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# 1. Nano DAP: An Implementation of Nano Science and Technology in Agriculture to Secure a Better Fertilizer Utilization and Sustainable Intensification in a Smart Way

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***Abstract:***

*Nano-fertilizers (NFs), developed through nanotechnology, revolutionize traditional fertilizers by enhancing efficiency and mitigating environmental impacts. These advanced fertilizers, created using nano-sized granules and nano-coating materials, reduce nutrient loss, decrease application frequency, and sustainably provide nutrients, thereby improving Fertilizer Use Efficiency (FUE). At the nanoscale, materials exhibit unique properties that optimize nutrient immobilization, release, and uptake while minimizing leaching and eutrophication. Nanotechnology in agriculture also aids in disease detection, targeted treatment, nutrient absorption enhancement, and environmental stress tolerance, promoting sustainable intensification. Nano-Diammonium Phosphate (Nano-DAP) significantly improves crop growth by enhancing nutrient uptake and reducing losses. Studies on crops like cabbage and pigeon pea show that Nano-DAP increases plant spread, leaf area, and nutrient concentrations, while in wheat, Nano-phosphorus (Nano-P) fertilizers boost growth parameters and yield. The gradual nutrient release from nano-fertilizers aligns with plant demand, reducing application frequency and environmental impact. As global phosphorus demand rises, nano-fertilizers offer a sustainable solution, addressing the inefficiencies of traditional fertilizers and protecting environmental health. Despite the potential benefits, ethical, environmental, and safety concerns necessitate responsible development and regulatory frameworks. Overall, the integration of nanotechnology into agriculture through nano-fertilizers represents a significant advancement, enhancing, Nutrient Use Efficiency reducing environmental* *impact, and supporting sustainable farming. These advancements highlight the importance of ongoing research in nanotechnology to fully realize its potential in improving food security and environmental protection.*

***Keywords:***

*Top down & Bottom up approach, Controlled release mechanism, Nano Fertilizers, Nano scale particles, Nitrogen Use Efficiency, Smart nutrient delivery*.

## 1.1 Introduction:

The use of advanced fertilizers has been promoted as a beneficial way to increase the efficiency of traditional fertilizer use and minimize its negative environmental impacts. Compared to conventional methods, advanced fertilizers offer several advantages, such as reducing fertilizer loss, lessening the frequency of application, providing nutrients in a sustainable manner, increasing Fertilizer Use Efficiency (FUE), and minimizing the potential negative effects of overuse. Currently, various government organizations, projects, and initiatives are focused on producing a special type of synthetic and modern fertilizer by combining concepts from chemistry, physics, and engineering at the nano scale level. This involves developing nano-sized fertilizer granules with a nano-coating material, known as Nano-fertilizers (NFs) or Smart Fertilizers, as part of a precision farming system.

### 1.1.1 General Concepts:

Bulk materials have continuous macroscopic physical properties, which also applies to steel and micron-sized materials like a grain of sand. However, when particles reach the nano-scale, about six times smaller in dimension, the principles of classical physics are no longer capable of describing their behavior such as movement and energy. At these dimensions, quantum mechanics principles apply. The same material, such as gold, at the nanoscale can exhibit properties such as optical, mechanical, and electrical, which are very different from its properties at the macro scale.

## 1.2 Definition: Nano Science and Nano Technology:

Nanotechnology and nanoscience are interdisciplinary fields at the forefront of scientific innovation. They explore phenomena and manipulate materials at the nanoscale level, typically ranging from 1 to 100 nanometers. At this scale, materials exhibit unique properties and behaviors that differ from their bulk counterparts. Nanotechnology harnesses these distinctive characteristics to create novel materials, devices, and systems with a wide range of applications across various industries.

### 1.2.1 Nano Science:

Nanoscience is an interdisciplinary field that combines chemistry, physics, biology, and engineering. It focuses on understanding, measuring, analyzing, and observing materials at the nanoscale level to identify their properties and behavior. This field encompasses a broad spectrum of disciplines including physics, chemistry, biology, engineering, and materials science. Nanoscience seeks to understand the fundamental principles governing nanoscale phenomena and explore their implications for technology and society.

