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REVIEW

Nanotechnology in agriculture: prospects and constraints

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Abstract: Attempts to apply nanotechnology in agriculture began with the growing realization that conventional farming technologies would neither be able to increase productivity any further nor restore ecosystems damaged by existing technologies back to their pristine state; in particular because the long-term effects of farming with "miracle seeds", in conjunction with irrigation, fertilizers, and pesticides, have been questioned both at the scientific and policy levels, and must be gradually phased out. Nanotechnology in agriculture has gained momentum in the last decade with an abundance of public funding, but the pace of development is modest, even though many disciplines come under the umbrella of agriculture. This could be attributed to: a unique nature of farm production, which functions as an open system whereby energy and matter are exchanged freely; the scale of demand of input materials always being gigantic in contrast with industrial nanoproducts; an absence of control over the input nanomaterials in contrast with industrial nanoproducts (eg, the cell phone) and because their fate has to be conceived on the geosphere (pedosphere)-biosphere-hydrosphere-atmosphere continuum; the time lag of emerging technologies reaching the farmers' field, especially given that many emerging economies are unwilling to spend on innovation; and the lack of foresight resulting from agricultural education not having attracted a sufficient number of brilliant minds the world over, while personnel from kindred disciplines might lack an understanding of agricultural production systems. If these issues are taken care of, nanotechnologic intervention in farming has bright prospects for improving the efficiency of nutrient use through nanoformulations of fertilizers, breaking yield barriers through bionanotechnology, surveillance and control of pests and diseases, understanding mechanisms of host-parasite interactions at the molecular level, development of new-generation pesticides and their carriers, preservation and packaging of food and food additives, strengthening of natural fibers, removal of contaminants from soil and water, improving the shelf-life of vegetables and flowers, clay-based nanoresources for precision water management, reclamation of salt-affected soils, and stabilization of erosion-prone surfaces, to name a few.

Keywords: clay minerals, crop production, crop protection, nanotechnology, nanocomposites, nanofabrication, nanotechnology, farming, food

Introduction

Historically, agriculture preceded the industrial revolution by around 90 centuries. However, while the seeds of research in nanotechnology started growing for industrial applications nearly half a century ago, the momentum for use of nanotechnology in agriculture came only recently with the reports published by Roco,[1] the United States Department of Agriculture,[2] the Nanoforum,[3] and Kuzma and VerHage,[4] along with similar publications. These reports focused on identifying the research areas that

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should be funded, and thus set the agenda for nanotechnology research in agricultural applications, which became the principal guiding force for many nations, especially those where agriculture is the primary occupation of the majority of the population. However, the conceptual framework, investigation pathways, and guidelines and safety protocols were left aside for scientific laboratories to innovate.

A casual Google Scholar search on nanotechnology in agriculture identified about 1,100 entries until 1999, which increased steadily to 13,900 in the last 4 years. Even now, the share of publications on nanotechnology in agriculture remains miniscule, ie, less than 5% of each of the kindred fields of power, energy, and materials, and one seventh that of nanomedicines. However, the accelerating pace reflects a growing recognition of the numerous potential agricultural applications of nanotechnology. It has been envisioned that the novel properties of nanoscale biomaterials combined with ingenious engineering would have innovative applications for agriculture and food systems; and as nanotechnology advances, agricultural crops might lead to design of new materials and devices.[5] A recent review of advances in nanofabricated materials for crop protection and detection of pathogens and pesticide residues concluded that nanotechnology would reduce the human footprint, provided that appropriate safety measures are in place.[6] Chen and Yada[7] and Rai and Ingle[8] enumerated the opportunities for nanotechnology applications in plant, animal, and environmental systems, especially for insect control, and highlighted the specific needs of farm-based economies in developing countries. For a country like India, applications could be in the areas of nanoinputs, nanofood systems, nanobiotechnology, and nanoremediation,[9] although nanotechnology is likely to overwhelm all spheres of agricultural activities: from tillage to silage, presowing field preparations to post-cooking and food serving, and seed germination to germplasm manipulation. Research endeavors so far have mostly been concentrated in two broad fields, ie, the post-harvest food arena and next-generation pesticide formulations. Some extensive reviews have been published on these issues.[6,10–13] It is interesting to note that both these fields are intrinsically linked to the interests of the powerful food industry[14] and pesticide giants, while on the other hand, research arenas which could possibly be beneficial to the less fortunate toiling masses, ie, the tillers, are yet to receive the desired attention.

