNanoparticles improved seed germination and seedling development of trees Boswellia ovaliofoliolata (Savithramma et al. 2012). Silver Nanoparticles expanded plants development profile (shoot and root length, leaf region) and biochemical qualities (chlorophyll, sugar and protein substance, cancer prevention capsulent chemicals) of Brassica juncea, regular bean and corn (Salama 2012; Sharma et al. 2012). In any case, Gruyer et al. (2013) revealed Silver Nanoparticles have both positive and negative impact on root prolongation relying upon the plants species. They announced that

root length was expanded in grain, yet was hindered in lettuce. Likewise, Yin et al. (2012) examined the impacts of SilverNanoparticles on germination of eleven wetland plants species (Lolium multiflorum, Panicum virgatum, Carex lurida, C. scoparia, C. vulpinoidea, C. crinita, Eupatorium fistulosum, Phytolaca Yankee folklore, Scirpus cyperinus, Lobelia cardinalis, Juncus effusus) and discovered SilverNanoparticles improved the germination rate of one animal varieties (E. fistulosum). SilverNP initiates root development by blocking ethylene motioning in Crocus sativus (Rezvani et al. 2012). The effect of Silver Nanoparticles on morphology and physiology of plants relies upon the size and state of Nanoparticles. Syu et al. (2014) considered the impact of 3 unique morphologies of Silver Nanoparticles on physiological and sub-atomic reaction of Arabidopsis and proposed that decahedral Silver Nanoparticles demonstrated the most elevated level of root development advancement (RGP); in any case, the round Silver Nanoparticles had no impact on RGP and set off the largest amounts of anthocyanin aggregation in Arabidopsis seedlings. The decahedral and round SilverNanoparticles gave the most minimal and most elevated qualities for Cu/Zn superoxide dismutase, individually. The three diverse size and state of SilverNanoparticles mancapsuled protein collections, for example, cell-division-cycle kinase 2, protochlorophyllide oxidoreductase, and fructose-1,6 bisphosphate aldolase and furthermore incited qualities articulation associated with cell occasions; for instance SilverNanoparticles instigated the quality articulation of indoleacetic corrosive protein 8 (IAA8), 9-cis-epoxycarotenoid dioxygenase (NCED3), and drying out responsive RD22. Likewise, SilverNanoparticles enacted the aminocyclopropane1-carboxylic corrosive (ACC)- determined restraint of root extension in Arabidopsis seedlings, just as diminished the statement of ACC synthase 7 and ACC oxidase 2, proposing that SilverNanoparticles went about as inhibitors of ethylene discernment and could meddle with ethylene biosynthesis.

7.1.6 Titanium Dioxide Nanoparticles

Like Silver Nanoparticles, various examines have concentrated on the effect of titanium dioxide nanoparticles (TiO2 Nanoparticles) on microscopic organisms, green growth, tiny fish, fish, mice, and rodents, however inquire about concentrating on the acknowledgment of the impacts of TiO2 Nanoparticles on plant stays deficient. TiO2 Nanoparticles improved seed germination and advanced radicle and plumule development of canola seedlings (Mahmoodzadeh et al. 2013). Jaberzadeh et al. (2013) detailed that TiO2 Nanoparticles increased wheat plant development and yielded parts submerged shortfall push condition. TiO2 Nanoparticles mancapsules chemicals action associated with nitrogen digestion, for example, nitrate reductase, glutamate dehydrogenase, glutamine synthase, and glutamic-pyruvic transaminase that causes the plants to assimilate nitrate and furthermore supports the transformation of inorganic nitrogen to natural nitrogen as protein and chlorophyll, that could expand the crisp weight and dry load of plant (Yang et al. 2006). TiO2 Nanoparticles

goes about as a photocatalyst and prompts an oxidation-decrease response. TiO2 Nanoparticles recognizably advances matured seeds' force and chlorophyll arrangement and animates Ribulose 1, 5-bisphosphate carboxylase (Rubisco) movement and builds photosynthesis, in this manner expanding plant development and improvement (Yang et al. 2006). TiO2 Nanoparticles builds light absorbance, hurry the vehicle and change of the light vitality, shield chloroplasts from maturing, and drsilver out the photosynthetic time of the chloroplasts (Yang et al. 2006). It might be expected to TiO2 Nanoparticles shields the chloroplast from unnecessary light by expanding the action of free radical generation, for example, catalase, superoxide dismutase, peroxidase, (Hong et al. 2005).

7.1.7 Role of Nanoparticles in Photosynthesis

As plants on the earth converts only 2–4% of the total incident light into chemical energy through the key process of photosynthesis and results promotion of plant growth. These days, researchers are endeavoring to enhance this low productivity of vascular plants by controlling strategies and quality controls. To accelerate the process of plant photosynthesis and turbocharged crops, researchers are working with Rubisco, an essential catalyst for photosynthetic procedure to catalyze the joining of carbon dioxide into natural mixes. As of delayed, Lin et al. (2014) developed new tobacco plants by substituting the Rubisco quality for carbon settling in tobacco plant, with two qualities of cyanobacterium Synechococcus prolongs; these new-built plants have more photosynthetic productivity than native ones. Likewise, in the field of nanobiotechnology, analysts need to create bionic plants that could have better photosynthesis effectiveness and biochemical detecting. Giraldo et al. (2014) detailed that inserted SW carbon nanotubes in the disconnected chloroplast enlarged multiple times higher photosynthetic action than that of controls, and improved greatest electron transport rates, and SW carbon nanotubes empowered the plants to detect nitric oxide, a flagging atom. They recommended that nanobionics way to deal with built plants would empower new and progressed useful properties in photosynthetic organelles. Likewise, they said that still broad research would be expected to see the effect of carbon nanotubes on definitive results of photosynthesis, for example, sugars and glucose. Additionally, Noji et al. (2011) announced that a nano-mesoporous silica compound (SBA) bound with photosystem II (PSII) and incited stable movement of a photosynthetic oxygen-advancing response, showing the light-determined electron transport from water to the quinone particles, and they recommended that PSII-SBA conjugate may have photosensors and counterfeit photosynthetic framework. Silicon dioxide Nanoparticles enhances photosynthetic rate by enhancing action of carbonic anhydrase and blend of photosynthetic colors (Siddiqui and Al-Whaibi 2014). Carbonic anhydrase supplies CO2 to the Rubisco, which may enhance photosynthesis. Nano-anatase TiO2 have a photocatalyzed trademark and enhances the light absorbance and the change from light vitality to electrical and synthetic vitality, and

furthermore prompts carbon dioxide osmosis. TiO2 Nanoparticles shield chloroplast from maturing for long time enlightenment (Hong et al. 2005; Yang et al. 2006). Nano-anatase TiO2 improves the photosynthetic carbon digestion by initiating Rubisco (complex of Rubisco and Rubisco activase) that could advance Rubisco carboxylation, along these lines expanding development of plants (Gao et al. 2006). Mama et al. examined the effect of nano-anatase on sub-atomic component of carbon response and proposed nano-anatase-prompted marker quality for Rubisco activase (rca) mRNA and upgraded protein levels and exercises of Rubisco activase brought about the enhancement of the Rubisco carboxylation and the high rate of photosynthetic carbon response. The exogenous use of TiO2 Nanoparticles enhances net photosynthetic rate, conductance to water, and transpiration rate in plants (Qi et al. 2013). As indicated by Lei et al. (2007) nano-anatase advanced firmly entire chain electron transport, photo reduction action of photosystem II, O2-developing and photophosphorylation movement of chlorophyll under both unmistakable and bright light. As per Govorov and Carmeli (2007), metal nanoparticles can incite the effectiveness of synthetic chemical energy production in photosynthetic frameworks. The chlorophyll in photosynthetic response focus ties to the AuNanoparticles and Silver nanocrystals, in this manner shaping a novel mixture framework that may create multiple times increasingly energized electrons due to plasmon reverberation and quick electron-opening division. The improvement components may help in the structure of artificial light-gathering frameworks.

7.2 Microencapsulation Techniques

Different systems are accessible for the embodiment of center materials. Comprehensively the techniques are separated into three sorts. Diverse kinds of microencapsulation strategies are.

1. Compound techniques
2. Physico-compound techniques
3. Physico-mechanical techniques

The previously mentioned procedures are generally utilized for microencapsulation of a few pharmaceuticals. Among these procedures, fluidized bed or air suspension strategy, coacervation and phase partition, spray drying and shower hardening, container covering and dissolvable dissipation strategies are broadly utilized. Contingent upon the physical idea of the core substance to be epitomized the method utilized will be differed.

7.2.1 Chemical Methods

7.2.1.1 Interfacial Polymerization (IFP)

In this method, the reactive multifunctional monomers will be polymerized to form the capsule shell will be at or on the surface of the droplet or particle as commonly used monomers are either individual particles or blend which includes multifunctional isocyanates and acid chlorides. The multifunctional monomer broke up in fluid center material and it will be scattered in watery phase containing dispersing agent. A co-reactant multifunctional amine will be added to the blend. This outcome in quick polymerization at interface and capsule shell happens (Scher 1983). On reaction of isocyanate with amine a polyurea shell will be formed, also polynylon or polyamide shell will be formed when acid chloride reacts with amine and when isocyanate reacts with hydroxyl containing monomer it produces a polyurethane shell. For instance, Saihi et al. (2006) embodied di-ammonium hydrogen phosphate (DAHP) by polyurethane-urea layer utilizing an interfacial polymerization technique. An elevated yield of blend (22%) of a powder of microcapsules was created with a fill substance of 62-wt% of DAHP as controlled by rudimentary investigation. The mean size of DAHP microcapsules is 13.35 mm. In addition, 95% of the measured particles have a width lower than 30.1 mm.

7.2.1.2 In Situ Polymerization

In polymerization, when monomers are added to the encapsulation reactor, it will lead to formation of capsule shell as like IFP; here no reactive agents are added to the core material, polymerization occurs exclusively in the continuous phase and on the continuous phase side of the interface formed by the dispersed core material and continuous phase. At first a low sub-atomic weight prepolymer will be shaped, over the long the prepolymer develops in size, it stores on the outside of the scattered center material there by creating a strong case shell (for example exemplification of different water-immiscible fluids with shells shaped by the response at acidic pH of urea with formaldehyde in watery media (Cakhshaee et al. 1985). Wang et al. (2013) prepared Carboxyl-functionalized magnetic microspheres by in situ polymerization of styrene and methyacrylic acid at 85C in the presence of nano-Fe3O4 in styrene, using lauroyl peroxide as an initiator.