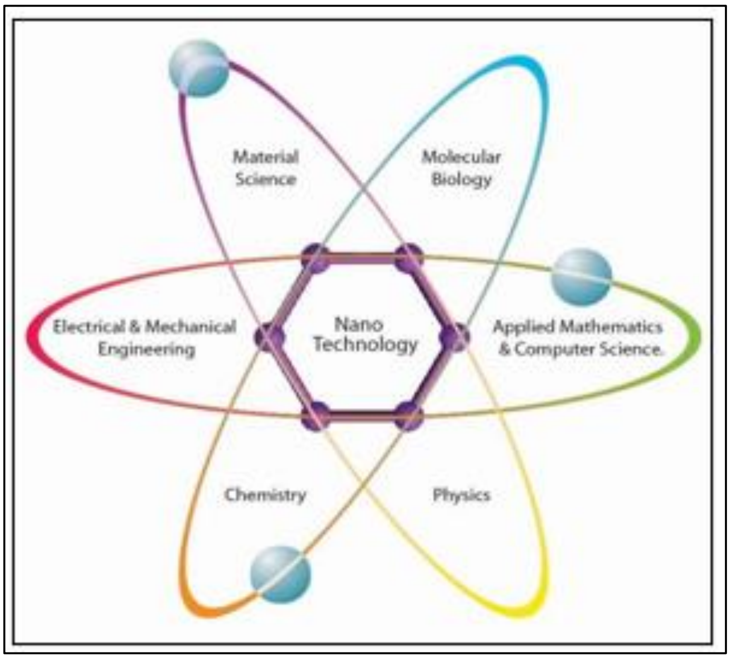


**Figure 1.1: Various Dimensions of Nanotechnology**

### 1.2.2 Nano Technology:

Nanotechnology focuses on designing, fabricating, and applying nanoscale materials and devices. It involves deliberately manipulating matter at the atomic or molecular level to create functional structures with specific properties and functionalities. These engineered nanomaterials have unique physical, chemical, mechanical, and optical properties that can be utilized for various purposes.

### 1.2.3 Nanotechnology in Agriculture and Food Production:

Sustainable intensification is a concept related to a production system aiming to increase yield without adverse environmental impact while cultivating the same agricultural area (The Royal Society, 2009). This paradigm provides a framework to evaluate the selection of the best combination of approaches to agricultural production, considering the influence of the current biophysical, social, cultural, and economic situation (Garnett and Godfray, 2012). In this context, nanotechnology has emerged as a transformative force in agriculture, offering a wide array of applications across various stages, from production to transportation. Nanomaterials, including inorganic, polymeric, and lipid nanoparticles synthesized through techniques like emulsification and polymerization, enhance productivity by creating intelligent nano systems for nutrient immobilization and release in soil, minimizing leaching, optimizing nutrient uptake, and mitigating eutrophication

(Liu and Lal, 2015; Usman *et al*., 2020).The interdisciplinary nature of nanotechnology enables its application in various fields such as disease detection, targeted treatment, nutrient absorption enhancement, disease resistance, and environmental stress tolerance across agriculture and food industries (Sharon *et al*., 2010).

Smart sensors and delivery systems developed through nanotechnology combat crop pathogens and improve agricultural efficiency (Joseph and Morrison, 2006).


**Figure 1.2: Various Applications of Nanotechnology**

Nanotechnology aids precision agriculture by optimizing resource management, pest control, and enabling insights at the atomic and molecular levels for creating nano-scale structures (Kumar, 2009).

Additionally, it contributes to environmental sustainability by aiding in soil remediation, pollution reduction, and environmentally friendly agricultural practices (Usman *et al*., 2020). However, along with its potential benefits, nanotechnology raises ethical, environmental, and safety concerns that need addressing to ensure responsible development and deployment (Kuzma and VerHage, 2006).

