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Nanotechnology: Cutting-Edge Tool for Increasing Agricultural Production

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Review Article

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ABSTRACT

India and many developing countries in Asia and Africa are posed with the challenges of food insecurity and poverty for the next three decades, because of the growing demand for food commodities and depletion of natural resources, and global warming. While efforts are being made to increase agricultural production, serious attempts are needed to increase crop yields and income of small holder farmers, without polluting the environment. Fortunately, the recent introduction of nanotechnology for increasing agricultural production has indicated its potential to increase crop yields, while improving soil productivity and reducing the use of agro chemicals as well as the cost of production. Presently, several macro and micro nutrients sold in India have confirmed the benefits in terms of higher yield and lower cost of production. Nano-carbon is another material having great promise for boosting agricultural production, because of its role as a nutrient, soil stabilizer, effective facilitator for absorption of nutrients and plant protection molecules from the soil, and immunity boosters against biotic and abiotic pressures. Farmers from Gujarat and Maharashtra states who have used this technology for growing cotton, groundnut, paddy, turmeric, sugarcane and a wide range of fruits and vegetables have been successful in significantly increasing their crop production without any chemical residues, while decreasing the cost of production. Nano-carbon-based materials have a promising future in India and other developing countries.

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1. INTRODUCTION

With the increasing population in the world, the challenge of addressing food security will be a major concern for most developing countries. By 2030, the world population will cross 8.548 billion and reach 9.1 billion in 2050. The population of India in 2022 reached 1.412 billion as compared to China's population of 1.458 billion. Within a few years, India's population will surpass that of China and rise to 1.515 billion in 2030. By 2050, India's population will grow to 1.668 billion, while the Chinese population will fall to 1.317 billion [1]. With the highest population in the world, India will continue to experience major challenges in food security and environmental safety, because of increasing demand for food, over-exploitation of natural resources such as land, water, livestock and forests, coupled with air and water pollution, caused by excessive use of fossil fuel and agro-chemicals. By 2050, the average household income, particularly of poor and middle-class families will rise by 2-3 times and over 70 percent of the world's population will be living in urban areas, resulting in a 70 percent increase in average per capita consumption of food and energy [2]. The demand for cereal food grains in the world will exceed 3 billion tons per annum, as compared to the production of 2.1 billion tons in 2020 [3]. Increasing food production will be a serious challenge for most developing countries, because of the limited scope for increasing the area under agricultural production. It is estimated that the developing countries can increase the area under agricultural production only by 20 percent and the remaining 80 percent increase in production will have to be met by increasing the crop yields and cropping intensity. This is considered to be a huge challenge because the global crop yield which had attained its peak during the Green Revolution era in the 1970s has been steadily declining at 1.5 – 2.0 percent per annum, while the cost of production has been increasing steeply.

1.1 Demand and Supply Status of Food in India

The agricultural production situation in India is more critical, because of several additional factors such as water scarcity, lower investment in technology and mechanisation and poor infrastructure for backward and forward integration. The food grain production in India is expected to reach 315.72 million tonnes in 2021-22, with a record production of rice, maize, gram, pulses, rapeseed and mustard, oilseeds and sugarcane [4]. During the next ten years, the demand is expected to increase particularly for high-value nutritious produce such as pulses, oilseeds, fruits, vegetables, milk and meat, in urban areas. The estimated demand and supply for various categories of food in 2032-33 are presented in Table 1 [5].

It can be observed in Table 1 that by 2032-33, India will have difficulty to fulfil the demand for coarse cereals, pulses, oil seeds and fruits. While the shortfall is less than 9 percent in coarse cereals and less than 3 percent in pulses and fruits, the gap is expected to be very wide in oil seeds, with about 40 percent shortage. Although the projected food supply situation seems to be marginally satisfactory, there are many constraints which are likely to pose a threat to food security from time to time because of unexpected weather calamities caused by climate change and several other factors listed below.