Fossil fuels are being depleted rapidly, as have certain other crucial natural resources. For example, rock phosphates are the source of >97% of phosphate materials, but this resource is likely to be exhausted by 2035.[15] Such alarms necessitate alternate technologies to support the rapid increase in farm productivity, along with a rapid reduction of the anthropogenic footprints on the environment through more efficient farming. Incidentally, agricultural crops are endowed with the power of synthesis of many future materials, especially because they are incubators of nanomaterials, and synthesize these through a bottom-up approach.[16,17] Crop production has always been positive in energy balance. Jansson and Siman[18] showed that, in Swedish agriculture, the approximate energy input was 14.5 GJ per hectare, while output through crops was 65 GJ per hectare. To sustain civilization, future agriculture will have to respond to needs for energy by, eg, entrapping of solar energy and material manufacturing, apart from its conventional role in producing food, fodder, and fuel. The present review is an attempt to sum up and assess the prospects of nanotechnology research, addressing the hereto uncovered arena of grass-root field-centric farming to secure food, nutrition, and livelihood that could ensure growth of all stake-holders.

Defining nanotechnology in agriculture

Nanotechnology is defined by the US Environmental Protection Agency[19] as the science of understanding and control of matter at dimensions of roughly 1–100 nm, where unique physical properties make novel applications possible. This definition is slightly rigid with regard to size dimensions. Greater emphasis could have been placed on the problem-solving capability of the materials. Other attempts to define nanoparticles from the point of view of agriculture include "particulate between 10 and 1,000 nm in size dimensions that are simultaneously colloidal particulate".[2,20]

Ultimately, nanotechnology could be described as the science of designing and building machines in which every atom and chemical bond is precisely specified. It is not a set of particular techniques, devices, or products, but the set of capabilities that we will have when our technology comes near the limits set by atomic physics.[21] Nanotechnology aims at achieving for control of matter what computers did for our control of information. For Drexler, the ultimate goal of nanomachine technology is the production of the "assembler". The assembler is a nanomachine designed to manipulate matter at the atomic level.[22] The burgeoning applications of nanotechnology in agriculture will continue to rely on the problem-solving ability of the material and are unlikely to adhere very rigidly to the upper limit of

100 nm. This is because nanotechnology for agricultural applications will have to address the large-scale inherent imperfections and complexities of farm production systems (eg, extremely low input use efficiency), that might require nanomaterials with flexible dimensions, which nevertheless perform tasks efficiently in agricultural production systems. This is in contrast with nanomaterials that might be working well in well-knit factory-based production systems.

Limits of conventional farming

Recent agricultural practices associated with the Green Revolution have greatly increased the global food supply. They have also had an inadvertent, detrimental impact on the environment and on ecosystem services, highlighting the need for more sustainable agricultural methods.[23] It is well documented that excessive and inappropriate use of fertilizers and pesticides has increased nutrients and toxins in groundwater and surface waters, incurring health and water purification costs, and decreasing fishery and recreational opportunities. Agricultural practices that degrade soil quality contribute to eutrophication of aquatic habitats and may necessitate the expense of increased fertilization, irrigation, and energy to maintain productivity on degraded soils. They also kill beneficial insects and other wildlife. Groundwater levels are retreating in areas where more water is being pumped out for irrigation than can be replenished by the rains.[24,25] Globally, 40% of crop production comes from the 16% of irrigated agricultural fields.[26,27] However, long-term irrigation and drainage practices have accelerated the rate of weathering of soil minerals, turned soils acidic, or caused salt buildups and eventual abandonment of some of the best farming lands.[28–30] Intensive tillage, irrigation, and fertilizer dressing have also caused more extensive damage to the carbon profile in soils than early agrarian practices did.[31]

The limitations of conventional technologies could be judged from the fact that advocates of alternative farming like "conservation agriculture"[32] propose conservation methods that are neither new[33] nor practical because farming works in an open system, and thereby conservation agriculture is thermodynamically not very tenable in such a system. All laws pertaining to conservation only work in isolated systems. Similarly, "organic farming" is based on acknowledgment of the harmful effects of Green Revolution technologies, but it can neither accomplish high productivity, nor ensure a better environment and better food products.[18] Similarly, rainfed/dry land farming falls short of matching the productivity that irrigated farming can provide.