Despite the benefits of nano fertilizers, further research is needed to evaluate their long-term impacts, and regulatory frameworks are required for their safe use (Usman *et al*., 2020). Nonetheless, nanotechnology integration in agriculture is expected to bring environmental advantages, especially in farm applications improving the efficiency and safety of administering pesticides, herbicides, and fertilizers (Kuzma and VerHage, 2006).

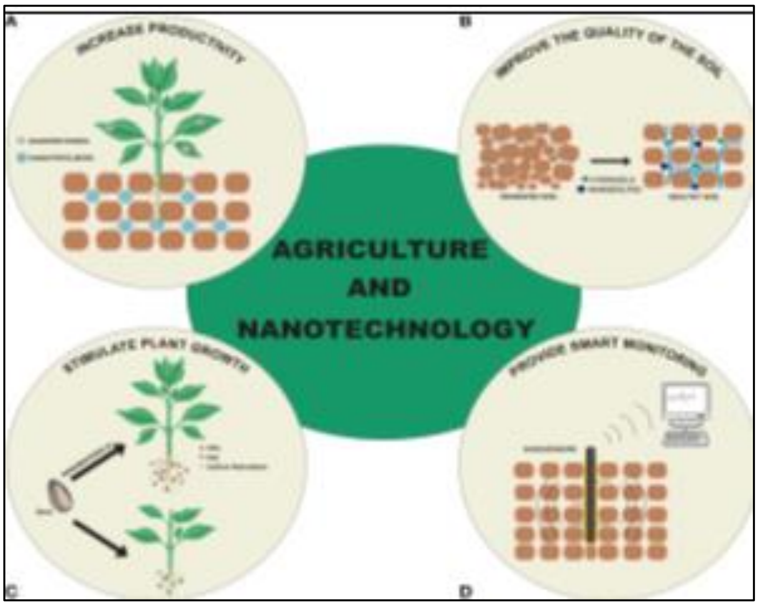


**Figure 1.3: Nanotechnology in Agriculture**

## 1.3 What are Nano Particles:

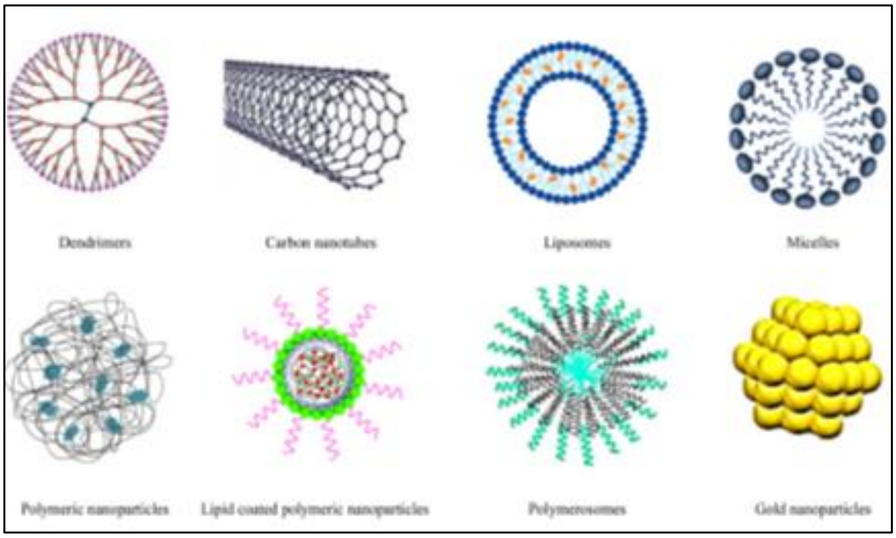


**Figure 1.4: Structural Arrangement of Various synthetic Nano Particles (Source- Yadav *et al.,* 2023)**

Nanoparticles are extremely small particles, with at least one dimension measuring between 1 and 100 nanometers (nm). They can be made from a variety of materials, including metals, metal oxides, polymers, ceramics, and carbon-based materials such as graphene. Due to their tiny size, nanoparticles often have unique properties compared to larger materials of the same composition.

