Research & Reviews in Biotechnology & Biosciences
Website: www.biotechjournal.in
Volume-8, Issue No: 1, Year: 2021 (January-June)
DOI: http://doi.org/10.5281/zenodo.5118402

ISSN No: 2321-8681
Review Paper
PP: 105-117
Peer Reviewed Journal

Applications of Nanotechnology in Precision Agriculture: A review

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Article History

Received: 15/04/2021
Accepted: 08/06/2021

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ABSTRACT

Agriculture has been by far the best of the revolution mankind has ever witnessed. 21st century faced a population explosion due to better health services, better nourishment, etc. To meet the requirements of the burgeoning population, farmers commenced using techniques (like fertilizer, pesticide, herbicide, etc) which caused the yield to grow faster compared to the original farming techniques. Perhaps, this proved to be costly and harmful to the environment in the long run. This brought about an urgent need to search for alternate techniques that are eco-friendly and cost-effective at the same time. Nanotechnology was found to be the most plausible alternative in this case. The unique characteristics of nanotechnology like- ultra-small size, high surface area, targeted delivery, high catalytic reactivity, slow and controlled release of molecules of interest, etc cater to provide novel and eco-friendly solutions to the problems. Nanofertilizers, Nanosensors, Nanopesticides, Nanomaterials, etc increase the efficiency of farming. With the advent of IoT i.e. Internet of things, precision agriculture came into being. Precision agriculture combines the Internet, satellite imaging, remote sensing, robots, drones (UAV), GPS, multi-spectral imaging, etc into agricultural practices. Nevertheless, the use of nanomaterials in farming still needs more investigations and research. The risks need to analyzed before application in the fields.

Keywords- Nanotechnology, Precision Farming/Agriculture, Nanopesticides, Nanosensors, Nanofertilizers, Drones.

INTRODUCTION

It is estimated that life on the planet Earth first appeared 3.5 billion years ago [1]. Life today has originated from a single common ancestor named LUCA (Last Universal Common Ancestor) [2]. These events marked the onset of the RNA world theory [3] and the Endosymbiosis theory for the origin of eukaryotic cells [4]. The transition from chemical evolution to biological evolution took place [5]. All animal life

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appeared during the Cambrian explosion, which occurred 540 million years ago [6]. Humans evolved 2.5 million years ago and started gathering plants, hunting animals, foraging into the wild for food, this was their lifestyle back then [7]. The transition to agriculture took place nearly 10,000 years ago [8] where humans sowed seeds, waited for the harvest and reared animals, that's where the Agricultural revolution i.e. Neolithic revolution set in (Neolithic means New Stone age) [9]. Humans started living in villages by forming communities, this was confirmed by the ruins found in Mesopotamia [10]. Since then the population is ever increasing. By the Bronze age population has reached 50 million, 1 billion by the middle of the eighteenth century [11]. According to FAO (Food and Agriculture Organization), 7.7 billion is the present population of the world, it is expected to reach 9.8 billion by the year 2050 [11]. According to Thomas Malthus and his theory of population published in the book "An Essay on Principle of

population", the human population grows geometrically and food resources arithmetically (Figure 1.) Thus, creating a shortage in food supply [12] [13].

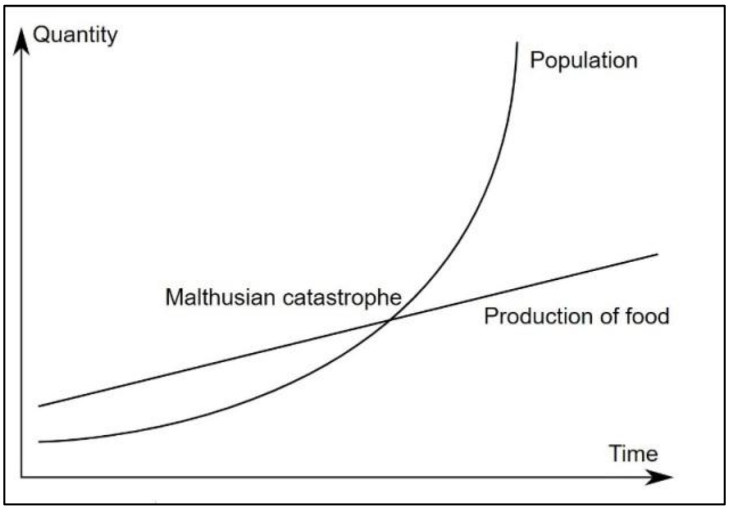

Figure 1- Malthusian curve: Population grows exponentially and food resources linearly ©commons.wikimedia.org.