Degraded ecosystems have become a serious threat to human health and civilization. The benchmark for ecosystem degradation is linked to its failure to retain carbon and prevent escape of various forms of nitrogen from the soil to water bodies and the atmosphere. A huge amount of biomass was added to soils during the Green Revolution era through a many-fold increase in yields of root mass from crops. Similarly, several attempts have been made to increase the organic matter in soils by adding crop residues. However, these efforts could neither retain carbon for long nor check pollution from nitrogen. The situation is aggravated with the rise in soil temperature across ecosystems. Many soils throughout the world, especially those brought under the Green Revolution during the second half of the last century, are contaminated with harmful trace metals and pesticide residues. It is not practically possible to clean up these lands through bioremediation (including phytoremediation) without relocating farmers and withdrawing their livelihood.[34] At the same time, opportunities exist to reengineer plants,[35] for which nanobiotechnology could be promising.

Advantages of nanomaterials over corresponding bulk materials

At the nanoscale, matter shows extraordinary properties that are not shown by bulk materials. For example, surface area, cation exchange capacity, ion adsorption, complexation, and many more functions of clays would multiply if they are brought to nanoscale. One of the principal ways in which a nanoparticle differs from bulk material is that a high proportion of the atoms in a nanoparticle are present on the surface.[36] Compared with particles of macrosize, nanoparticles may have different surface compositions, different types and densities of sites, and different reactivity with respect to processes such as adsorption and redox reactions,[37,38] which could be gainfully used in synthesizing nanomaterials for use in agriculture.

Distinctiveness of the agricultural production system

The government reports and reviews published so far have not highlighted either the uniqueness of the agricultural production system as compared with industry, or its variations according to cultural-specific and place-specific features, or the direction of development of field-centric farming. This could be one of the reasons for the sluggish penetration of nanotechnology into farming. Another reason could be the illusionary complacency arising out of the steady increase in agricultural production through improvement of farming practices by conventional means, and the near absence of the cutthroat competition experienced in the industrial sector. Between 1961 and 1999, global food production outstripped population growth, but this was achieved partly through a 12% increase in the global area of cropland and a 10% increase in the area of permanent pasture. During the same period, the overall food crop yield per unit area grew by 106%; however, this was linked to a 97% rise in the area of land under irrigation, and 638%, 203%, and 854% increases, respectively, in the use of nitrogenous and phosphate fertilizers and production of pesticides.[39] The situation could be gauged from data for the irrigated farming regions in India, where the return of grain yield per kilogram of nutrient use was reduced from 13.4 kg in 1970 to 3.7 kg in 2005.[40]

Unlike most of the industrial production systems, agricultural production functions in an open system, and could seldom be converted to an isolated system. All spheres, ie, the geosphere (pedosphere), biosphere, hydrosphere and atmosphere, are intrinsically linked and interdependent in farming. Energy and matter are exchanged freely from one sphere to the other in farming, and only the intensity varies from a local ecosystem to the terrestrial ecosystem. Linkage between farm ecology and terrestrial ecology is evident from the dusts generated during tillage of the Great Plains area in the western USA in the 1930s, and similar events. Similarly, various operations and cropping at farm scale ultimately contribute 31% of global carbon dioxide emission.[41]

The second important aspect of farming is the requirement of inputs on a gigantic scale. For example, the carbon nanowire requirement for 50 million cell phones might be 50 mg, but for every hectare of land, the requirement for nitrogen fertilizer could be 100 kg at optimum level! This is true for all inputs (including seed, fertilizer, water, and pesticides). Whether farm input is applied in the form of nanomaterials, or in the form of bulk materials, the requirements of plants to achieve optimum yield remain the same. However, input use efficiency can be improved substantially.