7.2.2 Physico-Chemical Methods

7.2.2.1 Coacervation and Phase Separation

Bungenberg de Jong and Kruyt (1929) and Bungenberg de Jong (1949) defined this as partial desolvation of a homogeneous polymer solution into a polymer-rich phase (coacervate) and the poor polymer phase (coacervation medium). The term originated from the Latin ‘acervus’ meaning ‘heap’. This was the first reported process to be adapted for the industrial production of microcapsules. Currently, two methods for coacervation are available, namely simple and complex processes. The mechanism of microcapsule formation for both processes is identical, except for the

way in which the phase separation is carried out. In simple coacervation a desolvation agent is added for phase separation, whereas complex coacervation involves complexation between two oppositely charged polymers. The three basic steps in complex coacervation are: (i) formation of three immiscible phases; (ii) deposition of the coating; and (iii) rigidization of the coating. The first step includes the formation of three immiscible phases; liquid manufacturing vehicle, core material and coating material. The core material is dispersed in a solution of the coating polymer. The coating material phase, an immiscible polymer in liquid state, is formed by (i) changing temperature of polymer solution, e.g. ethyl cellulose in cyclohexane12 (N-acetyl P-amino phenol as core), (ii) addition of salt, e.g. addition of sodium sulphate solution to gelatine solution in vitamin encapsulation (iii) addition of non-solvent, e.g. addition of isopropyl ether to methyl ethyl ketone solution of cellulose acetate butyrate (Heistand et al. 1966) (methylscopalamine hydrobromide is core), (iv) addition of incompatible polymer to the polymer solution, e.g. addition of polybutadiene to the solution of ethylcellulose in toluene (The National Cash Register Co. 1963) (methylene blue as core material) and (v) inducing polymer–polymer interaction, e.g. interaction of gum Arabic and gelatine at their iso-electric point (Brynko et al. 1967). The second step includes deposition of liquid polymer upon the core material. Finally, the prepared microcapsules are stabilized by cross-linking, desolvation or thermal treatment (Fig. 7.1).

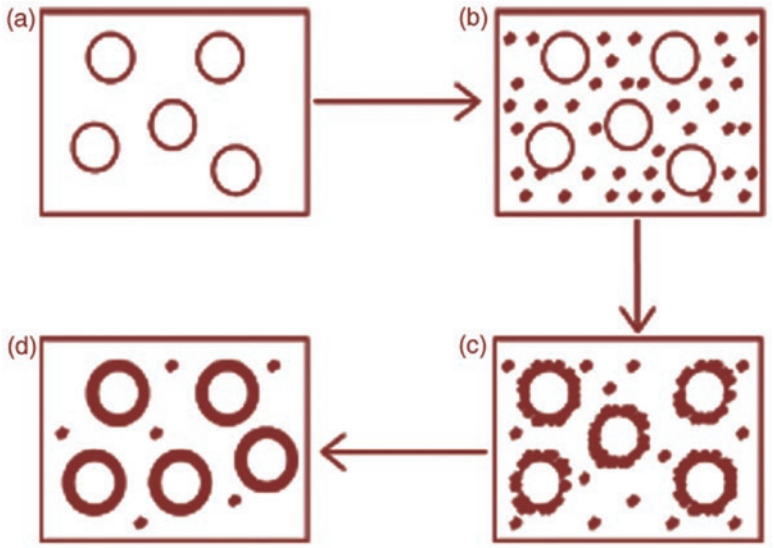

Fig. 7.1 Graphic Representation of the coa-cervation process (**a**) Core material dispersion in solution of shell polymer; (**b**) separation of coacervate from solution; (**c**) coating of core material by microdroplets of coacervate; (**d**) coalescence of coacervate to form continuous shell around core particles (Ghosh 2006)

During manufacturing or by a second reaction process, the primary monomers are polymerized as they are chemically crosslinked in order to make them insoluble which gives them a degree of cross-linked quantified molecular structure in terms of their cross-link density and have a profound impact on the swelling characteristics of the cross-linked system. For instance, derivatives of ethylene glycol di(meth) acrylate like, ethylene glycol diacrylate, di(ethylene glycol) diacrylate, tetra(ethylene glycol) diacrylate, ethylene glycol dimethacrylate, di(ethylene glycol) dimethacrylate, tri(ethylene glycol) dimethacrylate; derivatives of methylenebisacrylamide like N,N- Methylenebisacrylamide, N,NMethylenebisacrylamide, N,N-(1,2-Dihydroxyethylene) bisacrylamide (Klärner et al. 1999), glutaraldehyde, sodium tripolyphosphate, etc. Yin and Stöver (2003) prepared microspheres by poly (styrene-alt-maleic anhydride) partially grafted with methoxy poly(ethylene glycol) (SMA-g-MPEG) were prepared by reacting poly(styrene-alt-maleic anhydride) with a substoichiometric amount of MPEG lithium alcoholate. Aqueous solutions of the resulting SMA-g-MPEG formed complex coacervates with poly (diallyldimethylammonium chloride) (PDADMAC). These phase-separated liquid polyelectrolyte complexes were subsequently crosslinked by the addition of two different polyamines to prepare cross-linked hydrogel microspheres. Chitosan served as an effective cross-linker at pH 7.0, while polyethylenimine (PEI) was used as a cross-linker under basic conditions (pH 10.5). The resulting coacervate microspheres swelled with increasing salinity, which was attributed mainly due to the shielding of the electrostatic association within the polyelectrolyte complex. Huang et al. (2007) prepared microcapsules by using gelatine and gum Arabic by coacervation where the most frequently used cross-linking agent formaldehyde in the gelatin–acacia microencapsulation process was altered by glycerol and also it has been reported that the yield of gelatin–acacia microcapsules decreases at surfactant concentrations above or below the optimum. It has been investigated that the inhibition of coacervation due to high concentrations of surfactants and disturbance of microencapsulation due to high hydrophilic–lipophilic balance of (HLB) values. Generally the concentration of a surfactant required to increase the yield of microcapsules is too low to produce regular-sized droplets. The analysis of the size distribution shows that the microcapsules are multi-dispersed. In order to form negatively charged gelatin, the pH value of a continuous gelatin phase would be adjusted above its isoelectric point, which is able to create monodispersed droplets in the coacervation process. The positively charged gelatin is attracted to the negatively charged acacia to form coacervate droplets when the pH value is adjusted to below its isoelectric point. Therefore, theparticle size distributions of emulsion droplets are affected by the factors of pH adjustment, especially the adding rate of the acidifying agent. The report shows the indomethacin microcapsules had the slowest release rate when the coacervation pH was adjusted to the electrical equivalence pH value and not to the pH of maximum coacervate yield. It has been found that the gelatin is only stable at a pH 4–6 and this data shows that the alkalization caused the breaking of the wall of the microcapsule made by the cross-linking agent of glycerol. Not only is the purple-colour shikonin alkalized into a blue colour, but the saponification effects may also be undergone by the solvent (sesame oil) of extract containing shikonin reacting with sodium hydride.

However, this reaction would not be shown in the microcapsule made by the cross-linking agent of formaldehyde. This explains why the shell of the microcapsule made by formaldehyde is more rigid than that made by glycerol. In other words, the microcapsule made by glycerol has a more permeable shell than made by formaldehyde. The particle size of the microcapsule was not affected by the difference of cross-linking agents. Using the low concentration, 3% and 6% of plasticizer glycerol instead of formaldehyde, similar morphology results were obtained. Hence the mounting encapsulation ability has been achieved due to the amount of cross-linking agent. However, the results indicated that above 6% of glycerin, encapsulation ability decreases as the cross-linking agent increases due to the alteration of the mechanism and inability to integrate into the network even after the addition of an excess amount.

7.2.2.2 Polymer Encapsulation by Rapid Expansion of Supercritical Fluids

Supercritical fluids are highly compressed gasses that possess several advantageous properties of both liquids and gases. The most widely used being supercritical CO2, nitrous oxide (N2O) and alkanes (C2 to C4). At the critical point of supercritical fluids a small change in pressure or temperature causes a huge change in their density. Supercritical CO2 is widely used for its low critical temperature value, in addition to its non-toxic and non-flammable properties; it is also readily accessible, highly pure and commercial.

The most widely used methods are as follows:

(a) Rapid expansion of supercritical solution (RESS);
(b) Gas anti-solvent (GAS); and
(c) Particles from gas-saturated solution (PGSS).

(a) Rapid expansion of supercritical solution

During rapid expansion method, the active ingredient and the shell material are maintained at high pressure and then released at atmospheric pressure through a minute plunger in order to make supercritical solution. The shell material undergoes desolvation due to sudden drop in pressure which is then deposited around the active ingredient (core) and forms a coating layer (Fig. 7.2), but the drawback is that both the shell material and active ingredient must be very soluble in supercritical fluids. A least percent of polymers (e.g. polymethacrylates and polydimethylsiloxanes) are soluble in supercritical fluids such as CO_2, which possess low cohesive energy densities. As using can increase the solubility of polymers either the co-solvents or rarely non-solvents are used in supercritical fluids, but the shell materials do not dissolve at atmospheric pressure. Kiyoshi et al. very recently carried out microencapsulation of TiO2 nanoparticles with polymer by RESS using ethanol as a non-solvent for the polymer shell such as polyethylene glycol (PEG), poly(styrene)-b-(poly(methylmethacrylate)- copoly(glycidal methacrylate) copolymer (PS-b-(PMMAco-PGMA) and poly(methyl methacrylate).

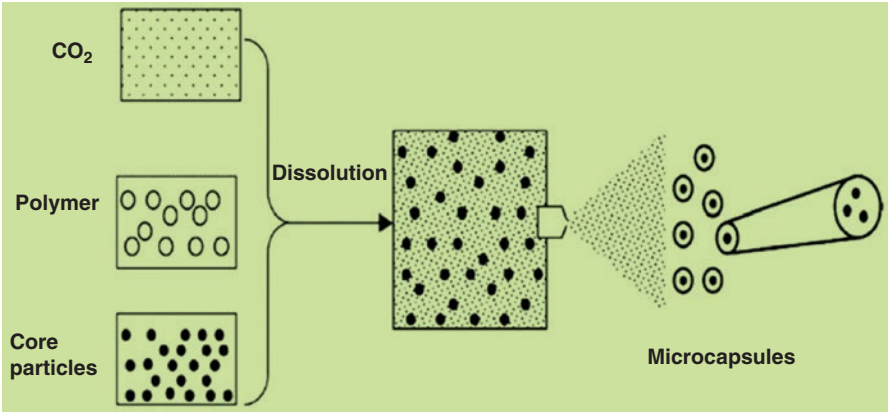

Fig. 7.2 Microencapsulation by rapid expansion of supercritical solutions (RESS) (Ghosh 2006)

(b) Gas anti-solvent (GAS) process

The Gas anti-solvent (GAS) process also referred as supercritical fluid anti-solvent (SAS) where supercritical fluid is added to a blend solution of shell material and the active ingredients at high pressure which will leads to a volume expansion of the solution that causes super saturation resulting into precipitation of the solute as the solute must be soluble in the liquid solvent, but not in the blend of solvent and supercritical fluid. While on the other side the supercritical fluid and liquid solvent must be miscible and this process is not suitable for the encapsulation of water-soluble ingredients, as water has low solubility in supercritical fluids.