1.2 Factors Affecting Food Production in India

Low crop yields: Despite India's success in increasing food production by six folds under the Green Revolution during the last five decades, the average yield of cereals in 2012 was only 2.88 tons/ha, as compared to the world average of 3.67 tons and 6.65 tons/ha in Western Europe [6]. In 2020, the average yield of cereals in India had increased to 3.283 tons/ha as against the yield of 4.072 tons/ha and 6.296 tons/ha for the world and China respectively [6]. Such low yields can be attributed to the non-availability of good quality seeds of high-yielding varieties, disproportionate use of fertilisers containing different nutrients, water scarcity and inefficient irrigation management, lack of attention to plant protection, harsh weather conditions caused by climate change and untimely tillage operations due to limited use of farm machinery by most of the small farmers.

Lack of precision technologies: It has been observed that with proper adjustments in the timing, placement and type of nitrogenous and phosphorus fertilisers, the yield of cereals such as wheat, rice and maize crops can be increased, while reducing the quantity of fertilisers by 13-29 percent [7]. Thus, in the absence of precision technologies which are not followed by most farmers, it is difficult to increase crop yields.

Scarcity of water resources: India has already been facing serious stress of its water resources which is worsening. The groundwater level is falling at an alarming rate in large parts of the country and over 600 million people are already facing high to extreme water stress. The agriculture sector consumes over 80 percent of the total water used in the country and yet about 50 percent cropping area is under rain-fed conditions. In areas covered under irrigation, water for irrigation is being used in excess through flood irrigation. Such wastage of water along with the use of unlined open channels for water distribution has resulted in poor water use efficiency, while turning fertile farm lands into saline wastelands [8].

Environmental concerns: Post-Green Revolution era in agriculture has adequately revealed that most of the crops do not respond to higher doses of fertilisers beyond certain levels. As a result, excessive use of agrochemicals to increase crop yields will increase the cost of production, while causing environmental pollution. Hence, other approaches for the efficient use of nutrients must be tried to boost the yield while ensuring chemical residue-free food production [9]. Prolonged rains caused by climate change increase the incidences of pests and diseases, while prolonged droughts suppress plant growth, resulting in low crop yields.

Inadequate infrastructure: India has still not developed adequate infrastructure to transfer appropriate technologies and manage post-harvest operations, including market linkage. In the absence of efficient storage, transportation, processing and marketing facilities, farmers are unable to realise higher returns and this has been discouraging farmers to invest in new technologies and inputs for increasing crop yields.

Lack of Interest in Agriculture: Agriculture in India has been engaging 42.3 percent of the total workforce and contributing only 16.5 percent of wealth to the National Gross Domestic Products (GDP). In the absence of diversification and value addition, the agricultural sector is unable to make a higher contribution to National GDP and the workforce engaged in agriculture is unable to generate higher wages, as compared to other sectors. Crop failures, uncertain markets, lack of communication and transportation and poor living conditions in rural areas have been discouraging the younger generations to continue their engagement in agriculture. As a result of lower income from agriculture, over 176 million people are living under poverty [10].

It is therefore, necessary to address the above problems both at macro and micro levels, while ensuring lower cost of production, environmental sustainability and remunerative engagement of the farm labour force in agriculture.

2. STRATEGY FOR SUSTAINABLE AGRICULTURAL PRODUCTION

While increasing agricultural production, it is also necessary to significantly increase the income of farmers to sustain their interest in agriculture. This can be achieved through improvement in crop productivity, increase in cropping intensity, improvement in livestock productivity, resource use efficiency to reduce the cost of production, diversification towards high-value crops and improvement in real prices received by farmers [11]. The problems of lower returns from agriculture have to be solved through the introduction of suitable technologies and making necessary investments. While many proven technologies are already available, huge investments have to be made in agricultural research and demand-driven agricultural logistics systems for post-production operations such as produce aggregation, transportation, warehousing, etc. Simultaneously, the promotion of crop-based value chains should be developed to integrate into a sector-wide supply chain. A farmer-centric National Agricultural Marketing System should be developed by restructuring the primary retail and wholesale agriculture markets and networking with online platforms. The development of a marketing intelligence system for demand-led decision-making and a demand and supply forecasting system for agricultural products can help to realise higher price.