Another interesting feature of the farm production system is that it would be virtually impossible to control the fate and behavior of nanomaterials whether they are added to the system intentionally (eg, fertilizers) or unintentionally (eg, engineered nanomaterials like zinc oxide, titanium oxide, and ferrite). Nanomaterials, when applied to soils or plants or with irrigation, would never remain a point source application, but spread all over the field. Their disposal cannot be managed in the same manner as for most consumer products; rather, the problem of disposal is similar to that of nanomedicines in humans and animals. Nanomaterials on farms cannot be controlled in the way they are controlled in other applications, from television to satellites, but a knowledge-based passive control system would pave the way. This could be illustrated by the fact that our precise understanding of reactivity, transformation, and fate of urea in soils helped us to eliminate nitrate contamination in ground water without losing crop yield.

Nevertheless, there exist many gray areas in making farm production systems responsive to desired productivity levels, maintenance of environmental quality, and adherence to societal ethics. With nanotechnology being a new entrant in agriculture, we need to revisit the contemporary theoretical foundations and practices of agriculture to conform to next-generation farming. Similarly, investigations need to be directed to simulation of the properties, behavior, transport, and reactivity of nanomaterials in the ecosystem in a predesigned and holistic manner. Our understanding of these aspects could possibly be improved if hitherto unexplored areas like the theory of chaos, especially in nonlinear dynamic systems, are used to the fullest extent, especially given that equilibrium thermodynamics never works with anything approaching perfection in the natural environment.

Foresight and patience are essential for applying nanotechnology in agriculture because generation of data in most agricultural fields is time-consuming and expensive, and success is uncertain due to involvement of a large number of variables in farm production systems, and because of the complex intrinsic relationship between nanomaterials and nature. It is worthwhile to recognize that a large number of nanomaterials have existed since time immemorial in soils, plants, and the atmosphere.[42–44]

What nanotechnology can do for agriculture

Nature is a great teacher, and nanotechnology applications in agriculture can be successful if natural processes are simulated in greater scientific sophistication/articulation for successful implementation. For example, the goal might be to make soils more capable in order to improve efficient nutrient use for greater productivity and better environmental security. Nutrient management with nanotechnology must rely on two important parameters, ie, ions must be present in plant-available forms in the soil system, and since nutrient transport in soil-plant systems relies on ion exchange (eg, NH_4^+, $H_2PO_4^-$, HPO_4^{2-}, PO_4^{3-}, Zn^{2+}), adsorption-desorption (eg, phosphorus nutrients) and solubility-precipitation (eg, iron) reactions, nanomaterials must facilitate processes that would ensure availability of nutrients to plants in the rate and manner that plants demand. Since clay minerals control these reactions, they could be used as receptacles. Nanofabricated materials containing plant nutrients can be used in aqueous suspension and hydrogel forms, so as to enable hazard-free application, easy storage, and a convenient delivery system. Similarly, application of zerovalent iron nanoparticles and even nanoparticles from iron rust could be harnessed for remediation of soils contaminated with pesticides, heavy metals, and radionuclides, given the high adsorption affinity these nanomaterials have for organic compounds and heavy metals. Iron nanoparticles also have excellent soil binding properties, similar to those of calcium carbonate nanoparticles, which help in formation of soil microaggregates and macroaggregates.[45]

Further opportunities for applying nanotechnology in agriculture lie in the areas of genetic improvement of plants,[35,46] delivery of genes and drug molecules to specific sites at the cellular level in plants and animals,[47] and nanoarray-based technologies for gene expression in plants to overcome stress and development of sensors[48,49] and protocols for its application in precision farming,[50] management of natural resources, early detection of pathogens and contaminants in food products, smart delivery systems for agrochemicals like fertilizers and pesticides, and integration of smart systems for food processing, packaging, and monitoring of agricultural and food system security.[51,52] With nanofertilizers[53] emerging as alternatives to conventional fertilizers, buildup of nutrients in soils and thereby eutrophication and contamination of drinking water may be eliminated.[54,55] Overdependence on supplementary irrigation, vulnerability to climate, and poor input and energy conversion are the three dominant issues in the current agricultural production system, and nanotechnology could possibly reduce their impact. Also, it has been observed that nanoremediation could be effective not only in reducing the overall costs of cleaning up large contaminated sites, but also in decreasing clean-up time by eliminating the need for treatment and disposal of contaminated soil and reducing some contaminant concentrations to near zero, all in situ, although caution is required, especially for full-scale ecosystem-wide studies, to prevent any potential adverse environmental impacts.[34] Much existing knowledge could possibly be translated to other areas with the help of nanotechnology. For example, soil acidity could possibly be ameliorated by the use of nanozeolites. The phenomenon of zeolites supplying bases and retaining smectite-kaolinite in a stable phase since the early Tertiary (geologic) period in tropical humid climates with plenty of Al^{3+} ions in the system has been reported in some soils of the Western Ghat in India.[56]