It is said that hunger and poverty decreased by 1990s [11], still 815 million people were undernourished and this number can reach 2 billion by 2050 [11] [14]. Agricultural yield increase has decreased since the 1960s' [11] (Figure 2.)

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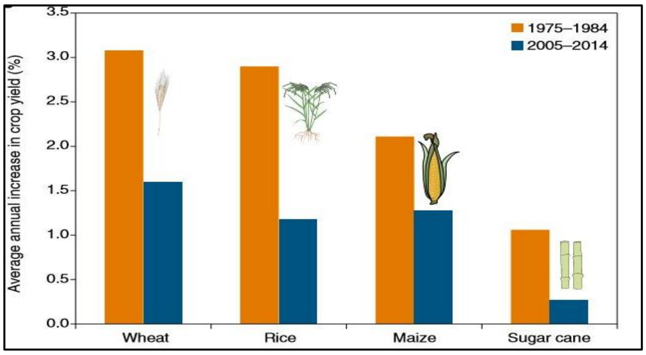

Figure 2- Comparison between Average annual yield increase in crop yield (1975- 1984 & 2005-2014) ©Kah M., et al 2019.

As the yield decreased, farmers started using fertilizer, pesticides, herbicides to increase the yield. Then overusing of fertilizers and pesticides became a problem, it led to the loss of soil fertility, nutrient loss, eutrophication, failed target delivery to the desired part of the plant (10-75% pesticides do not reach the required location) [11]. Some pests became resistant to pesticides [15]. To be at par with the burgeoning and exploding population, new eco-friendly and sustainable methods need to be employed and practiced at large scale to increase the yield of the crops without causing much harm to the environment. One such method is Precision agriculture or farming along with Nanotechnology [16].

Nanoscience and Nanotechnologies exhibit great capacity and have a huge prospective to bring about changes and variation in the field of - Medicine, Electronics, Agriculture, Computers, Material Sciences, Biotechnology, Industries, Environmental Science, Photonics, etc. Nanoscience and Nanotechnology is the science that involves creating ultra-small particles (between the Nanoscale of 1 to 100nm) with exceptional and novel properties. These properties **include -** high surface area, better catalytic reactivity, high mobility [17]. These are the properties that set aside Nanotechnology from other conventional methods. European Commission has recognized Nanotechnology as one of its six "Key Enabling Technologies" which is responsible for a greener and more sustainable environment [18]. Research in Nanotechnology and Nanoscience began at the end of the 20th century and reached its peak in the 21st century [19]. Agri-nanotechniques and Phytonanotechnology is the term designated to the use of Nanotechnology in the field of Plant Science, Agriculture [20] [21].

Precision Farming

Precision agriculture/farming is the sum total of all the activities that make farming more accurate, with maximum outputs and least wastage. It also minimizes the use of pesticides and fertilizers. It is basically site-specific crop management. Farmers use Internet, GPS (Global Positioning System), sensors, drones, robots, software, automated vehicles, etc. Site-specific delivery and controlled release of macromolecules, fertilizers, herbicides and pesticides are the features of precision farming. Also, the

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environmental stresses, plant diseases can be monitored by field – sensing systems. "Internet of Nano Things" (IoNT) which is the combination of nano devices and internet are being used in Precision agriculture to enhance the productivity of the field [17]. Temporal, spatial, and individual data from the field and tested experiments are combined with information that is accessible to the farmers. A detailed report is generated, which includes the levels of salinity, pH, fertilizer usage, water usage, etc. This report helps the farmers to monitor the field more efficiently [22].