These properties can include altered chemical reactivity, increased surface area, enhanced electrical conductivity, and different optical or magnetic behaviors. [1 nanometer (nm) = 10 angstroms (Å)]

### 1.3.1 What's Different About a Nanoparticle - Properties of Nano particles:

Nanoparticles, having a higher surface-to-volume ratio as compared to their bulky form, possess distinctive characteristics due to their small, confined size, resulting in quantum effects that alters materialistic properties like strength, melting point, magnetic properties etc. For instance, metals like gold, which are typically chemically inert in larger quantities, exhibit remarkable catalytic activity at the nanoscale. Carbon nanotubes, structured on the nanometer scale, are 100 times more rigid than steel in. For an example, a spherical particle the ratio of surface area ($A = 4\pi r^2$) to volume ($V= 4/3\ \pi r^2$) is inversely proportional to the particle radius r according to equation: $A/V=3/r$. As a particle becomes smaller, its surface area becomes an increasingly larger component of its overall form. As particles decrease in size, their surface area becomes proportionally larger, leading to distinct bonding and reactivity characteristics compared to larger particles.

For an example, a spherical particle has the relationship between its surface area ($A = 4\pi r^2$) and volume ($V= 4/3\ \pi r$) is inversely proportional to its radius (r), as described by the equation: $A/V=3/r$. As particles become smaller in size, their surface area becomes proportionally larger, resulting in distinct reactivity and bonding characteristics compared to its bulky form.