Nanotechnology in agriculture for security of livelihoods

There is unanimity in recognizing the role of nanotechnology in agriculture, especially with regard to improvement of livelihood among the poor in third world nations.[57–59] With progressive implementation of the Agreement on Trade Related Aspects of Intellectual Property Rights, one of the three pillars of the 1994 trade agreements under the World Trade Organization, an increasing number of developing countries are adopting intellectual property rights. The number of international and US patents is increasing for all types of nanotechnologies worldwide.[60] A large majority of these patents originate from developed countries that are leaders in nanotechnology, like the USA, Western European nations, Japan, South Korea, and Australia.[61] In the developing world, so far, only large emerging economies (such as the People's Republic of China) have developed patented technologies.[14] The intellectual property rights regime is likely to be strengthened further in the future, and might create a knowledge divide between developed and poor nations.

Agricultural nanotechnology is a tool that can provide greater dividends for poor nations because it is powerful in ameliorating problems related to poor input use efficiency, water scarcity, poor sanitary conditions, and other similar problems experienced by poor nations. However, poor nations can harvest the fruits of nanotechnology if it is realized that future cost of importing farm-technology could be higher than that of developing it indigenously in a sustained manner.

Nanofabrications in agriculture

Nanofabrication could be defined as the design and manufacture of devices that measure dimensions in nanometers. It is a vibrant field, so many new classes of materials with innovative fabrication technology are expected to appear in the future. Current engineered nanomaterials are grouped into four classes,[19] ie, carbon-based materials, metal-based materials, dendrimers, and composites. It is difficult to generalize the processes of nanofabrication with accuracy, because they are fabricated by methods specific to the requirements of the materials themselves, and in many cases are protected by intellectual property rights.

Conventionally, nanofabrication can proceed by scaling down integrated circuit fabrication involving removal of one atom at a time to obtain the desired structure (top-down approach) or by a more sophisticated hypothetical scheme involving assembly of a structure atom-by-atom (bottom-up approach). Industry has been applying a variety of techniques, including physical and chemical vapor deposition, laser ablation, arc discharge, lithography electron, laser, ultraviolet light, photons, X-ray, focused ion beams, scanning probes for nanodeposition or nanomachining of atoms, molecules, compounds or structures, nanoimprinting (soft and hard), and self-assembly to generate nanomaterials/nanoproducts or nanomaterial-containing products. These approaches, although quite useful for industrial purposes (like melting materials at a high temperature to segregate atoms/ions at plasma state), could not be replicated or simulated to obtain the safer products required by the agriculture sector. Nanomaterials for application in farming could be fabricated by combining the top-down and bottom-up methods on the basis of an understanding of the nanodynamics of interacting nanomaterials and interfacing nanostructures.

In my laboratory, we have had some success in using clay minerals and composites as nanomaterials and also as receptacles, ie, the architectural component. For example, we found that kaolin was useful for retaining PO_4^{3-}, and a Zn^{2+} in $Zn_6(OH_2)_{12}$ sheet form could be intercalated in smectite.[62] Similar successes have been reported by other researchers.[63] The advantages of using clay minerals and composites are: their crystalline nature and unit cell dimensions that are in nanometer scale in all three dimensions (x, y, and z); their ordered arrangements; their large adsorption capacity; their shielding against sunlight (ultraviolet radiation); their ability to concentrate organic chemicals; and their ability to serve as polymerization templates. These materials are available in abundance and are cheap, so farmers would be able to afford them when they are commercialized. From the viewpoint of the environment and biosafety, the inseparable association of clays with the origin and evolution of life makes them most desirable.