DISCUSSION

Drones and Precision Agriculture-

Precision agriculture is also known as Satellite farming. The goal of Precision agriculture is to create an information system/database where the data of the whole farm can be accessed. It makes use of many technologies developed in the 21st century, here are a few of them - GPS (Global positioning system), GNSS (Global Navigation System), Phyto geomorphological approach, Satellite imaging, Unmanned Aerial Vehicles, (UAV) viz. Drones, Robots, Sensors, Remote sensing, Smartphone applications, etc [24] [25] [26] [27].

Drones make use of mostly all the above technologies; Drones are unmanned aerial vehicles (UAV). They are the mini versions of an aircraft/helicopter but pilotless. They are operated using radio-based remote control from a distance. They are also fitted with sensors and cameras for surveillance purposes. They make use of aerodynamic airlift to work. They differ by the ranges (short, medium and long) they operate in. Previously drones were used by the military for patrolling the borders, spying over enemy countries, etc. The advantage of using UAVs' are cost-effective, versatile, easy to handle and small in size. The drawbacks include - slower compared to manned aircraft, can be detected by radars, data connectivity issues [23].

Based on this concept agricultural drones are developed, which help farmers in many aspects. It enables farmers to view their farmland from the top and create a bird's eye view, this view helps detect irrigation problems, pest or fungal infections and enables to spray pesticides and fertilizers. This is possible via the sensors and digital cameras installed onto the drones. It makes use of false render imaging and multi-spectral imaging. The images are further processed to create Orthophotos (geometrically corrected aerial photograph) and NDVI Maps Normalized Difference Vegetation Index indicate the crop health, [28] [29]. False render imaging is color developed other than true color (not the color you normally see). Multi spectral image consist of various channels or band belonging to a specific wavelength. In Figure 3, The top image - vegetation density displays variation in color, dark blues and green show lush vegetation and reds show bare soil areas. The middle image - Water deficit- greens and blues show wet soil whereas reds are dry soil. The last one on the bottom, Crop stress- Fields 119 and 120 are under stress with red and yellow pixels. The reason behind this is, they weren't watered on that specific day [30].

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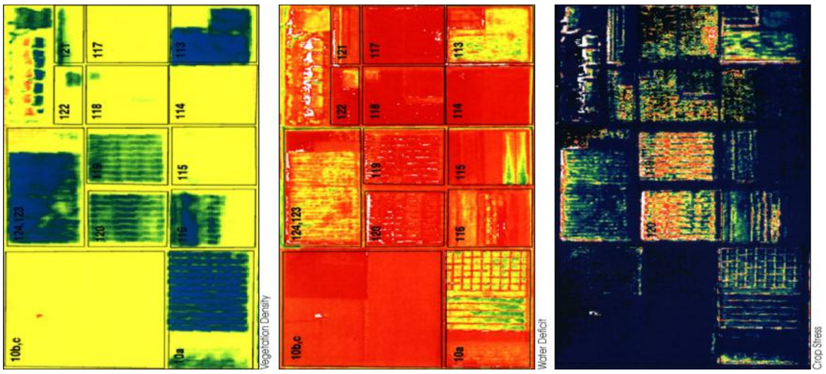

Figure 3- False-color images showing a remote sensing application. Susan Moran, Landsat 7 Science Team and USDA Agricultural Research Service (U.S Government work)

Nanotechnology is being used in UAV, drones. Nanotechnology helps to reduce the cost of production, reduce the weight of the drone, increased performance, durability and easier flight. An Australian start-up company, Nano nouvelle manufactures drones with nanostructured Lithium-ion batteries. It decreases the weight of the drone, boosts battery life which in turn helps travel longer distances [31] [32] [33]. Drones (UAV) are being used in the palm oil plantations in Malaysia for palm tree census, yield estimation and monitoring productivity (Figure 4) [58].