Table 1. Food demand and supply estimates in India in 2032-33

Commodities	Estimated Demand (Million Tons)	Estimated Supply (Million Tons)	Net Surplus /Loss (Million Tons)
Rice	120.84	151.6	+ 30.76
Wheat	113.46	138.8	+ 25.34
Coarse Cereals	67.48	61.7	- 5.78
Total Cereals	301.78	352.3	+ 50.52
Pulses	35.23	33.9	- 1.33
Food grains	337.01	386.2	+ 49.19
Oilseeds	99.59	59.9	- 39.69
Fruits	203.55	202.6	- 0.95
Vegetables	360.77	362.8	+ 2.03
Milk and products	292.15	329.7	+ 37.55

Source: NITI Aayog (2018)

At the micro level, major problems to be addressed to ensure sustainable production are residue-free production of farm produce at low cost with climate resilient cropping system, without causing environmental pollution. This will reduce the risk of crop failures, while enhancing income. Organic farming is considered to be an important practice to prevent soil and water pollution. Fortunately, several cutting-edge technologies are now available for boosting agricultural production. The promising among them are nanotechnology for crop nutrition and protection, gene editing for breeding new crop varieties, sensor-based irrigation, satellite imaging to monitor the crop health, vertical farming, robot farmworkers, etc. Nanotechnology is an emerging cutting-edge technology for efficient crop nutrition management and crop protection, which has not been exploited so far in India.

2.1 Nanotechnology for Profitable Agriculture and Improving Safe Food Production

Nanotechnology is the use of various materials with particle sizes varying from 10 to 1,000 nm (nanometre). At the nano scale, matter shows extraordinary properties such as wider surface area, higher cation exchange capacity, ion adsorption and many other functions. This technology has gained momentum in the last two decades for improving the efficiency of plant nutrients through nano-formulations of fertilisers, increasing crop yields, surveillance and control of pests and diseases, preservation of food and food additives, removal of contaminants from soil and water, improving the shelf-life of vegetables and flowers, etc. [12].

The major benefit of nanotechnology is a significant reduction in the bulk use of chemical inputs which are very expensive and harmful to human health, while polluting agricultural lands and ground water. As the nutrient transport in soil-plant systems takes place through ion exchange (ions such as NH_{4+} , $H2PO_{4-}$, Zn^{2+} etc.), nanotechnology helps to supply the required nutrients in such plant-available forms in the soil and facilitates the release of nutrients as per the demand by plants. Nano-nutrients can be used in aqueous suspension and hydrogel forms, and this technology is hazard-free and convenient for adoption [13]. Commercial production of nano-fertilisers containing zinc, silica, titanium dioxide, iron, etc. has already been started and is being used as nutrients, plant growth regulators and immunity enhancers. These compounds also serve as agents for maintaining soil fertility, boosting plant growth and monitoring contamination in soil and water. Nano-encapsulated pesticides have demonstrated effective control of pests with very small doses, indicating the scope for developing non-toxic pesticides which can reduce the harmful impacts of agrochemicals on the ecosystem [14].

In traditional farming systems, large doses of chemical fertilisers were being applied to the soil but most of these were not easily available to the plants. With the introduction of nano fertilisers, there will be a paradigm shift in agriculture to grow safe food at a low cost, without polluting the ecosystem. Nano-fertilisers are available in powder, capsules and emulsions. These fertilisers provide suitable nutrients for increasing plant growth via foliar and soil applications [15].