(c) Particles from a gas-saturated solution (PGSS)

At high pressure, when core and shell materials are mixed to form the supercritical fluid as during this process supercritical fluid penetrates the shell material, causing swelling. After heating the mixture above the glass transition temperature (Tg), the polymer liquefies while the shell material is allowed to deposit onto the active ingredient slowly upon releasing the pressure and also the core and shell materials may not be soluble in the supercritical fluid.

7.2.3 Physico-Mechanical Process

7.2.3.1 Spray Drying and Congealing

Nowadays, a low-cost commercial process which is commonly used for the encapsulation of fragrances, flavors and oils is Microencapsulation by spray drying in which the core particles are dispersed in a polymer solution and sprayed into a hot chamber (Fig. 7.3). The shell material solidifies onto the core particles as the solvent evaporates such that the microcapsules obtained will be of matrix type or poly-nuclear.

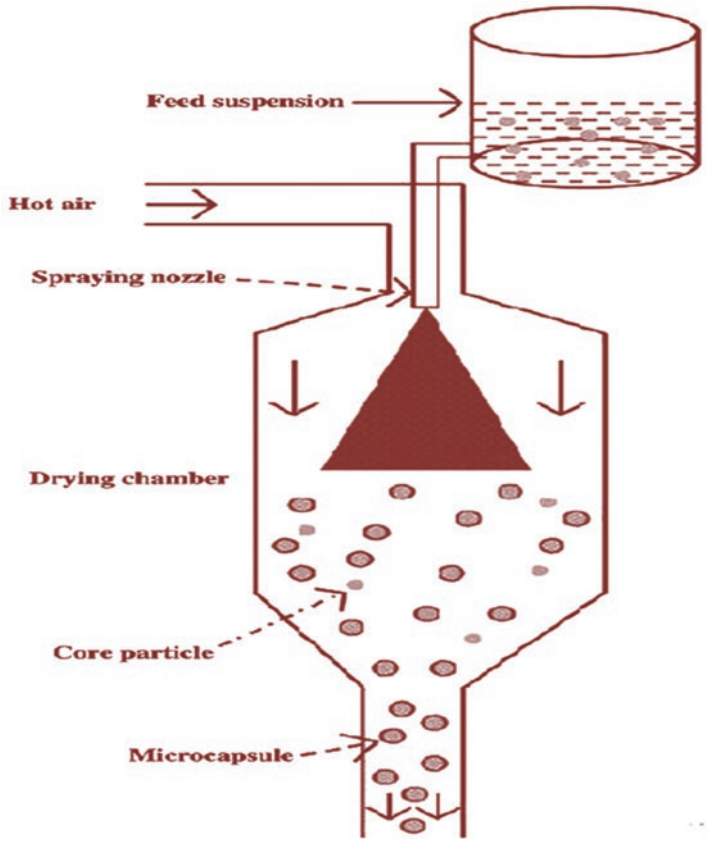

Fig. 7.3 Schematic illustrating the process of micro-encapsulation by spray drying. (Redrawn from Ghosh 2006)

Chitosan microspheres cross-linked with three distinctive cross-connecting specialists viz., formaldehyde (FA), gluteraldehyde (GA) and tripolyphosphate (TPP) have been set up by splash drying procedure. It has been widely analyzed that the impact of these cross-connecting operators on the properties of splash dried chitosan microspheres. The molecule size and epitome efficiencies of in this manner arranged chitosan microspheres went basically between 4.1–4.7 mm and 95.12–99.17%, separately. Surface morphology, rate disintegration, rate water take-up and medicate discharge properties of the shower-dried chitosan microspheres was amazingly impacted by the sort (substance or ionic) and degree (1 or 2% w/w) of cross-connecting operators. Splash dried chitosan microspheres cross-connected with TPP displayed higher swelling limit, rate water take-up, rate disintegration and medication discharge rate at both the cross-connecting degrees (1 and 2% w/w) when contrasted with those cross-linked with FA and GA. The globular and surface smoothness of the splash dried chitosan microspheres was lost when the cross-connecting degree was expanded from 1% to 2% w/w. Discharge rate of the medication from spray dried

chitosan microspheres diminished when the crosslinking degree was expanded from 1% to 2% w/w. The physical condition of the drug in chitosan-TPP, chitosan-FA and chitosan-GA lattices was affirmed by the X-beam diffraction (XRD) study and found that the medication stays in a crystalline state even after its embodiment. Arrival of the medication from chitosan-TPP, chitosan-FA and chitosan GA networks pursued Fick's law of dissemination (Desai and Park 2005).

Core material is dispersed in a coating material melt rather than a coating solution while as coating solidification is accomplished by spraying the hot mixture into cool air flow. At room temperature the substances, which are solids, like alcohols, waxes, fatty acids and polymers but they melt at their appropriate melting temperatures and are appropriate for spray congealing. The designed muco-adhesive microparticles is an innovative vaginal delivery system for econazole nitrate (ECN) to enhance the drug anti-fungal activity as the 7 different formulations were prepared by spraycongealing, a lipid-hydrophilic matrix (Gelucire ((R)) 53/ 10) was used as carrier and several muco-adhesive polymers such as sodium carboxymethylcellulose, chitosan, and poloxamers (Lutrol((R)) F68 and F127) were added (Albertini et al. 2008).

7.2.3.2 Fluidized-Bed Technology

As the outer layer on the particles can be achieved by spraying the liquid coating onto the particles which is accelerated by the rapid evaporation and also thickness and formulations of the coating can be obtained as per the requirements. Various types of fluid-bed coaters include bottom spray, top spray, and tangential spray (Fig. 7.4). While case of top spray system, the coating material is sprayed downwards on to the fluid bed in order to form encapsulated as by moving the solid or porous particles over the coating region. The opposing flows of the coating materials and the particles can be used for increased encapsulation efficiency and the prevention of cluster configuration. Dripping of the coated particles depends on the formulation of the coating material. Top spray fluid-bed coaters produce higher yields of encapsulated particles than either bottom or tangential sprays.

The bottom spray is also known as 'Wurster's coater' who has been named after its development by Wurster (1953). This procedure utilizes a coating chamber that has a tube shaped spout and a punctured base plate. The cylindrical nozzle is utilized for splashing the covering material. As the particles move upwards through the punctured base plate and pass the nozzle region, the covering material epitomizes them. The coating material adheres to the particle surface by evaporation of the solvent or cooling of the encapsulated particle. This procedure is preceded until the ideal thickness and weight is acquired. In spite of the fact that it is a tedious procedure, the multilayer coating technique helps in diminishing molecule surrenders. The tangential splash comprises of a pivoting circle at the base of the covering chamber, with indistinguishable breadth from the chamber. Amid the procedure the plate is raised to make a hole between the edge of the chamber and the circle. The tangential nozzle is placed above the rotating disc through which the coating material is release. The particles travel through the hole into the showering zone and are epitomized as they travel a base separation there is a higher yield of classified particles.

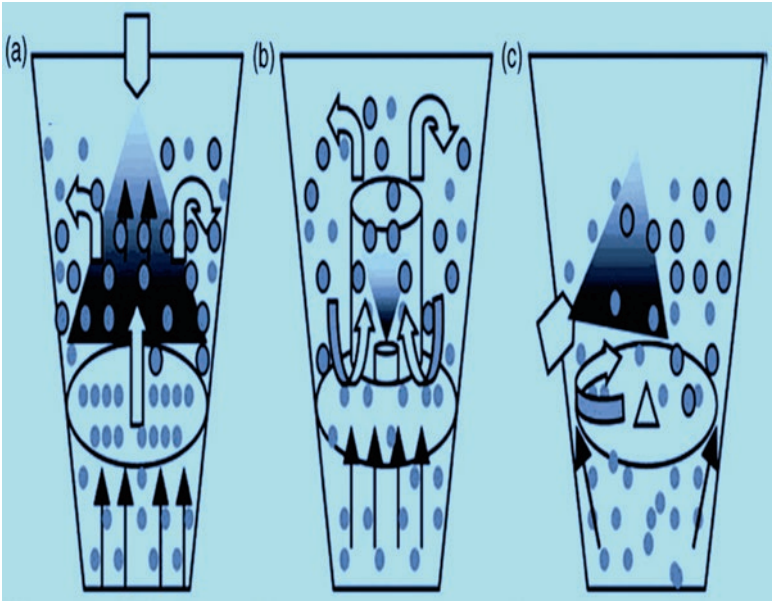

Fig. 7.4 Schematics of a fluid-bed coater. (**a**) Top spray (**b**) bottom spray (**c**) tangential spray. (Redrawn from Ghosh 2006)

7.2.3.3 Solvent Evaporation

Three phases are present in solvent evaporation process i.e., core, coat material and liquid manufacturing vehicle (LMV). At first, cost material will be dissolved in a volatile solvent, which is not soluble in LMV phase. A core material to be epitomized needs to be dispersed or dissolved in the coating polymer solution then this mixture is added to the liquid manufacturing vehicle phase with agitation, the blend is heated to evaporate the solvent for polymer. Here the coat material shrinks around the core material and encapsulates it. Microspheres of 5-fluorouracil have been prepared, using three grades of ethyl cellulose as wall forming materials, and utilizing a solvent evaporation technique under ambient conditions. An alcoholic solution of 5-fluorouracil and polymer was dispersed in liquid paraffin containing 33.3% n-heptane. The effect of stirring rate, time of stirring, and drug loading and polymer grade on drug release in two different media was evaluated. The drug-loaded particles were globular in shape having diameter range of 25–200 mm and were suitable for incorporating into a gel base. In aqueous media, the research related to drug release showed that acidic media provide a faster release rate than neutral media and an aqueous gel base preparation at pH 7.0 through a synthetic membrane was found to be promising for formulation of a gel-microsphere product for the treatment of skin lesions (Ghorab et al. 1990). Pseudoephedrine hydrochloride, a highly water-soluble drug, was entrapped within poly (methyl methacrylate) microspheres by a water/oil/water emulsification-solvent evaporation method. An aqueous drug solution was emulsified into a solution of the polymer in methylene chloride, followed by emulsification

of this primary emulsion into an external aqueous phase to form a water/oil/water emulsion. The middle organic phase separated the internal drug-containing aqueous phase from the continuous phase. Microspheres were formed after solvent evaporation and polymer precipitation. The drug content of the microspheres extended with expanding hypothetical drug stacking, increased measures of natural dissolvable, polymer and polymeric stabilizer and diminished with expanding mixing time, expanding pH of the consistent stage and expanded volume of the inside and outside aqueous stage (Rainer and Bodmeier 1990).