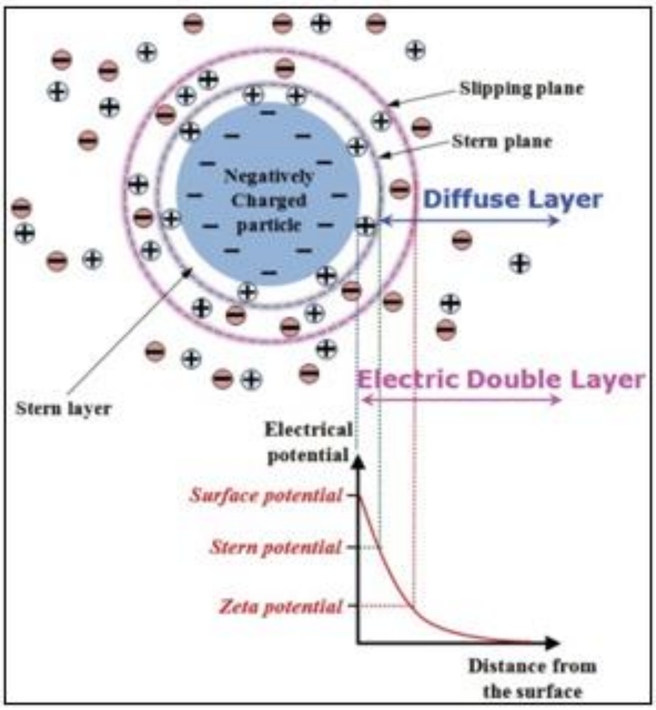


**Figure 1.5: Electrical Double Layer Around a Nano Colloid**

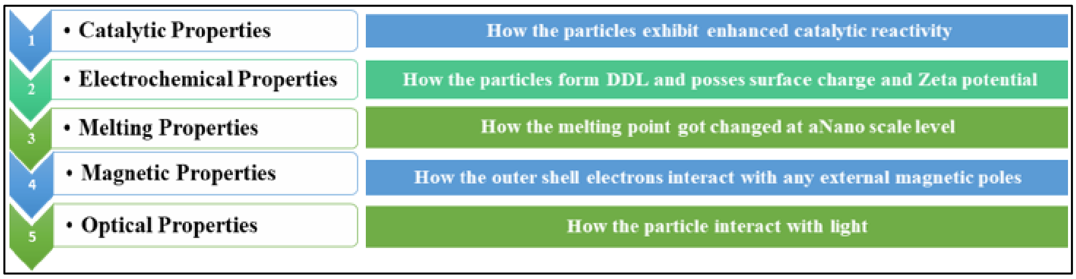


**Figure 1.6: Properties of a Nano Particle**

## 1.3.2 Classification of Nanoparticles:

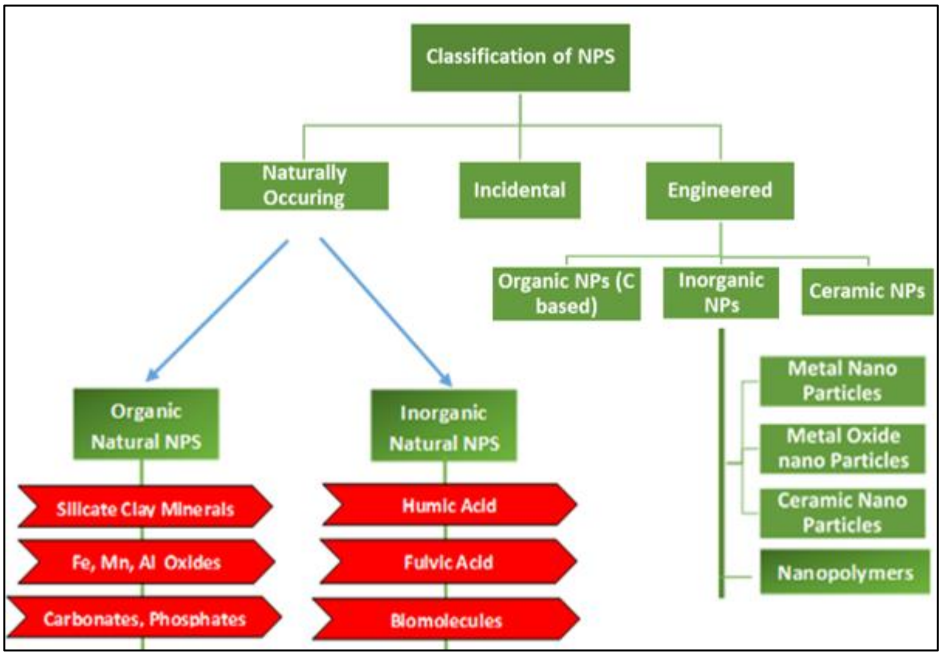


**Figure 1.7: Classification of Nano Particles**

The different types of nanoparticles are classified based on their source as well as morphology, size, and shape. As per Tarafdar and Adhikari, 2015, Nanoparticles are broadly classified into three groups:

## A. Naturally Occurring Nano particles:

Naturally occurring Nano ranged colloidal particles, macromolecules, clay fractions, humus, sea spray, volcanic ash, mineral composites, etc. are example of Naturally Occurring Nano particles. Moreover, Biological nanoparticles or bio-nanoparticles are also belonged to this group. Ex- intracellular structures (e.g., magnetosomes) and extracellular structures (e.g., lipoproteins and viruses), magnetosomes, exosomes, ferritin, lipoproteins, viruses etc.

## B. Incidental Nano particle:

These are the nano particles have been formed due to several anthropogenic activities. Diesel exhausts, sandblasting, welding fumes etc. are the example of Incidental nanoparticles.

## C. Engineered Nano Particles:

These are artificially synthesized nano particles. Ex-Carbon nano tubes, Nano urea, Nano DAP, Quantum dots, Zinc Oxide, Paints, Sunscreen particles etc. Engineered Nanoparticles can be further classified as the following types:

**a. Organic Nanoparticles**:

These nanoparticles are non-toxic, biodegradable, and some, like micelles and liposomes, have a hollow sphere structure known as nan capsules, they are heat and light sensitive (Tiwari *et al.*, 2018). Due to these properties, organic nanoparticles, or polymeric nanoparticles, are ideal for drug delivery, especially targeted drug delivery. The most common shapes are nanospheres or nano capsules (Mansha, 2017). In nanospheres, the entire mass is solid, while nano capsules encapsulate the solid mass, with the outer boundary adsorbing other molecules.