Nanofabrication involving clay is a distinct field, because it departs from the conventional field of nanotechnology (eg, nanoelectronics, nanomaterials), and is far more challenging than conventional applications (eg, cell phones, computers, sensors, clothes, and other industrial products). This is because clay is an interface between the physical world and biological world, and soil is the central domain of geosphere, biosphere, atmosphere, and the hydrosphere, so soil scientists have the responsibility to support life and protect environment. The methods followed in industry cannot be copied for applications in agricultural nanotechnology involving clays. However, the soil system obeys the laws of ion exchange, adsorption-desorption, aggregation-dispersion, and solubility-dissolution, and such phenomena must be used to make the system responsive to nanotechnology. For example, nanofertilizers must be capable of releasing nutrient ions in plant-available forms. One of the key aspects of nanofabrication could possibly be manipulation of bonds, which is a common occurrence in clay minerals. Clay minerals have both covalent and ionic bonds, a feature that could be advantageous in developing a passive control system for achieving a nutrient supply mechanism. In clay minerals, there are numerous examples of bonds being changed from one form to another through isomorphous substitution or insertion of small ions (eg, Li^+), or by use of organic compounds. The routes of fabrication could rely on charge properties such as: density, origin, and nature of charges; intensity and degree of manifestation of charge in nanoscale; and the nature (geometry) and extent of the interface available for reaction. Fabrication may include extraction, purification, and functionalization involving mild nontoxic materials such as Na_2CO_3 at low concentration. Our experience shows that the ultrasonic method is most appropriate for top-downing clays into nanoclays, and manipulation of pH and zeta potential can help to maneuver desired ions to the targeted place, such as interlattice, edges, and broken bonds. Historically, nanosynthesis has come a long way from the top-down and bottom-up approaches to what Zubarev has described as, "any way you want it".[64] This should be the essence for nanofabrication as well. For the reasons outlined above, nanofabrication for agricultural applications might require a route distinct from that of industrial nanomaterial fabrication. It is worth mentioning that the fate and disposal of nanomaterials in farmlands are not comparable with those of their industrial counterparts.

In spite of the modest pace of emergence of new nanoproducts for agriculture, a number of commercially promising products have been manufactured (see Table 1).[65]

Public acceptance of nanotechnology

Application of nanotechnology is essential, given the millions of people worldwide who continue to lack access to safe water, reliable sources of energy, health care, education, and other basic human development needs. Since 2000, the United Nations Millennium Development Goals have set targets for meeting these needs. In recent years, an increasing number of government, scientific, and institutional reports have concluded that nanotechnology could make a significant contribution to alleviating poverty and achieving the Millennium Development Goals, but with a caution on the potential risks of nanotechnology for developing countries.[59,66] In a public opinion survey, respondents in the USA did not consider the risks and benefits of nanotechnology independently, and perceived nanotechnology as relatively neutral, less risky, and more beneficial than a number of other technologies, such as genetically modified organisms, pesticides, chemical disinfectants, and human genetic engineering. On the other hand, it was seen as more

Table 1 Some examples of recent breakthroughs in nanotechnology in agriculture[a]

Product	Application	Institution
Nanocides	Pesticides encapsulated in nanoparticles for controlled release	BASF, Ludwigshafen, Germany
	Nanoemulsions for greater efficiency	Syngenta, Greensboro, NC, USA
Buckyball fertilizer	Ammonia from buckyballs	Kyoto University, Kyoto, Japan
Nanoparticles	Adhesion-specific nanoparticles for removal of *Campylobacter jejuni* from poultry	Clemson University, Clemson, SC, USA
Food packaging	Airtight plastic packaging with silicate nanoparticles	Bayer AG, Leverkusen, Germany
Use of agricultural waste	Nanofibers from cotton waste for improved strength of clothing	Cornell University, Ithaca, NY, USA
Nanosensors	Contamination of packaged food	Nestle, Kraft, Chicago, USA
	Pathogen detection	Cornell University, Vevey, Switzerland
Precision farming	Nanosensors linked to a global positioning system tracking unit for real-time monitoring of soil conditions and crop growth	US Department of Agriculture, Washington, DC, USA
Livestock and fisheries	Nanoveterinary medicine (nanoparticles, buckyballs, dendrimers, nanocapsules for drug delivery, nanovaccines; smart herds, cleaning fish ponds (Nanocheck [Nano-Ditech Corp., Cranbury, NJ, USA]), and feed (iron nanoparticles)).	Cornell University NanoVic, Dingley, Australia