7.2.3.4 Pan Coating

Over the coating pan, the coating solution is applied as atomized spray to the solid core material and this coating solvent is removed by passing warm air over the coated material. Hence this method is employed to coat effectively the larger sized particles.

7.2.3.5 Factors Influencing Encapsulation Efficiency

As various parameters affect the encapsulation efficiency of the microcapsule, microparticle or microsphere, the factors influencing encapsulation efficiency has been documented as-.

7.2.3.6 Solubility of Polymer in the Organic Solvent

Mehta et al. (1996) investigated the effect of solubilities of different PLGAs polymers in methylene chloride, compared by measuring the methanol cloud point (Cs): Higher Cs meant that the polymer was more soluble in methylene chloride and, thus, required a larger amount of methanol to precipitate from the polymer solution. The PLGA polymer of a relatively high L/G ratio (75/25) had a higher solubility in methylene chloride than the other PLGA (L/G ratio ¼ 50/50). A lower molecular weight polymer had a higher solubility in methylene chloride than a higher molecular weight polymer. End-capped polymers, which were more hydrophobic than non-end-capped polymers of the same molecular weight and component ratio, were more soluble in methylene chloride. Diffusion of drugs into the continuous phase mostly occurred during the first 10 min of emulsification; therefore, as the time the polymer phase stayed in the no solidified (semi-solid) state was extended, encapsulation efficiency became relatively low. In Mehta et al.'s (1996) study, polymers having relatively high solubilities in methylene chloride took longer to solidify and resulted in low encapsulation efficiencies, and vice versa. Particle size and bulk density also varied according to the polymer. Since polymers having higher solubilities in methylene chloride stayed longer in the semi-solid state, the dispersed phase became more concentrated before it completely solidified, resulting in denser micro particles. Johansen et al. (1998) showed that the use of relatively hydrophilic PLGA, which carried free carboxylic end groups resulted in, significantly higher encapsulation efficiency compared to that of an end-capped polymer. A similar explanation as above applies to this observation: Hydrophilic PLGA is relatively less soluble in the solvent, methylene chloride, and precipitates more quickly than the end-capped one. High solidification rate might have increased the encapsulation

efficiency. On the other hand, the authors attribute the increase to the enhanced interaction between PLGA and the protein through hydrogen bonding and polar interactions (Johansen et al. 1998). Walter et al. (2001) also observed increased encapsulation efficiency from using relatively hydrophilic PLGA in DNA microencapsulation. The hydrophilicity of the polymer enhanced the stability of the primary emulsion and it contributed to such an increase.

7.2.3.7 Solubility of Organic Solvent in Water

Bodmeier and McGinity (1988) found that methylene chloride resulted in a higher encapsulation efficiency as compared with chloroform or benzene, even though methylene chloride was a better solvent for poly (lactic acid) (PLA) than the others. Methylene chloride is more soluble in water than chloroform or benzene. The 'high' solubility allowed relatively fast mass-transfer between the dispersed and the continuous phases and led to fast precipitation of the polymer. The significance of solubility of the organic solvent in water was also confirmed by the fact that the addition of water-miscible cosolvents such as acetone, methanol, ethyl acetate or dimethyl sulphoxide (DMSO) contributed to increase of the encapsulation efficiency. Knowing that the methanol is a non-solvent for PLA and a water-miscible solvent, it can be assumed that methanol played a dual function in facilitating the polymer precipitation: First, the presence of methanol in the dispersed phase decreased the polymer solubility in the dispersed phase (Jeyanthi et al. 1997). Secondly, as a water-miscible solvent, methanol facilitated diffusion of water into the dispersed phase. In order to explain the low encapsulation efficiency obtained with benzene, the authors mention that the benzene required a larger amount of water (non-solvent) than methylene chloride for precipitation of the polymer and the drug was lost due to the delayed solidification. However, given that benzene is a poorer solvent than methylene chloride for a PLA polymer, this argument does not agree with the widely spread idea that a poor solvent requires a smaller amount of non-solvent to precipitate a polymer. In fact, there could have been a better explanation if they had considered that the delayed solidification was due to the low solubility of benzene in water: As a poor solvent for a PLA polymer, benzene requires only a small amount of non-solvent for complete solidification of the polymer. However, since benzene can dissolve only a tiny fraction of water, it takes much longer to uptake water into the dispersed phase. That is, while solubility of a polymer in an organic solvent governs the quantity of a non-solvent required in precipitating a polymer, solubility of the organic solvent in the non-solvent limits diffusion of the non-solvent into the polymer phase. Thus, when a cosolvent system is involved, both solubility of a polymer in a solvent and solubility of the solvent in a non-solvent participate in determining the solidification rate of the dispersed phase.

Park et al. (1998) prepared lysozyme-loaded PLGA microparticles using the oil in water (o/w) single emulsion technique. Here, the authors used a co-solvent system, varying the ratio of the component solvents. DMSO was used for solubilization of lysozyme and PLGA and methylene chloride was used for generation of emulsion drops as well as solubilization of PLGA. Encapsulation efficiency increased and initial burst decreased as the volume fraction of DMSO in

the co-solvent system increased. Particle size increased and density of the microparticle matrix decreased with increasing DMSO. Overall, these results indicate that the presence of DMSO increased the hydrophilicity of the solvent system and allowed fast extraction of the solvent into the continuous phase, which led to higher encapsulation efficiency and larger particle size.

7.2.3.8 Concentration of the Polymer

Encapsulation efficiency increases with increasing polymer concentration (Mehta et al. 1996; Rafati et al. 1997; Li et al. 1999). For example, the encapsulation efficiency increased from 53.1% to 70.9% when concentration of the polymer increased from 20.0% to 32.5% (Mehta et al. 1996). High viscosity and fast solidification of the dispersed phase contributed to reduce porosity of the microparticles as well (Schlicher et al. 1997). The contribution of a high polymer concentration to the encapsulation efficiency can be interpreted in two ways. First, when highly concentrated, the polymer precipitates faster on the surface of the dispersed phase and prevents drug diffusion across the phase boundary. Secondly, the high concentration increases viscosity of the solution and delays the drug diffusion within the polymer droplets (Bodmeier and McGinity 1988).

7.2.3.9 Ratio of Dispersed Phase to Continuous Phase (DP/CP Ratio)

Encapsulation efficiency and particle size increase as the volume of the continuous phase increases (Mehta et al. 1996; Li et al. 1999). For eg. The encapsulation efficiency increased more than twice as the ratio of the dispersed phase to the continuous phase (DP/CP ratio) decreased from 1/50 to 1/300 (Mehta et al. 1996). It is likely that a large volume of continuous phase provides a high concentration gradient of the organic solvent across the phase boundary by diluting the solvent, leading to fast solidification of the microparticles. A relevant observation is described in the literature (Sah 1997). In this example, which utilized ethyl acetate as a solvent, the formation of microparticles was dependent on the volume of the continuous phase. When 8 mL of PLGA solution (o) was poured into 20 or 50 mL of water phase (w), the polymer solution was well disintegrated into dispersed droplets. On the other hand, when the continuous phase was 80 mL or more, the microspheres hardened quickly and formed irregular precipitates. This is because the large volume of continuous phase provided nearly a sink condition for ethyl acetate and extracted the solvent instantly. Due to the fast solidification of the polymer, particle size increased with increasing volume of the continuous phase. Microparticles generated from a low DP/CP ratio had a lower bulk density (0.561 g/cc at 1/50 vs 0.357 g/cc at 1/300), which the authors interpret as an indication of higher porosity of the polymer matrix (Mehta et al. 1996). On the other hand, a different example shows that a higher DP/CP ratio resulted in increased porosity, providing a large specific surface area (measured by the BET method) and the scanning electron microscope (SEM) pictures as evidence (Jeyanthi et al. 1997). This apparent discrepancy can be explained by the fact that low bulk density (Mehta et al. 1996) is not a true reflection of porosity but a result of large particle size. In fact, porosity increases with increasing DP/CP ratio, i.e. decreasing rate of the polymer precipitation.

7.2.3.10 Rate of Solvent Removal

The method and rate of solvent removal influence the solidification rate of the dispersed phase as well as morphology of the resulting microparticles (Mehta et al. 1994). In the emulsion-solvent evaporation/extraction method, the solvent can be removed by (i) evaporation, in which the solvent is evaporated around its boiling point, or (ii) extraction into the continuous phase. The temperature ramp or the evaporation temperature in the former and can control the rate of solvent removal by the volume of the dilution medium in the latter. PLGA microparticles containing salmon calcitonin (sCT) were prepared by emulsification, followed by different solvent removal processes (Mehta et al. 1994). In the temperature-dependent solvent removal process, the solvent (methylene chloride) was removed by increasing the temperature from 15 to 40 °C at different rates. The microparticles that resulted from this process had a hollow core and a porous wall. The core size and wall thickness were dependent on the temperature ramp. A rapid rise in temperature resulted in a thin wall and a large hollow core, whereas a stepwise temperature rise (15–25, then to 40 °C) resulted in a reduced core size. It is believed that the hollow core was due to the rapid expansion of methylene chloride entrapped within the solidified micro particles. In controlled extraction of the solvent, the solvent was removed gradually and slowly by dilution of the continuous phase, which left the micro particles in the soft state for a longer period of time. The resulting micro particles showed a highly porous honeycomb-like internal structure without a hollow core. In the later study, it was noted that the porosity was a function of the amount of water diffused into the dispersed phase from the continuous phase, which could only be allowed before the dispersed phase solidified completely (Li et al. 1995). In other words, the high porosity of the micro particles was due to the slow solidification of the micro particles. Even though it is generally assumed that fast polymer solidification results in high encapsulation efficiency, this does not apply to the observation of Yang et al. (2000). Here, the solvent evaporation temperature did not affect the encapsulation efficiency. It may be due to the different processing temperatures influencing not only the rate of polymer solidification but also the diffusivity of the protein and its solubility in water. While the high temperature facilitated solidification of the dispersed phase, it enhanced diffusion of the protein into the continuous phase, compromising the positive effect from the fast solidification.

7.2.3.11 Interaction Between Drug and Polymer

Interaction between protein and polymer contributes to increasing encapsulation efficiency (Boury et al. 1997). Generally, proteins are capable of ionic interactions and are better encapsulated within polymers that carry free carboxylic end groups than the end-capped polymers. On the other hand, if hydrophobic interaction is a dominant force between the protein and the polymer, relatively hydrophobic end-capped polymers are more advantageous in increasing encapsulation efficiency. For example, encapsulation efficiencies of more than 60% were achieved for salmon

calcitonin (sCT) microparticles despite the high solubility of sCT in the continuous phase (Jeyanthi et al. 1997). This is attributed to the strong affinity of sCT to hydrophobic polymers such as PLGA. On the other hand, such interactions between protein and polymer can limit protein release from the microparticles (Crotts and Park 1997; Park et al. 1998; Kim and Park 1999). In certain cases, a co-encapsulated excipient can mediate the interaction between protein and polymer ((Johansen et al. 1998). Encapsulation efficiency increased when gamma-hydroxypropylcyclodextrin (g-HPCD) was co-encapsulated with tetanus toxoid in PLGA microparticles. It is supposed that the g-HPCD increased the interaction by accommodating amino acid side groups of the toxoid into its cavity and simultaneously interacting with PLGA through van der Waals and hydrogen bonding forces.