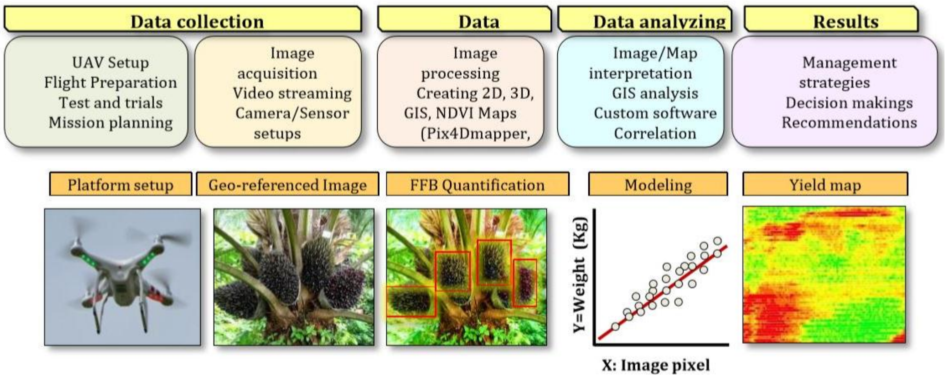

Figure 4- Illustration of a yield monitoring system for Oil Palm. ©Redmond R., et al 2017.

Tata Consultancy Services (TCS) makes use of the drones in agriculture to monitor crop health, irrigation and soil health, further it uses cloud-based analysis for early prediction of water stress, nutrient stress and pest infestations. Crop health analysis is done using multi-spectral imaging (Figure 5).

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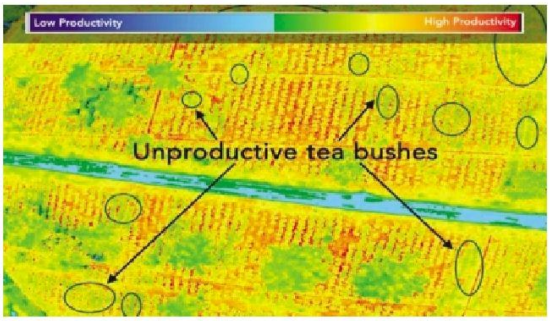

Figure 5- Tea plantation health mapping by Multi-spectral imaging ©TCS.

PRECISION FARMING AND NANOFERTILIZERS-

Chemical fertilizers no doubt increase the yield of crops, but at the same time, there is a lot of wastage of fertilizer by volatilization and leaching (lack of target-specific delivery). 50-70% Nitrogen applied to the soil using conventional methods is lost due to leaching by forming water-soluble nitrates, emission of gaseous ammonia, etc (DeRosa, 2010) [59]. Nanoformulations of porous nanomaterials like Zeolite, Chitosan, Clay reduce the loss of nitrogen [38]. This loss of fertilizer affects the environment negatively, pollutes the underground water table, kills the aquatic life and in some cases leads to Eutrophication [14]. Nanofertilizers are nanostructured formulations designed for easy uptake and slow release. Nanoparticles are made of Fe, Mn, Zn, Cu, Mo, Ti, Carbon nanotubes, gold nanorods, Metal oxides (ZnO, Al_2O_3, TiO_2, FeO), Core-shell nanoparticles, Phosphorus (P), Nitrogen (N), Potassium (K), Magnesium (Mg), Sulphur (S), Calcium (Ca), etc [34] [35]. The high surface area characteristic of Nanoparticles reduces the amount of fertilizer used and increases efficiency. The sieve-like cell wall structures of the plant take up the nanoparticles and further the pathway remains unknown [36]. Calcium and phosphate hydroxyapatite nanoparticles were incorporated in the *Glycine max* plant. It was found that the yield increases 20-30% (Figure 5) [37]

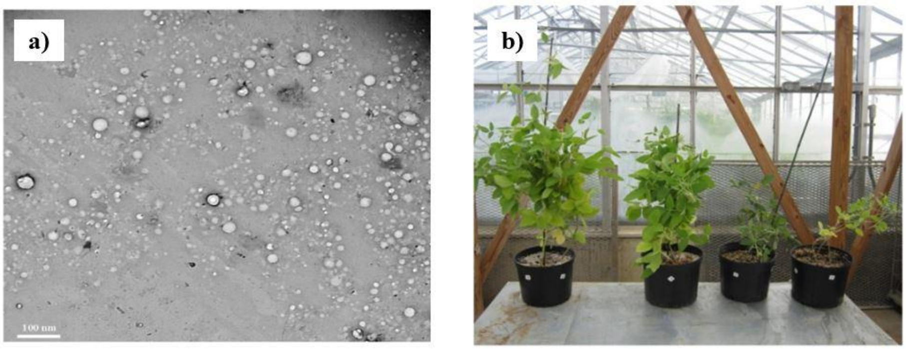

Figure 6- Growth of Soybean plant using nanofertilizer under different conditions. a) Hydroxyapatite nanoparticles, b) L-R treated with fertilizer and hydroxyapatite, treated with fertilizer and regular

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Phosphate (P) fertilizer, treated with fertilizer without P, treated with tap water only. ©Liu., et al 2015.