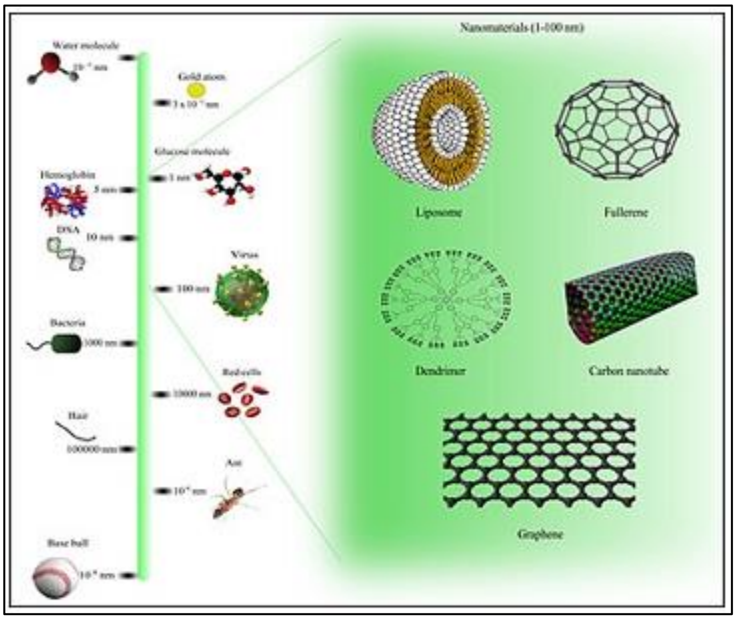


**Figure 1.8: Various Engineered Nano particles**

**b. Inorganic Nanoparticles** -which does not contain carbon, are non-toxic, biocompatible, hydrophilic, and more stable than organic nanoparticles. They are classified into metal and metal oxide nanoparticles.

- **Metal nanoparticles**: Synthesized using destructive or constructive methods from metal precursors, metal nanoparticles possess unique optoelectrical properties due to plasmon resonance. The synthesis is controlled by shape, facet, and size. Common metal nanoparticles include aluminum, gold, iron, lead, silver, cobalt, zinc, cadmium, and copper, known for their distinctive properties like size (10–100 nm), surface area to volume ratio, surface charge, pore size, and various shapes (spherical, rod, hexagonal, etc.) (Dreaden *et al.*, 2012).
- **Metal oxide nanoparticles**: Synthesized to enhance the properties of their respective metals, such as increased reactivity and efficiency. Examples include zinc oxide, silicon dioxide, iron oxide, aluminum oxide, cerium oxide, titanium oxide, and magnetite (Tai, 2007).
- **Ceramic nanoparticle**s: Nonmetallic solids synthesized through heating or cooling processes, available in polycrystalline, amorphous, porous, dense, or hollow forms. They are widely used in photodegradation of dyes, photocatalysis, catalysis, and imaging applications (Thomas *et al*., 2017).

### 1.3.3 Synthesis of Nano Particles – a Brief about Bi-directional Approaches:

In nanotechnology, the top-down and bottom-up approaches are two fundamental strategies for the fabrication and assembly of nanoscale structures.

**A. Top-Down Approach:** This approach was advanced by Richard Feynman, (the father of Nanotechnology). In this method, techniques such as machining, templating, mechanical milling and lithographic methods are utilized to break down a bulk solid into smaller portions to create nanostructures. One advantage of this method is its ability to produce precise and uniform nanostructures. However, despite it's effectiveness in achieving precise nano-scale structures, these methods are often slow and costly, making them less suitable for large-scale production.