7.2.3.12 Solubility of Drug in Continuous Phase

Drug loss into the continuous phase occurs while the dispersed phase stays in a transitional, semi-solid state. If the solubility of the drug in the continuous phase is higher than in the dispersed phase, the drug will easily diffuse into the continuous phase during this stage. For example, the encapsulation efficiency of quinidine sulphate was 40-times higher in the alkaline continuous phase (pH 12, in which quinidine sulphate is insoluble) than in the neutral continuous phase (pH 7, in which quinidine sulphate is very soluble) (Bodmeier and McGinity 1988).

7.2.3.13 Molecular Weight of the Polymer

Fu et al. (2005) studied the effect of molecular weight of the polymer on encapsulation efficiency and developed a long-acting injectable huperzine A-PLGA microsphere for the chronic therapy of Alzheimer's disease, the microsphere was prepared by using o/w emulsion solvent extraction evaporation method. The morphology of the microspheres was observed by scanning electron microscopy. A confocal laser-scanning microscope observed the distribution of the drug within microspheres. The results indicated that the PLGA 15000 microspheres possessed a smooth and round appearance with average particle size of 50 mm or so. The encapsulation percentages of microspheres prepared from PLGA 15000, 20,000 and 30,000 were 62.75, 27.52 and 16.63%, respectively. The drug release percentage during the first day decreased from 22.52% of PLGA 30000 microspheres to 3.97% of PLGA 15000 microspheres, the complete release could be prolonged to 3 weeks. The initial burst release of microspheres with higher molecular weight PLGA could be explained by the inhomogeneous distribution of drug within microspheres. The encapsulation efficiency of the microspheres improved as the polymer concentration increase in oil phase and PVA concentration decreased in aqueous phase. Reducing the polymer concentration could control the burst release. Evaporation temperature had a large effect on the drug release profiles. It had better be controlled under 30C. Within a certain range of particle size, encapsulation efficiency decreased and drug release rate increased with the reducing of the particle size (Fu et al. 2005).

7.3 Nanotechnology and Agricultural Sustainable Development

7.3.1 Nano Pesticides

In future, nanoparticles will be employed for crop production as well as for crop protection. NPs may play key role in the control of insect pests and pathogens as the insect pests are the predominant ones in the agricultural fields, which result in economic loss. As with advent of nano-encapsulated pesticide formulation, which has slow releasing, properties with enhanced specificity, permeability, solubility and stability (Bhattacharyya et al. 2016). In order to protect the active ingredients the encapsulation is necessary for premature degradation or to increase their pest control efficacy for a longer period of time. Nanoencapsulated pesticides formulation results in dosage reduction of pesticides and exposure of human beings to them, which is environmentally friendly for crop protection (Nuruzzaman et al. 2016). Therefore, to increase the global food production while reducing the negative environmental impacts; progress of non-toxic and promising pesticide delivery systems is necessary (de Oliveira et al. 2014; Kah and Hofmann 2014; Bhattacharyya et al. 2016; Grillo et al. 2016). The nanoencapsulation also known as microencapsulation is used to develop the quality of products of desired chemicals release to the target biological process. Few numbers of chemical companies openly promote nanoscale pesticides for sale as "microencapsulated pesticides" very recently as some products from Syngenta (Switzerland) such as Karate ZEON, Ospray's Chyella, Subdue MAXX, Penncap-M, and microencapsulated pesticides from BASF may fit for nanoscale (Gouin 2004). In Australia, Syngenta also markets some products such as the Subdue MAXX, Primo MAXX, Banner MAXX, etc. which confirms very thin interface between the term of microemulsion and nanoemulsion. This method is commonly employed for formulations of organic nanoparticles (Gouin 2004) containing active agrochemicals or substances of interest.

7.3.2 Nanoherbicides

Worldwide the agriculture has been affected by weed infestation which results in loss of huge quantity of crops as removal of weeds by conventional means are time consuming. As currently number of herbicides are available which eradicate the weeds but possess various threats to the biotic and aboitic components of environment. Hence, to adapt alternative method, which could be eco friendly like nanoherbicides as epitomization of polymeric nanoparticles, will help to solve the problem (Kumar et al. 2015; Pérez-de-Luque and Rubiales 2009). Prolonged use of chemical herbicides results in pile of soil residues, which damages the succeeding crops and also leads to weed resistance against same herbicide [Chinnamuthu and Boopathi 2009]. Effectiveness of nano zerovalent iron (nano ZVI) has been assessed

to dechlorinate herbicide atrazine (2-chloro-4ethylamino-6-isopropylamino-1, 3, 5-triazine) from atrazine-contaminated water and soil [Satapanajaru et al. 2008]. For delivery in roots of weeds, target specific nanoparticles used to load with herbicides as these molecules enter into the roots system of the weeds, translocate to cells and inhibit metabolic pathways such as glycolysis, which eventually leads to death of plants [Nair et al. 2010]. Toxicity of poly (ε-caprolactone) nanocapsules containing ametryn and atrazine against alga Pseudokirchneriella subcapitata and the microcrustacean Daphnia similis has been tested. Herbicides encapsulated in the poly (ε-caprolactone) nanocapsules resulted in lower toxicity to the algae (Pseudokirchneriella subcapitata) and higher toxicity to the microcrustacean (Daphnia similis) as compared to the herbicides alone (Clemente et al. 2014).

7.3.3 Nano Fertilizers

In the ongoing decade nanofertilizers are openly accessible in the market, yet especially the agricultural fertilizers are still not shaped by the major chemical companies (Table 7.2). Nanofertilizers may contain nano silica, iron, zinc and titanium dioxide, ZnCdSe/ZnS center shell QDs, Mn/ZnSe QDs, InP/ZnS center shell QDs, gold nanorods, center shell QDs, and so forth just as have to underwrite control discharge and enhance the its quality (Dimkpa 2014; Zhang et al. 2016) (Table 7.2).

Table 7.2 list of some commercial product of nano-fertilizers

Commercial product	Content	Company
Nano-GroTM	Plant growth regulator and immunity enhancer	Agro Nanotechnology Corp., FL, United States
Nano Green	Extracts of corn, grain, soybeans, potatoes, coconut, and palm	Nano Green Sciences, Inc., India
Nano-Ag Answer R	Microorganism, sea kelp, and mineral electrolyte	Urth Agriculture, CA, United States
Biozar Nano-Fertilizer	Combination of organic materials, micronutrients, and macromolecules	Fanavar Nano-Pazhoohesh Markazi Company, Iran
Nano Max NPK Fertilizer	Multiple organic acids chelated with major nutrients, amino acids, organic carbon, organic micro nutrients/trace elements, vitamins, and probiotic	JU Agri Sciences Pvt. Ltd., Janakpuri, New Delhi, India
Master Nano Chitosan Organic Fertilizer	Water soluble liquid chitosan, organic acid and salicylic acids, phenolic compounds	Pannaraj Intertrade, Thailand
TAG NANO (NPK, PhoS, Zinc, Cal, etc.) fertilizers	Proteino-lacto-gluconate chelated with micronutrients, vitamins, probiotics, Seaweed extracts, humic acid	Tropical Agrosystem India (P) Ltd., India

Source: Prasad et al. (2017)

7.4 Ecological Implications of Nanoparticles in Agriculture

The advancement of nanotechnologies has introduced significant degrees of manufactured NPs into the nature. So as to defend human wellbeing and plant from the intended opposing impacts of a wide scope of nanomaterials, an intensifying number of research have concentrated on the appraisal of the harmfulness of the nanoparticles typically utilized in industry (Yang and Watts 2005; Rana and Kalaichelvan 2013; Du et al. 2017; Tripathi et al. 2017a, b). Various factors like solubility, binding specificity to a biological site etc. determines the metal toxicity as metal nanoparticles exhibit antibacterial, anticandidal, and antifungal exercises (Aziz et al. 2016; Patra and Baek 2017). Depending on the charge at membrane surface, metal nanoparticles exert cytotoxicity and also the efficiency of nanotoxic effects of nanoparticles are certainly depending on structure of targeted cell-wall, thus the susceptibility order should be mould > yeast > Gram-negative > Gram-positive. Nanotoxicity may be accredited to electrostatic interaction between membrane and with nanoparticles and their accumulation in cytoplasm (Rana and Kalaichelvan 2011; Aziz et al. 2015, 2016).

The photochemically active nanoparticles include titanium dioxide, zinc oxide and silicon dioxide and Fullerenes as when they are exposed to light, the excited electrons are generated then form superoxide radicals in the presence of oxygen by direct electron transfer (Hoffmann et al. 2007). When organisms are simultaneously exposed to UV light and nanoparticles (particularly UV light has higher energy than visible light), the cells act in response to oxidative stress by increasing a number of protective enzymatic or genetic constitutions that can easily be measured (Kovochich et al. 2005; Vannini et al. 2014), thus the stress parameter is used to determine reactive oxygen species (ROS) that can be exploited in determination of the context of toxicity and ecotoxicity. Sayes et al. (2004) reported that in vitro studies on the toxicity of nanoparticles have confirmed the generation of ROS like fullerenes and titanium oxide while on other hand, some authors revealed that nanoparticles (fullerenes and silicon nanoparticles) may protect against oxidative stress (Daroczi et al. 2006; Venkatachalam et al. 2017). Significantly more inquires interactions among cells and nanoparticles just as robotic aspects of nanoparticles metabolism in organisms and specific cells are expected to clear up this division. Ecotoxicological research would progressively consideration on the ecological result of the materials and multifaceted nature of regular frameworks. Broad research would be important to determine delayed impacts of environmental exposure to nanoparticles and to help determine possible adaptive mechanisms (Cox et al. 2017; Singh et al. 2017). Nanoparticles in plants enter cell framework, translocate them to shoot and aggregate in different and accumulate in various aerial parts the likelihood of their cycling in the environment increments through different trophic dimensions. The rate of respiration, transpiration, photosynthesis, and interfere with translocation of food material have been affected by nanoparticles (Shweta et al. 2016; Du et al. 2017). The degree of toxicity is linked to this surface and to the surface properties of the nanoparticles and the ecotoxicity of nanoparticles is thus very important as it creates a direct link between the adverse effects of nanoparticles and the organisms

including microorganisms, plants, and other organisms including humans at various trophic levels (Rana and Kalaichelvan 2013). Reflection on what was referenced with respect to the examination of the conceivable results of nanotechnology and the factors utilized in the past investigations just as the examination of various researchers assessments drives one to social, financial, wellbeing, and social viewpoints as the components that are affected by nanotechnology. These outcomes can be positive or negative as the appropriately.