Nanofertilizers are prepared by encapsulation. Nanoparticles are encapsulated within engineered and programmed capsules. The capsules are either made of a nanoporous material coating or thin film of polymers. The capsule breaks open under certain circumstances like pH, Moisture, etc. It also depends upon the speed of release - Slow or Quick [17] (Figure 6). Nanofertilizers are generally required in trace amounts <=100ppm [35].

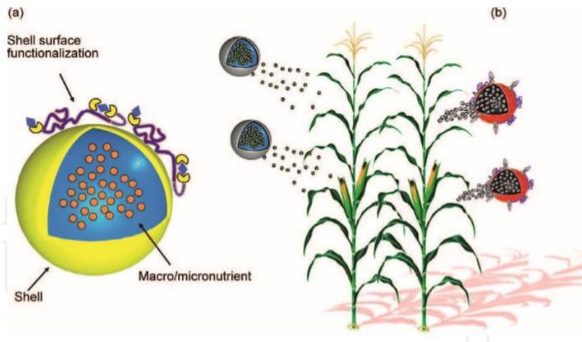

Figure 7- (a) Model of nanocapsule. (b)Opening of nanocapsules. © Luca Marchiol 2018.

Nanoparticles made of Carbon Nanotubes (CNT) were used as nanofertilizer for Tomato plants. Using different concentrations of CNTs, it was found that seed germination rate and growth was higher in the plant with CNTs rather than the normal ones [39] [40]. The effect of CNTs on the environment needs further investigation. Indian Farmers Fertilisers Cooperative Limited (IFFCO), founded in 1967 has launched on-field trials for nanofertilizers [40] [41]. More studies have to be done on the impact of Nanofertilizers on plants, environment, and ecosystem keeping in mind the commercial value.

Nanopesticides-

The large surface area of nanoparticles is an advantage to control the pests in the field. The large surface area comes in contact with more pests while only small amount of pesticide is being used. Pesticides are usually encapsulated to facilitate target delivery, specificity and increase efficacy [54]. Smart field systems are installed on the farms i.e. wireless sensors connected to satellite and connected to the computer/Laptop/Mobile. It helps farmers to detect crop infestations, regulate the amount of nanopesticide being supplied and observe the statistics, etc.

A company called PhilRice i.e. Philippine Rice Research Institute is conducting trials on rice cultivation by drones. They found out using drones can significantly reduce the usage of pesticides by 90% compared to the conventional spraying method of pesticides over the field [52] [53]. Imidacloprid (IMI) is a pesticide which kills insects. IMI treated plants showed 100% mortality after 142 hours, but Nano/SDS/Ag/TiO_2 was more lethal on the pests and proved out to be eco-friendly by being photodegradable [54]. Nanopesticides are made using carrier

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systems like- Chitosan, Alginate, Silica, Polyethylene glycol, etc. Nanosilica gets absorbed in the cuticle of the insects and causes death [56]. Nanopesticides made of ZnO (inorganic) showed effective growth control against *Alternaria alternata, F. oxysporum, Fusarium graminearum*, etc [56]. Nano-Cu was more effective against *Phytopthora infestans* than the non-nano Cu pesticides [57]. Further, extensive research has to carried out to know the potential of nanoparticles as pesticides in depth to attain clarity.

NANOSENSORS

A sensor is a device, transducer or a machine wherein a physical measure or quantity is converted into signals which are then processed and read by an instrument or observed digitally. Most of the times, sensors are paired up with electronics. Nanosensors are nanoscale (1-100nm) sensors. Nanosensors are quite sensitive and specific. Large surface area of nanoparticles gives nanosensors an edge over other conventional sensors. Nanosensors are comparatively cost effective and portable [42]. Nanosensors follow a rudimentary working procedure i.e. Analyte binds to the sensor, transducer converts the signal into electric impulses, which are then detected and displayed. Nanosensors are fabricated by top down lithography, molecular self-assembly, bottom down approaches, etc [43]. There are different types of nanosensors, to name a few- FRET nanosensors, Surface-enhanced Raman scattering nanosensors, Piezoelectric nanosensors [44], Optical nanosensors, Electrochemical nanosensors, etc [43].