2.2 Benefits of Nano Carbon for Agriculture

Carbon is an interesting element having the ability to form a wide range of structures, with different properties, including hard diamond and soft graphite. Carbon atoms being smaller in size with a special electron structure, can remain in different molecular forms, known as allotropes, possessing different properties. During the last 2-3 decades, several new forms of carbon have been identified, including the discovery of new low-dimensional nano-carbon forms. Carbon materials, which contain particles of dimensions between 1 and 1000 nm in size are known as nano-carbons and these are classified according to their geometrical structures such as carbon nanotubes (CNTs), fullerenes and graphene. Tube-shaped nanoparticles are called carbon nanotubes, horn-shaped particles are known as nano-horns and sphere or ellipsoid-shaped particles are termed fullerenes. In fullerenes, carbon atoms are on a spherical surface. Fullerene C60 is the most common fullerene, consisting of 60 carbon atoms, with a diameter of 0.7 nm [16]. Carbon nanotubes (CNTs) are cylindrical structures, consisting of rolled graphene sheets, varying in length, diameter, chirality (symmetry of the rolled graphite sheet) and the number of layers. CNTs are classified into two main groups, based on their structure, namely single-walled nanotubes (SWCNTs) and multi-walled nanotubes (MWCNTs). Depending on the structure, CNTs gain special properties of rigidity, strength and elasticity. Graphene is a two-dimensional nano-carbon, formed by a single layer of carbon atoms, which represents a structural element of some other carbon such as graphite, carbon nanotubes and fullerenes. The carbon nano material family also includes carbon dots (CDs) and graphene oxide (GO), apart from carbon nanotubes, carbon fullerenes, graphene, nanohorns and carbon nanofibres. These materials exhibit unique features as promising materials, with a wide range of applications [16]. Although these carbon-based nanoparticles naturally existed in very minute quantities, technologies have now been developed to easily synthesise them as required for different purposes.

Nano-carbon containing materials have various commercial applications. Carbon nanotubes have the capacity to adsorb cyanobacterial toxins, lead, copper, antibiotics, herbicides as well as nitrogen and phosphorus in wastewater. CNMs are very effective in their functioning, because of their vast surface area, mechanical and thermal stability, high chemical affinity for aromatic compounds and potential antibacterial properties. CNMs also have some antimicrobial properties. However, their mode of action is still not clear.

Nanocarbon-based technology has good potential to increase production and profitability in agriculture. The following are the areas where modern nanotechnology can support agriculture.

1. As plant growth promoters, nanocarbon can increase crop productivity;
2. Nano-fertilisers can release the nutrients slowly as and when needed by plants and reduce the volume of normal chemical fertilisers, thereby bringing down environmental pollution and the cost of production;
3. Nanomaterial-based plant protection products are effective as pesticides and herbicides;
4. Nanocarbon-based materials induce tolerance to abiotic stress in plants;
5. Nanotechnologies are ideal for promoting precision farming.

It has been reported that CNMs have a major contribution of about 40 percent of nanotechnology to improve agricultural production [17]. In most cases, when amended mineral and organic fertilisers were applied with nano-carbon, the latter acted as fertiliser synergists for improving plant nutrient availability, reducing nutrient losses and stimulating plant growth. In a way, nanocarbon efficiently regulates the delivery of nutrients in the soil. It has been observed that fertilisers encapsulated by graphene oxide films can facilitate slow release [18]. Such encapsulation of major nutrients is feasible for commercial application. Thus, the studies conducted so far, have confirmed the benefits of nanocarbon for agricultural production and environmental protection, as presented in Table 2 [16].

Nano-sensors can be used to monitor crop maturity and health, detect residues of fertilisers, pesticides and moisture in the soil. Thus, CNM-based nano-sensors are good tools for monitoring pesticide residues and heavy metal detection [19].

Table 2. Benefits of Nanocarbon for Agriculture and Environmental Protection.