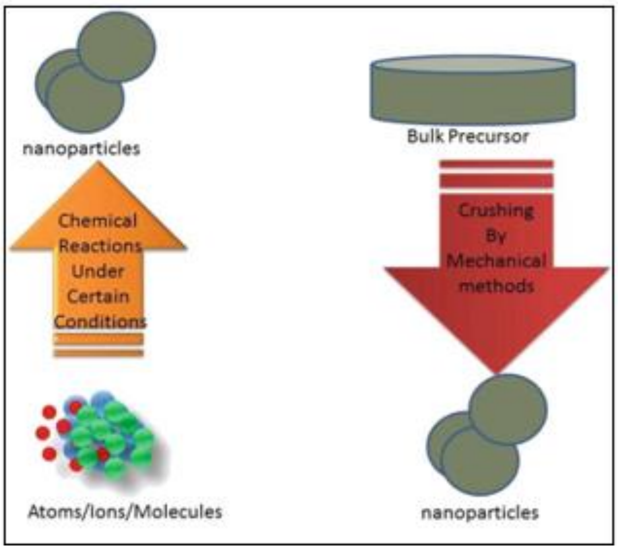


**Figure 1.9: Bottom Up (Left) & Top-Down Approach (Right)**

**B. Bottom-Up Approach:** The Bottom-Up approach, pioneered by Jean-Marie Lehn, involves the gradual addition of atoms and molecules to build nanostructures. It relies on the condensation of atoms or molecules in either the gas phase or solution phase, allowing them to grow until they reach the nanoscale size. One of the advantages of this approach is that the fabrication cost of nanoparticles is often lower compared to top-down methods. Techniques commonly used in the bottom-up approach include sol-gel processing, chemical vapor deposition, plasma spraying synthesis, Self-assembly, molecular beam epitaxy, and and molecular condensation. One of the key advantages of this method is its potential for producing complex and novel nanostructures with precise control over composition and arrangement. However, it may be limited by challenges such as achieving uniformity and scalability in production.