Nanosensors can be classified as –

- Nanoprobes.
- Nanoparticle based nanosensor.
- Nanostructured nanosensors.
- Nanowire nanosenors.
- Nanosystems: cantilevers, NEMS (Nano electrochemical systems) [43].

Researchers from the Claussen lab at Iowa State University, have developed a nanosensor that detects microscopic contaminants in water. It detects organophosphates which are 40 times smaller [45]. Researchers from MIT have created a sensor using carbon nanotubes which can detect water shortage, the nanosensor is printed upon the leaves. When the stomata are closed the electric current passes through the nanotubes and the current can be measured and while the stomata are open no current flows through the circuit [46]. When a plant is stressed/injured it releases Hydrogen peroxide (H_2O_2) can be sensed by the embedded nanosensor made of Carbon nanotubes. A smartphone alert helps farmers know which plant is stressed/injured [47] [48].

Explosives can be detected by a sensor embedded in a Spinach leaf. When there are explosive materials/pollutants nearby, they are sucked into the roots and transferred to the leaves, the nanosensor further emits signals which are detected by an Infrared camera. The camera is connected to a computer which generates email alerts [49] [50].

Singapore's DiSTAP (Disruptive and Sustainable Technologies for Agricultural Precision) aims at developing nanosensors and new tools for the betterment of precision agriculture [51]. Still, more research on the use and efficacy of nanosensors has to carried out.

CONCLUSION-

Nanotechnology has plenty of applications in precision agriculture like nanopesticides, nanofertilizers, nanosensors, nanoparticle enabled target delivery, satellite farming, etc. The major challenge which lies ahead is a better understanding of the fate and environmental impacts of using Nanotechnology. Interdisciplinary research among different areas and field of expertise is required to create a full- proof, standardized, cost-effective, and eco-friendly nanomaterials. Different plants, agricultural fields, and farmland would demand a completely different set of conditions so by experiments and thorough research their individual needs can be fulfilled. Precision agriculture is a splendid discovery, it helps farmers access their farms remotely, monitor crops, detect water stress, nutrient availability, soil fertility, pest infestations, etc but it has its own limitations. With the combined action of research and application of nanomaterials in the field, we can achieve greater insights. Also, brief knowledge would aid the large-scale production and implementation of nano-based strategies and nanomaterials.

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FIGURE REFERENCES

Figure1- Malthusian curve: Population grows exponentially and food resources linearly ©commons.wikimedia.org. Source-commons.wikimedia.org

Figure 2- Comparison between Average annual yield increase in crop yield (1975- 1984 & 2005-2014) ©Kah M., et al 2019. Source- Kah, M., Tufenkji, N. & White, J.C. Nano-enabled strategies to enhance crop nutrition and protection. Nat. Nanotechnol. **14,** 532–540 (2019). https://doi.org/10.1038/s41565-019-0439-5

Figure 3- False-color images showing a remote sensing application. Susan Moran, Landsat 7 Science Team and USDA Agricultural Research Service (U.S Government work). Source- Feature article on earthobservatory.nasa.gov Susan Moran, Landsat 7 Science Team and USDA Agricultural Research Service (U.S Government work)

Figure 4- Illustration of a yield monitoring system for Oil Palm [58] ©Redmond R., et al 2017. Source- Redmond R. Shamshiri Controller Design for an Osprey Drone to Support Precision Agriculture Research in Oil Palm Plantations an ASABE Meeting Presentation DOI: https://doi.org/10.13031/aim.201700014

Figure 7- Tea plantation health mapping by Multi-spectral imaging ©TCS.

Figure 6- Liu, R., Lal, R. Synthetic apatite nanoparticles as a phosphorus fertilizer for soybean (Glycine max). Sci Rep **4,** 5686 (2015). https://doi.org/10.1038/srep05686.

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