Scope	Benefits
Increase in Productivity	Soil Improvement, Nutrient supply, Growth stimulation
Nano-encapsulation	Slow release of nutrients, pesticides, fungicides and herbicides; Triggered release of capsules
Plant Protection	As active constituents of pesticides, fungicides and herbicides
Antimicrobial Agents	For water disinfection, anti-microbial surface coating
Environmental Sensing	Concentration of contaminants, sensing of soil and crop health
Sorbents	Water purification, soil remediation, pollutant removal
Nano-biotechnology	Target Genetic engineering, biomolecule delivery
Renewable energy	Solar energy collection, Energy storage

2.3 Crop-wise studies on the effect of Nanocarbon materials in Agriculture

Many crop-based studies were carried out to observe the effect of nanocarbon on plant growth with a view to tap its potential for giving a boost to agricultural production.

1. **Effect on Seed Germination:** Depending on the concentration of water soluble nanocarbon materials, different species of plants have been responding differently. Chickpea seeds treated with water-soluble multi-walled carbon nanotubes (MWCNT), had better germination and a higher rate of growth, but the rate of germination was low in corn and rye seeds [20]. MWCNTs did not affect on the germination of castor seeds, but the root length and wet weight of the plant were better in the seedling stage [21]. In other studies, the positive influence of MWCNTs was reported on seed germination and plant growth of radish, rapeseed, rye, lettuce, maize and cucumber [22]. Improved seed germination and a higher rate of seedling growth were reported by different scientists in other crops such as tomato, BT cotton, mustard, black gram, rice, etc. [23].

2. **Improvement in Plant Growth and Fruiting:** Treatment of MWCNT improved biomass, flowering and fruit yield of bitter gourd and tomato crops. Improved growth and gain yields were also recorded in many crops such as rice, maize, beans, wheat, mustard, etc. Most of the studies conducted in India have also confirmed the potential for using nanocarbon as organic fertiliser for promoting plant growth and increasing crop yields [24]. Apart from serving as a nutrient, carbon nanotubes can serve as a nutrient carrier for macro and microelements and also for slow-release nutrients [25].

3. **Plant Protection:** While some of the nanocarbon materials have antimicrobial and pesticide properties, many of them can also serve as transfer agents to facilitate easy absorption of the fungicidal molecules by the plant roots. Thus, the application of nano materials can improve plant growth, induce tolerance to pests and diseases and ensure higher production [23].

3. ADAPTATION OF NANOTECHNOLOGY BY FARMERS IN INDIA

Fortunately the farmers in many states of India have started using products containing nano-materials as nutrients and growth stimulants during the last 2-3 years. Presently macro and micro nutrients such as Nano-nitrogen, Nano-phosphorous, Nano-NPK (19:19:19), Nano-zinc, Nano-copper, Nano mixture of micro-nutrients (Zn + Mn + Cu + Fe + Mg) are produced and marketed in India by different manufacturers, which are found to be beneficial to increase the crop yield by correcting the nutritional deficiency, balancing of nutrients, strengthening the structure and functioning of cell walls. Generally these are sprayed on crops at very low concentrations, which helps to increase crop growth, crop yield and quality. These nano-materials enhance the absorption of nutrients by crops, and enable them to develop resistance to environmental and biological stress [26].

There are several nano-growth stimulants with a combination of micro-nutrients and other materials having growth promotion and bactericidal or pesticide properties, which have very favourable impact on seed germination, plant growth and crop yields. Some of the products which have gained popularity in recent years are listed below.

3.1 Soil Guard

This product is based on Phase Transfer Catalysis technology (PTC). The ingredients include activated nano-carbon (N300), nano-trace elements, humic acid, extracts of Aloe vera and *Moringa oleifera*, leaves and *Pongamia pinnata* seeds, along with a phase transfer catalyst and a sustained release catalyst. Soil Guard when applied as a soil drench, the activated nano carbon helps to develop a good root system, alleviates biotic and abiotic stresses, and facilitates better absorption of nutrients. The botanical extracts help to boost immunity and suppress the soil-borne pests, resulting in increased crop yield by 40% to 50%. The most significant benefits recorded were in the case of cotton, groundnut, wheat, paddy, soya bean, sun flower, turmeric, onion, potato, sugarcane, seasonal vegetables and different fruit crops.