References

Albertini, B., Passerini, N., Di Sabatino, M., Vitali, B., Brigidi, P., & Rodriguez, L. (2008). Polymer-lipid based mucoadhesive microspheres prepared by spray-congealing for the vsilverinal delivery of econazole nitrate. *European Journal of Pharmaceutical Sciences, 36*(4–5), 591–601. 2009 March 2.

Arora, S., Sharma, P., Kumar, S., Nayan, R., Khanna, P. K., & Zaidi, M. G. H. (2012). Au-nanoparticle induced enhancement in growth and seed yield of *Brassica juncea*. *Plant Growth Regulation, 66*, 303–310.

Aziz, N., Faraz, M., Pandey, R., Sakir, M., Fatma, T., Varma, A., et al. (2015). Facile algae-derived route to biogenic silver nanoparticles: Synthesis, antibacterial and photocatalytic properties. *Langmuir, 31*, 11605–11612. https://doi.org/10.1021/acs.langmuir.5b03081.

Aziz, N., Pandey, R., Barman, I., & Prasad, R. (2016). Leveraging the attributes of Mucor hiemalis-derived silver nanoparticles for a synergistic broad-spectrum antimicrobial platform. *Frontiers in Microbiology, 7*, 1984. https://doi.org/10.3389/fmicb.2016.01984.

Bao-shan, L., Shao-qi, D., Chun-hui, L., Li-jun, F., Shu-chun, Q., & Min, Y. (2004). Effect of TMS (nanostructured silicon dioxide) on growth of Changbai larch seedlings. *Journal of Forest Research, 15*, 138–140.

Barrena, R., Casals, E., Colón, J., Font, X., Sánchez, A., & Puntes, V. (2009). Evaluation of the ecotoxicity of model nanoparticles. *Chemosphere, 75*, 850–857.

Begum, P., & Fugetsu, B. (2012). Phytotoxicity of multi-walled carbon nanotubes on red spinach (*Amaranthus tricolor* L) and the role of ascorbic acid as an antioxidant. *Journal of Hazardous Materials, 243*, 212–222.

Begum, P., Ikhtiari, R., & Fugetsu, B. (2014). Potential impact of multi-walled carbon nanotubes exposure to the seedling stcapsule of selected plant species. *Nanomaterials, 4*(2), 203–221.

Bhattacharyya, A., Duraisamy, P., Govindarajan, M., Buhroo, A. A., & Prasad, R. (2016). Nano-biofungicides: Emerging trend in insect pest control. In R. Prasad (Ed.), *Advances and applications through fungal nanobiotechnology* (pp. 307–319). Cham: Springer. https://doi.org/10.1007/978-3-319-42990-8_15.

Bodmeier, R., & McGinity, J. W. (1988). Solvent selection in the preparation of PLA microspheres prepared by the solvent evaporation method. *International Journal of Pharmaceutics, 43*, 179–186.

Boury, F., Marchais, H., Proust, J. E., & Benoit, J. P. (1997). Bovine serum albumin release from poly(alpha-hydroxy acid) microspheres: Effects of polymer molecular weight and surface properties. *Journal of Controlled Release, 45*, 75–86.

Brynko C, Bakan JA, Miller RE, Scarpelli JA (1967) US Patent 3,341466.

Bungenberg de Jong, H. G. (1949). In H. R. Kruyt (Ed.), *Colloid science* (pp. 232–258). Amsterdam: Elsevier.

Bungenberg de Jong, G., & Kruyt, H. (1929). *Prog Kungl Ned Acad Wetensch, 32*, 849–856.

Cakhshaee, M., Pethrick, R. A., Rashid, H., & Sherrington, D. C. (1985). *Polymer Communications, 26*, 185–192.

Chinnamuthu, C., & Boopathi, P. M. (2009). Nanotechnology and agroecosystem. *Madras Agricultural Journal, 96*, 17–31.

Christou, P., McCabe, D. E., & Swain, W. F. (1988). Stable transformation of soybean callus by DNA coated au particles. *Plant Physiology, 87*, 671–674.

Clemente, Z., Grillo, R., Jonsson, M., Santos, N. Z., Feitosa, L. O., & Lima, R. (2014). Ecotoxicological evaluation of poly(ε-caprolactone) nanocapsules containing triazine herbicides. *Journal of Nanoscience and Nanotechnology, 14*, 4911–4917.

Cox, A., Venkatachalam, P., Sahi, S., & Sharma, N. (2017). Reprint of: Silver and titanium dioxide nanoparticle toxicity in plants: A review of current research. *Plant Physiology and Biochemistry, 110*, 33–49. https://doi.org/10.1016/j.plaphy.2016.08.007.

Crotts, G., & Park, T. G. (1997). Stability and release of bovine serum albumin encapsulated within PLGA microparticles. *Journal of Controlled Release, 44*, 123–134.

Daroczi, B., Kari, G., McAleer, M. F., Wolf, J. C., Rodeck, U., & Dicker, A. P. (2006). In vivo radioprotection by the fullerene nanoparticle DF-1 as assessed in a zebra fish model. *Clinical Cancer Research, 12*, 7086–7091. https://doi.org/10.1158/1078-0432.CCR-06-0514.

de la Rosa, G., Lopez-Moreno, M. L., de Haro, D., Botez, C. E., Peralta-Videa, J. R., & Gardea-Torresdey, J. L. (2013). Effects of ZnO nanoparticles in alfalfa, tomato, and cucumber at the germination stcapsule: Root development and X-ray absorption spectroscopy studies. *Pure and Applied Chemistry, 85*(12), 2161–2174.

de Oliveira, J. L., Campos, E. V., Bakshi, M., Abhilash, P. C., & Fraceto, L. F. (2014). Application of nanotechnology for the encapsulation of botanical insecticides for sustainable agriculture: Prospects and promises. *Biotechnology Advances, 32*, 1550–1561. https://doi.org/10.1016/j.biotechadv.2014.10.010.

Desai, K. G., & Park, H. J. (2005). Preparation of cross-linked chitosan microspheres by spray drying: Effect of cross-linking capsulent on the properties of spray dried microspheres. *Journal of Microencapsulation, 22*, 377–395.

Dimkpa, C. O. (2014). Can nanotechnology deliver the promised benefits without negatively impacting soil microbial life? *Journal of Basic Microbiology, 54*, 889–904. https://doi.org/10.1002/jobm.201400298.

Du, W., Tan, W., Peralta-Videa, J. R., Gardea-Torresdey, J. L., Ji, R., Yin, Y., et al. (2017). Interaction of metal oxide nanoparticles with higher terrestrial plants: Physiological and biochemical aspects. *Plant Physiology and Biochemistry, 110*, 210–225. https://doi.org/10.1016/j.plaphy.2016.04.024.

Fu, X., Ping, Q., & Gao, Y. (2005). Effects of formulation factors on encapsulation efficiency and release behaviour in vitro of huperzine A-PLGA microspheres. *Journal of Microencapsulation, 22*, 57–66.

Gao, F. Q., Hong, F. S., Liu, C., Zheng, L., & Su, M. Y. (2006). Mechanism of nano-anatase TiO2 on promoting photosynthetic carbon reaction of spinach: Inducing complex of rubisco–rubisco activase. *Biological Trace Element Research, 111*, 286–301.

Ghorab, M. M., Zia, H., & Luzzi, L. A. (1990). Preparation of controlled release anticancer capsulents I: 5-fluorouracil-ethyl cellulose microspheres. *Journal of Microencapsulation, 7*, 447–454.

Ghosh, S. K. (2006). *Functional coatings by polymer microencapsulation* (pp. 221–258). Weinheim: WILEY-VCH.

Giraldo, J. P., Landry, M. P., Faltermeier, S. M., McNicholas, T. P., Iverson, N. M., Boghossian, A. A., Reuel, N. F., Hilmer, A. J., Sen, F., Brew, J. A., & Strano, M. S. (2014). Plant nanobionics approach to augment photosynthesis and biochemical sensing. *Nature Materials, 13*, 400–408. https://doi.org/10.1038/nmat3890.

Gopinath, K., Gowri, S., Karthika, V., & Arumugam, A. (2014). Green synthesis of au nanoparticles from fruit extract of *Terminalia arjuna*, for the enhanced seed germination activity *of Gloriosa superba*. *Journal of Nanostructure in Chemistry, 4*, 1–11.

Gouin, S. (2004). Microencapsulation: Industrial appraisal of existing technologies and trends. *Trends in Food Science and Technology, 15*, 330–347. https://doi.org/10.1038/nature.2015.17987.

Govorov, A. O., & Carmeli, I. (2007). Hybrid structures composed of photosynthetic system and metal nanoparticles: Plasmon enhancement effect. *Nano Letters, 7*(3), 620–625.

Grillo, R., Abhilash, P. C., & Fraceto, L. F. (2016). Nanotechnology applied to bio-encapsulation of pesticides. *Journal of Nanoscience and Nanotechnology, 16*, 1231–1234. https://doi.org/10.1016/j.tifs.2003.10.005.

Gruyer, N., Dorais, M., Bastien, C., Dassylva, N., & Triffault-Bouchet, G. (2013). Interaction between sliver nanoparticles and plant growth. In *International symposium on new technologies for environment control, energy-saving and crop production in greenhouse and plant factory*. Jeju, Korea: Greensys, 6–11 Oct 2013.

Haghighi M, Afifipour Z, Mozafarian M (2012) The effect of N-Si on tomato seed germination.

Heistand EN, Wagner JG, Knoechel EL. 1966. US Patent 3,242,051.

Helaly, M. N., El-Metwally, M. A., El-Hoseiny, H., Omar, S. A., & El-Sheery, N. I. (2014). Effect of nanoparticles on biological contamination of in vitro cultures and organogenic regeneration of banana. *Australian Journal of Crop Science, 8*, 612–624.

Hoffmann, M., Holtze, E. M., & andWiesner, M. R. (2007). Reactive oxygen species generation on nanoparticulate material. In MRWiesner & J. Y. Bottero (Eds.), *Environmental nanotechnology. Applications and impacts of nanomaterials* (pp. 155–203). New York: McGraw Hill.

Hong, F., Zhou, J., Liu, C., Yang, F., Wu, C., Zheng, L., & Yang, P. (2005). Effect of nano-TiO2 on photochemical reaction of chloroplasts of spinach. *Biological Trace Element Research, 105*(1–3), 269–279.