Note: [a]Adapted from Kalpana-Sastry et al.[65]

risky and less beneficial than solar power, vaccination, hydroelectric power, and computer display screens.[67]

However, despite the public acceptance, we must remember that we have little understanding of the fate, transport, and behavior of engineered nanoparticles in the environment (including soils and the hydrosphere) outside of their original commercial or industrial domains. At our current level of knowledge, it is difficult to predict the potential environmental impacts of nanoparticles.[68,69] More care is required in regard to their synthesis and use in agriculture than for commercial or industrial products.

Human resource requirements

To be successful in the novel emerging field of agricultural nanotechnology, human resources must be well trained to experiment, innovate, assess, interpret, and successfully assimilate the theory, tools, and techniques of nanotechnology for its application in agriculture. Presently, nanotechnology is taught in several engineering and traditional institutions at both the undergraduate and postgraduate levels. Their curricula and degree programs cater to the needs of industry and industry-oriented institutions. Nanotechnology teaching programs in engineering and traditional institutions do not train their students to handle the issues critical to agriculture. For example, the intricate relationships that interplay in the components of life (ie, soil, plants, animals, and humans) and the effect of nanomaterials on the food chains, the food web, and farm wastes do not get sufficient coverage in the courses run by technical institutions. There is an urgent need to develop human resources with an understanding of the complexities of the agricultural production system to serve nanotechnology applications in agriculture successfully. By and large, agricultural education has not been able to attract sufficient numbers of brilliant minds the world over, while personnel from kindred disciplines might lack an understanding of agricultural production systems. Instruction programs in agricultural nanotechnology, if initiated, might fill this void by fulfilling the twin goals of attracting brilliant learners and developing a body of skilled farm-focused personnel.

Conclusion

The opportunity for application of nanotechnology in agriculture is prodigious. Research on the applications of nanotechnology in agriculture is less than a decade old. Nevertheless, as conventional farming practices become increasingly inadequate, and needs have exceeded the carrying capacity of the terrestrial ecosystem, we have little option but to explore nanotechnology in all sectors of agriculture. It is well recognized that adoption of new technology is crucial in accumulation of national wealth.[70] Nanotechnology promises a breakthrough in improving our presently abysmal nutrient use efficiency through nanoformulation of fertilizers, breaking yield and nutritional quality barriers through bionanotechnology, surveillance and control of pests and diseases, understanding the mechanism of host-parasite interactions at the molecular scale, development of new-generation pesticides and safe carriers, preservation and packaging of food and food additives, strengthening of natural fiber, removal of contaminants from soil and water bodies, improving the shelf-life of vegetables and flowers, and use of clay minerals as receptacles for nanoresources involving nutrient ion receptors, precision water management, regenerating soil fertility, reclamation of salt-affected soils, checking acidification of irrigated lands, and stabilization of erosion-prone surfaces, to name a few. Revisiting our understanding of the theoretical foundations of the agricultural production system along the geosphere (pedosphere)-biosphere-atmosphere continuum coupled with application of advanced theories like the theory of chaos and string theory may open up new avenues. Nanotechnology requires a thorough understanding of science, as well as fabrication and material technology, in conjunction with knowledge of the agricultural production system. The rigor of this challenge might attract brilliant minds to choose agriculture as a career. To achieve success in the field, human resources need sophisticated training, for which new instruction programs, especially at the graduate level, are urgently needed.

The editors of *Nature* estimated that any technology takes some 20 years to emerge from the laboratory and be commercialized.[71] Nanotechnology in agriculture might take a few decades to move from laboratory to land, especially since it has to avoid the pitfalls experienced with biotechnology. For this to happen, sustained funding and understanding on the part of policy planners and science administrators, along with reasonable expectations, would be crucial for this nascent field to blossom.

Disclosure

The author reports no conflicts of interest in this work.

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