3.2 Sneha Sampoorna

It is an organic source of nutrients for plants, while improving soil productivity. The major ingredients of this product are activated nano-carbon (N300), a phase transfer catalyst, botanical extract (*Sargassum wightii* and *Saccharum officinarum*) which is rich in potash, fulvic acid, humic acid, trace elements and beneficial bacteria [27]. Drenching of this product is recommended for fruit and vegetable crops to induce flower buds, reduce flower and fruit drops, and induce early tillering in sugarcane.

3.3 Bio-Shield

It contains activated nano-carbon (N300), enriched with fulvic acid, botanical extracts and nano trace elements, which promote photosynthesis, absorption of nutrients, repel foliar insects and accelerate plant growth, resulting in higher yield. Bio-shield has also been recommended to improve the size, colour, texture, appearance and shelf life of fruits and vegetables. Foliar spraying of Bio-shield at the flowering stage, followed by 2-3 additional sprays at 20 days intervals is reported to be most beneficial for horticultural crops.

During the year 2021-22, the producer of the above three products, Snehasrushti Pvt. Ltd. recommended using all the above three products simultaneously on different crops in Gujarat and Maharashtra states. Drenching of Soil-Guard and Sneha Sampoorna followed by foliar spray of Bio-Shield in 3.6 ha cotton fields (Bollgard variety of BT cotton), owned by nine farmers in Dhandhuka Tahashil in Botad district in Gujarat resulted in a bumper harvest of 4500 kg cotton/ha, as against the yield of 2125 kg/ha in control fields (Personal communication with Ashish Patel, Head of Samratha Agro FPO, Ahmedabad). Similar results were recorded in Wardha and Prabhani districts of Maharashtra. Application of Soil Guard + Sneha Sampoorna + Bio Shield on Kranti-24 variety of groundnut crop in Modasa Tahashil of Himmatnagar district in Gujarat yielded 3350 kg groundnut/ha as compared to the yield of 2500 kg/ha in control fields. Application of these products for turmeric crops in Botad district in Gujarat and Prabhani district in Maharashtra yielded 6750 kg turmeric/ha as compared to the yield of 3000 kg/ha in control fields. Treatment of these three products on sugarcane crops in Mandavgan block of Ahmednagar in Maharashtra enabled the farmers to harvest 110 tons of sugarcane per ha as compared to 45 – 50 tons/ha in control fields (Personal communication with farmers). Thus the nano-carbon-based growth stimulants and nutrients have made a very significant impact in the field.

Many of the manufacturers of nano-products have now started offering crop and location-specific products, based on local needs. This technology has immediate benefits, at a significantly low cost to produce safe and residue-free farm produce. Nano-technology also has the potential to promote climate resilient agriculture and to produce residue-free safe food in the future.

4. CONCLUSION

Nano technology is the new cutting-edge technology, which has demonstrated its benefits for increasing agricultural production without increasing the use of expensive agro-chemicals. Among many nano-products, nanocarbon materials have been found to have multiple uses as nutrients, soil moisture retainers, growth stimulants, pesticides and fungicides. However, the potential of nanotechnology has yet to be fully exploited in developing countries. Being less expensive and hazard-free technology, Indian farmers can take advantage of nanotechnology to boost their agricultural production and ensure food security in the near future.

DISCLAIMER

The author is an independent Agricultural specialist, not affiliated with any manufacturers of agro-chemicals and nano products. The yield data included in this paper were directly collected from the farmers. The products listed in the paper are only indicative of the range of products available in the Indian market.

COMPETING INTERESTS

Author has declared that no competing interests exist.

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