Huang, Y.-I., Cheng, Y.-H., Yu, C.-C., Tsai, T.-R., & Cham, T.-M. (2007). Microencapsulation of extract containing shikonin using gelatin– Acacia coacervation method: A formaldehyde-free approach. *Colloids and Surfaces. B, Biointerfaces, 58*, 290–297.

Husen, A., & Siddiqi, K. S. (2014). Carbon and fullerene nanomaterials in plant system. *Journal of Nanotechnology, 12*, 1–10.

Ikhtiar, R., Begum, P., Watari, F., & Fugetsu, B. (2013). Toxic effect of multiwalled carbon nanotubes on lettuce (*Lactuca Sativa*). *Nano Biomed, 5*, 18–24.

Jaberzadeh, A., Moaveni, P., Moghadam, H. R. T., & Zahedi, H. (2013). Influence of bulk and nanoparticles titanium foliar application on some agronomic traits, seed gluten and starch contents of wheat subjected to water deficit stress. *Notulae Botanicae Horti Agrobo, 41*, 201–207.

Jeyanthi, R., Mehta, R. C., Thanoo, B. C., & DeLuca, P. P. (1997). Effect of processing parameters on the properties of peptidecontaining PLGA microspheres. *Journal of Microencapsulation, 14*, 163–174.

Johansen, P., Men, Y., Audran, R., Corradin, G., Merkle, H. P., & Gander, B. (1998). Improving stability and release kinetics of microencapsulated tetanus toxoid by co-encapsulation of additives. *Pharmaceutical Research, 15*, 1103–1110.

Kah, M., & Hofmann, T. (2014). Nanopesticides research: Current trends and future priorities. *Environment International, 63*, 224–235. https://doi.org/10.1016/j.envint.2013.11.015.

Kalteh, M., Alipour, Z. T., Ashraf, S., Aliabadi, M. M., & Nosratabadi, A. F. (2014). Effect of silica nanoparticles on basil (*Ocimum basilicum*) under salinity stress. *Journal of Chemical Health Risks, 4*, 49–55.

Ke, P. C., Lin, S., Reppert, J., Rao, A. M., & Luo, H. (2011). Uptake of carbon-based nanoparticles by mammalian cells and plants. In K. D. Sattler (Ed.), *Handbook of nanophysics: Nanomedicine and nanorobotics* (pp. 1–30). New York: CRC Press.

Khodakovskaya, M. V., Kim, B. S., Kim, J. N., Alimohammadi, M., Dervishi, E., Mustafa, T., Cernigla CE Khota, L. R., Sankarana, S., Majaa, J. M., Ehsania, R., & Schuster, E. W. (2012). Applications of nanomaterials in agricultural production and crop protection: A review. *Crop Protection, 35*, 64–70. https://doi.org/10.1016/j.cropro.2012.01.007.

Kim, H. K., & Park, T. G. (1999). Microencapsulation of human growth hormone within biodegradable polyester microspheres: Protein aggregation stability and incomplete release mechanism. *Biotechnology and Bioengineering, 65*, 659–667.

Klärner, G., et al. (1999). Cross-linkable Polymers Based on Dialkylfluorenes. *Chemistry of Materials, 11*, 1800–1805.

Kovochich, M., Xia, T., Xu, J., Yeh, J. I., & Nel, A. E. (2005). Principles and procedures to assess nanoparticles. *Environmental Science & Technology, 39*, 1250–1256.

Krishnaraj, C., Jagan, E. G., Ramachandran, R., Abirami, S. M., Mohan, N., & Kalaichelvan, P. T. (2012). Effect of biologically synthesized silver nanoparticles on *Bacopa monnieri* (Linn.) Wettst. plant growth metabolism. *Process Biochemistry, 47*, 651–658.

Kumar, V., Guleria, P., Kumar, V., & Yadav, S. K. (2013). Au nanoparticle exposure induces growth and yield enhancement in *Arabidopsis thaliana*. *Science of the Total Environment, 461*, 462–468.

Kumar, S., Bhanjana, G., Sharma, A., Sarita, S. M. C., & Dilbaghi, N. (2015). Herbicide loaded carboxymethyl cellulose nanocapsules as potential carrier in agrinanotechnology. *Science of Advanced Materials, 7*, 1143–1148.

Lahiani, M. H., Dervishi, E., Chen, J., Nima, Z., Gaume, A., Biris, A. S., & Khodakovskaya, M. V. (2013). Impact of carbon nanotube exposure to seeds of valuable crops. *ACS Applied Materials & Interfaces, 5*, 7965–7973.

Lei, Z., Mingyu, S., Chao, L., Liang, C., Hao, H., Xiao, W., Xiaoqing, L., Fan, Y., Fengqing, G., & Fashui, H. (2007). Effects of nanoanatase TiO2 on photosynthesis of spinach chloroplasts under different light illumination. *Biological Trace Element Research, 119*, 68–76.

Li, W.-I., Anderson, K. W., Mehta, R. C., & DeLuca, P. P. (1995). Prediction of solvent removal profile and effect on properties for peptide-loaded PLGA microspheres prepared by solvent extraction/evaporation method. *Journal of Controlled Release, 37*, 199–214.

Li, X., Deng, X., Yuan, M., Xiong, C., Huang, Z., Zhang, Y., & Jia, W. (1999). Investigation on process parameters involved in preparation of polylactide-poly(ethylene glycol) microspheres containing Leptospira Interrogans antigens. *International Journal of Pharmaceutics, 178*, 245–255.

Lin, D., & Xing, B. (2007). Phytotoxicity of nanoparticles: Inhibition of seed germination and root growth. *Environmental Pollution, 150*(2), 243–250.

Lin, M. T., Occhialini, A., Andralojc, P. J., Parry, M. A. J., & Hanson, M. R. (2014). A faster Rubisco with potential to increase photosynthesis in crops. *Nature, 513*, 547–550. https://doi.org/10.1038/nature13776.

Ma, L., Liu, C., Qu, C., Yin, S., Liu, J., Gao, F., & Hong, F. (2008). Rubisco activase mRNA expression in spinach: Modulation by nanoanatase treatment. *Biological Trace Element Research, 122*(2), 168–178.

Mahajan, P., Dhoke, S. K., & Khanna, A. S. (2011). Effect of nano-ZnO particle suspension on growth of mung (*Vigna radiata*) and gram (*Cicer arietinum*) seedlings using plant agar method. *Journal of Nanotechnology, 2011*, 1–7. https://doi.org/10.1155/2011/696535.

Mahmoodzadeh, H., Nabavi, M., & Kashefi, H. (2013). Effect of nanoscale titanium dioxide particles on the germination and growth of canola (*Brassica napus*). *Journal of Ornamental Hortic Plants, 3*, 25–32.

Mehta, R. C., Jeyanthi, R., Calis, S., Thanoo, B. C., Burton, K. W., & DeLuca, P. P. (1994). Biodegradable microspheres as depot system for parenteral delivery of peptide drugs. *Journal of Controlled Release, 29*, 375–384.

Mehta, R. C., Thanoo, B. C., & DeLuca, P. P. (1996). Peptide containing microspheres from low molecular weight and hydrophilic poly(D,L-lactideco- glycolide). *Journal of Controlled Release, 41*, 249–257.

Morla, S., Ramachandra Rao, C. S. V., & Chakrapani, R. (2011). Factors affecting seed germination and seedling growth of tomato plants cultured in vitro conditions. *Journal of Chemical, Biological and Physical Sciences B, 1*, 328–334.

Nair, R., Varghese, S. H., Nair, B. G., Maekawa, T., Yoshida, Y., & Kumar, D. S. (2010). Nanoparticulate material delivery to plants. *Plant Science, 179*, 154–163.

Nalwade, A. R., & Neharkar, S. B. (2013). Carbon nanotubes enhance the growth and yield of hybrid Bt cotton Var. ACH-177-2. *International Journal of Advanced Scientific and Technical Research, 3*, 840–846.

Noji T, Kamidaki C, Kawakami K, Shen JR, Kajino T, Fukushima Y, Sekitoh T, Itoh S (2011).

Nuruzzaman, M., Rahman, M. M., Liu, Y., & Naidu, R. (2016). Nanoencapsulation, nano-guard for pesticides: A new window for safe application. *The Journal of Agricultural and Food Chemistry, 64*, 1447–1483. https://doi.org/10.1021/acs.jafc.5b05214.

Park, T. G., Lee, H. Y., & Nam, Y. S. (1998). A new preparation method for protein loaded poly(D,L-lactic-co-glycolic acid) microspheres and protein release mechanism study. *Journal of Controlled Release, 55*, 181–191.

Patra, J. K., & Baek, K.-H. (2017). Antibacterial activity and synergistic antibacterial potential of biosynthesized silver nanoparticles against foodborne pathogenic bacteria along with its anticandidal and antioxidant effects. *Frontiers in Microbiology, 8*, 167. https://doi.org/10.3389/fmicb.2017.00167.

Pérez-de-Luque, A., & Rubiales, D. (2009). Nanotechnology for parasitic plant control. *Pest Management Science, 65*, 540–545.

Prasad, T. N. V. K. V., Sudhakar, P., Sreenivasulu, Y., Latha, P., Munaswamy, V., Reddy, K. R., Sreeprasad, T. S. P., Sajanlal, R., & Pradeep, T. (2012). Effect of nanoscale zinc oxide particles on the germination, growth and yield of peanut. *Journal of Plant Nutrition, 35*(6), 905–927.

Prasad, R., Bhattacharyya, A., & Nguyen, Q. D. (2017). Nanotechnology in sustainable agriculture: Recent developments, challenges, and perspectives. *Frontiers in Microbiology, 8*, 1014. https://doi.org/10.3389/fmicb.2017.01014.

Qi, M., Liu, Y., & Li, T. (2013). Nano-TiO2 improve the photosynthesis of tomato leaves under mild heat stress. *Biological Trace Element Research, 156*(1–3), 323–328.

Rafati, H., Coombes, A. G. A., Adler, J., Holland, J., & Davis, S. S. (1997). Protein-loaded PLGA microparticles for oral administration: Formulation, structural and release characteristics. *Journal of Controlled Release, 43*, 89–102.

Rainer, A., & Bodmeier, R. (1990). Encapsulation of water-soluble drugs by a modified solvent evaporation method. I. Effect of process and formulation variables on drug entrapment. *Journal of Microencapsulation, 7*, 347–355.

Raliya, R., & Tarafdar, J. C. (2013). ZnO nanoparticle biosynthesis and its effect on phosphorous-mobilizing enzyme secretion and gum contents in cluster bean (*Cyamopsis tetrsilveronoloba* L.). *Agricultural Research, 2*, 48–57.

Ramesh, M., Palanisamy, K., Babu, K., & Sharma, N. K. (2014). Effects of bulk & nano-titanium dioxide and zinc oxide on physio-morphological changes in *Triticum aestivum* Linn. *Journal of Global Biosciences, 3*, 415–422.

Rana, S., & Kalaichelvan, P. T. (2011). Antibacterial effects of metal nanoparticles. *Advanced Biotech, 2*, 21–23.

Rana, S., & Kalaichelvan, P. T. (2013). Ecotoxicity of nanoparticles. *ISRN Toxicology, 2013*, 574648. https://doi.org/10.1155/2013/574648.

Raskar, S. V., & Laware, S. L. (2014). Effect of zinc oxide nanoparticles on cytology and seed germination in onion. *International Journal of Current Microbiology and Applied Sciences, 3*(2), 467–473.

Rezvani, N., Sorooshzadeh, A., & Farhadi, N. (2012). Effect of nano-silver on growth of saffron in flooding stress. *World Academy of Science, Engineering and Technology, 1*, 517–522.

Sah, H. (1997). Microencapsulation techniques using ethyl acetate as a dispersed solvent: Effects of its extraction rate on the characteristics of PLGA microspheres. *Journal of Controlled Release, 47*, 233–245.

Saihi, D., Vroman, I., Giraud, S., & Bourbigot, S. (2006). Microencapsulation of ammonium phosphate with a polyurethane shell. Part II. Interfacial polymerization technique. *Reactive Functional Polymer, 66*, 1118–1125.

Salama, H. M. H. (2012). Effects of silver nanoparticles in some crop plants, common bean (*Phaseolus vulgaris* L.) and corn (*Zea mays* L.). *International Research Journal of Biotechnology, 3*(10), 190–197.

Satapanajaru, T., Anurakpongsatorn, P., Pengthamkeerati, P., & Boparai, H. (2008). Remediation of atrazine-contaminated soil and water by nano zerovalent iron. *Water, Air, & Soil Pollution, 192*, 349–359.

Savithramma, N., Ankanna, S., & Bhumi, G. (2012). Effect of nanoparticles on seed germination and seedling growth of *Boswellia ovalifoliolata* an endemic and endangered medicinal tree taxon. *Nano Vision, 2*, 61–68.

Sayes, C. M., Fortner, J. D., Guo, W., Lyon, D., Boyd, A. M., Ausman, K. D., Tao, Y. J., et al. (2004). The differential cytotoxicity of water-soluble fullerenes. *Nano Letters, 4*, 1881–1887. https://doi.org/10.1002/btpr.707.

Scher, H. B. (1983). In J. Miyamoto & P. C. Kearny (Eds.), *Pesticide chemistry—Human welfare and environment* (Vol. 4, pp. 295–300). Oxford: Pergamon press.

Schlicher, E. J. A. M., Postma, N. S., Zuidema, J., Talsma, H., & Hennink, W. E. (1997). Preparation and characterization of poly(D,L-lactic-co-glycolic acid) microspheres containing desferrioxamine. *International Journal of Pharmaceutics, 153*, 235–245.

Sedghi, M., Hadi, M., & Toluie, S. G. (2013). Effect of nano zinc oxide on the germination of soybean seeds under drought stress. *Ann West Uni Timisoara ser Biol XVI, 2*, 73–78.

Shah, V., & Belozerova, I. (2009). Influence of metal nanoparticles on the soil microbial community and germination of lettuce seeds. *Water, Air, and Soil Pollution, 197*, 143–148.

Sharma, P., Bhatt, D., Zaidi, M. G., Saradhi, P. P., Khanna, P. K., & Arora, S. (2012). Silver nanoparticle mediated enhancement in growth and antioxidant status of *Brassica juncea*. *Applied Biochemistry and Biotechnology, 167*, 2225–2233.

Shweta, Tripathi, D. K., Singh, S., Singh, S., Dubey, N. K., & Chauhan, D. K. (2016). Impact of nanoparticles on photosynthesis: challenges and opportunities. *Materials Focus, 5*, 405–411. https://doi.org/10.1166/mat.2016.1327.

Siddiqui, M. H., & Al-Whaibi, M. H. (2014). Role of nano-silicon dioxide in germination of tomato (*Lycopersicum esculentum* seeds Mill.). *Saudi Journal of Biological Sciences, 21*, 13–17.

Siddiqui, M. H., et al. (Eds.). (2015). *Nanotechnology and plant sciences*. Switzerland: Springer. https://doi.org/10.1007/978-3-319-14502-0_2.

Singh, S., Vishwakarma, K., Singh, S., Sharma, S., Dubey, N. K., Singh, V. K., et al. (2017). Understanding the plant and nanoparticle interface at transcriptomic and proteomic level: A concentric overview. *Plant Gene, 11*, 265–272. https://doi.org/10.1016/j.plgene.2017.03.006.

Srinivasan, C., & Saraswathi, R. (2010). Nano-agriculture-carbon nanotubes enhance tomato seed germination and plant growth. *Current Science, 99*, 273–275.

Suriyaprabha, R., Karunakaran, G., Yuvakkumar, R., Rajendran, V., & Kannan, N. (2012). Silica nanoparticles for increased silica availability in maize (*Zea mays* L) seeds under hydroponic conditions. *Current Nanoscience, 8*, 902–908.

Syu, Y. Y., Hung, J. H., Chen, J. C., & Chuang, H. W. (2014). Impacts of size and shape of silver nanoparticles on *Arabidopsis* plant growth and gene expression. *Plant Physiology and Biochemistry, 83*, 57–64.

Tiwari, D. K., Dasgupta-Schubert, N., Villaseñor-Cendejas, L. M., Villegas, J., Carreto-Montoya, L., & Borjas-García, S. E. (2014). Interfacing carbon nanotubes (CNT) with plants: Enhancement of growth, water and ionic nutrient uptake in maize (*Zea Mays*) and implications for nanoagriculture. *Applied Nanoscience, 4*, 577–591.

Tripathi, S., & Sarkar, S. (2014). Influence of water soluble carbon dots on the growth of wheat plant. *Applied Nanoscience, 5*, 609–616. https://doi.org/10.1007/s13204-014-0355-9.

Tripathi, D. K., Singh, S., Singh, S., Srivastava, P. K., Singh, V. P., Singh, S., et al. (2017a). Nitric oxide alleviates silver nanoparticles (SilverNanoparticles)-induced phytotoxicity in Pisum sativum seedlings. *Plant Physiology and Biochemistry, 110*, 167–177. https://doi.org/10.1016/j.plaphy.2016.06.015.

Tripathi, D. K., Tripathi, A., Shweta, S. S., Singh, Y., Vishwakarma, K., Yadav, G., et al. (2017b). Uptake, accumulation and toxicity of silver nanoparticle in autotrophic plants, and heterotrophic microbes: A concentric review. *Frontiers in Microbiology, 8*, 07. https://doi.org/10.3389/fmicb.2017.00007.

Vannini, C., Domingo, G., Onelli, E., De Mattia, F., Bruni, I., Marsoni, M., et al. (2014). Phytotoxic and genotoxic effects of silver nanoparticles exposure on germinating wheat seedlings. *Journal of Plant Physiology, 171*, 1142–1148. https://doi.org/10.1016/j.jplph.2014.05.002.

Venkatachalam, P., Jayaraj, M., Manikandan, R., Geetha, N., Rene, E. R., Sharma, N. C., et al. (2017). Zinc oxide nanoparticles (ZnONanoparticles) alleviate heavy metal induced toxicity in Leucaena leucocephala seedlings: A physiochemical analysis. *Plant Physiology and Biochemistry, 110*, 59–69. https://doi.org/10.1016/j.plaphy.2016.08.022.

Walter, E., Dreher, D., Kok, M., Thiele, L., Kiama, S. G., Gehr, P., & Merkle, H. P. (2001). Hydrophilic poly(D,L-lactide-co-glycolide) microspheres for the delivery of DNA to human-derived macrophcapsules and dendritic cells. *Journal of Controlled Release, 76*, 149–168.

Wang, X., Han, H., Liu, X., Gu, X., Chen, K., & Lu, D. (2012). Multi-walled carbon nanotubes can enhance root elongation of wheat (*Triticum aestivum*) plants. *Journal of Nanoparticle Research, 14*(6), 1–10.

Wang, S. H., Gao, S. C., Xu, H. W., Zhang, H. X., & Chang, H. Q. (2013). Effects of exogenous nanometer silicon on expression of *γ-ECS* gene in rice seedlings under cd stress. *Southwest China Journal of Agricultural Science, 3*, 850–853, Article number: 1001-4829(2013)03-0850-04.

Wang, A., Zheng, Y., & Peng, F. (2014). Thickness-controllable silica coating of CdTe QDs by reverse microemulsion method for the application in the growth of rice. *Journal of Spectroscopy, 2014*, 1–5.

Wurster, D. E. (1953). US Patent 2648609

Xie, Y., Li, B., Zhang, Q., Zhang, C., Lu, K., & Tao, G. (2011). Effects of nano-TiO2 on photosynthetic characteristics of *Indocalamus barbatus*. *Journal of Northeast Forestry University, 39*, 22–25.

Yang, L., & Watts, D. J. (2005). Particle surface characteristics may play an important role in phytotoxicity of alumina nanoparticles. *Toxicology Letters, 158*, 122–132. https://doi.org/10.1016/j.toxlet.2005.03.003.

Yang, Y.-Y., Chia, H.-H., & Chung, T.-S. (2000). Effect of preparation temperature on the characteristics and release profiles of PLGA microspheres containing protein fabricated by double emulsion solvent extraction/evaporation method. *Journal of Controlled Release, 69*, 81–96.

Yang, F., Hong, F., You, W., Liu, C., Gao, F., Wu, C., & Yang, P. (2006). Influence of nano-anatase TiO2 on the nitrogen metabolism of growing spinach. *Biological Trace Element Research, 110*(2), 179–190.

Yin, X., & Stöver, H. D. H. (2003). Hydrogel microspheres formed by complex coacervation of partially MPEG-grafted poly(styrene-alt-maleic anhydride) with PDADMAC and crosslinking with polyamines. *Macromolecules, 36*, 8773–8779.

Yin, L., Colman, B. P., McGill, B. M., Wright, J. P., & Bernhardt, E. S. (2012). Effects of silver nanoparticle exposure on germination and early growth of eleven wetland plants. *PLoS One, 7*, 1–7.

Zhang, Q., Han, L., Jing, H., Blom, D. A., Lin, Y., Xin, H. L., et al. (2016). Facet control of au nanorods. *ACS Nano, 10*, 2960–2974. https://doi.org/10.1021/acsnano.6b00258.

Zheng, L., Hong, F., Lu, S., & Liu, C. (2005). Effect of nano-TiO2 on strength of naturally capsuled seeds and growth of spinach. *Biological Trace Element Research, 104*(1), 83–91.