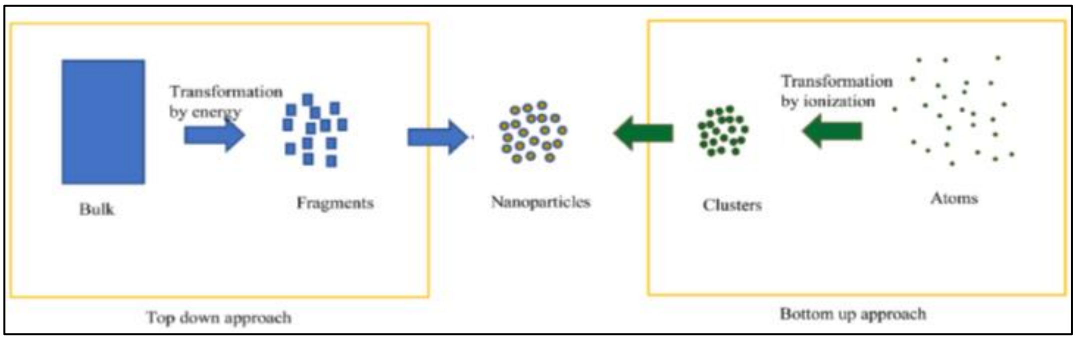


**Figure 1.10: Nano Particle Synthesis Approaches (Yadav *et al.*, 2023)**

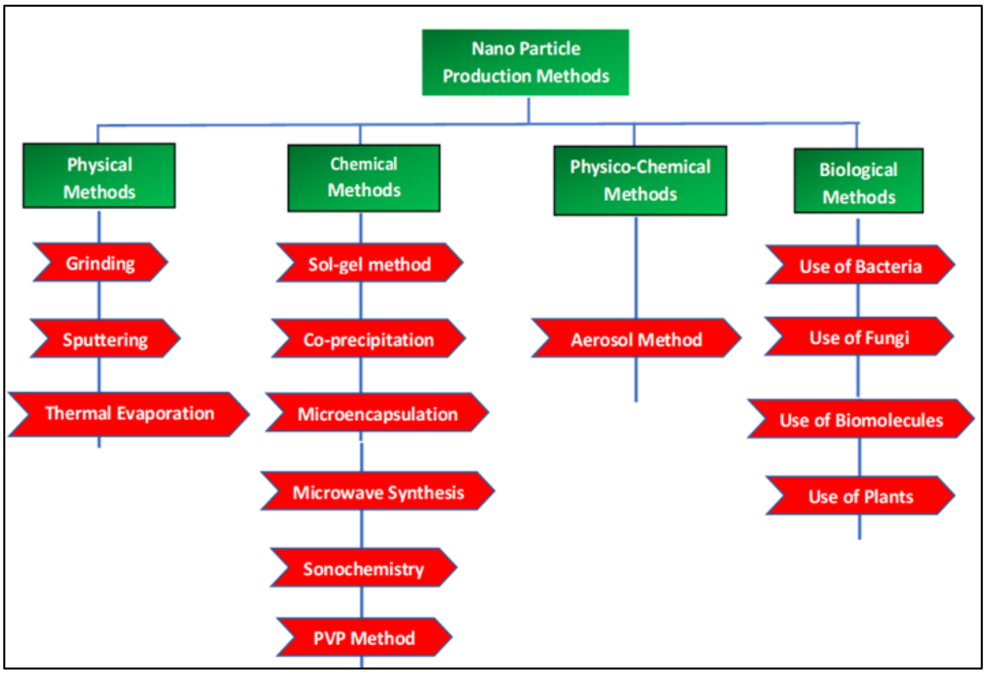


**Figure 1.11: Nano Particles Production Methods**

## 1.4 Nano Fertilizers:

Agricultural production and crop quality heavily depend on plant nutrition, with fertilizers contributing to 40–60% of global food production (Roberts, 2009).

However, traditional fertilizers have low nutrient use efficiency, with significant losses due to runoff, leaching, denitrification, fixation, and microbial immobilization.

Typically, 40–70% of nitrogen, 80–90% of phosphorus, and 50–70% of potassium from fertilizers are lost to the environment, leading to economic losses and environmental pollution (Wu and Liu, 2008).

Nanotechnology offers a solution through the development of nano-based fertilizers. These fertilizers use nanoencapsulation techniques for slow and controlled nutrient release, enhancing nutrient use efficiency and reducing environmental losses (Abobatta 2018).

Nano-fertilizers release nutrients in response to plant demand, preventing premature nutrient conversion to unavailable forms, such as the volatilization of ammonia from urea (De Rosa *et al*. 2010).

Due to their large surface area to volume ratio, nanomaterials provide a stable, long-term nutrient reservoir for plants (Navarro *et al*. 2008).

Nano fertilizers, also known as smart fertilizers, have gained interest for their potential to increase crop yields and minimize environmental impact by releasing nutrients slowly and in alignment with plant requirements. This reduces the need for frequent applications and enhances overall agricultural sustainability.

### 1.4.1 Why Nano Fertilizers:

Nano-fertilizers (NFs) are gaining interest for their potential to boost crop yields and reduce environmental impact. Composed of nanoscale particles (less than 100 nanometers) such as metal oxides or organic compounds, NFs improve nutrient delivery and plant uptake.

Traditional fertilizers suffer from nutrient leaching and low efficiency, causing pollution. NFs address these issues by providing nutrients in tiny particles with a high surface area, allowing efficient delivery and gradual release, aligned with plant growth stages.

This reduces nutrient loss and enhances soil health. Nanotechnology enables encapsulation of nutrients within protective materials, ensuring targeted delivery to plant roots and minimizing waste.

Though currently produced on a small scale (Dimkpa and Bindraban, 2017), NFs are expected to be widely adopted, promoting precision agriculture and sustainability.

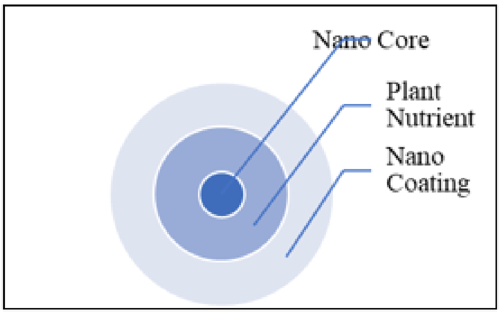


**Figure 1.12: Nano Core Fertilizer**

**Table 1.1: Differences between Nano and Conventional Fertilizers (Source – Cui *et al.*, 2010)**

| Properties | Nano fertilizers | Conventional fertilizers |
|---|---|---|
| Solubility and dispersion of mineral micronutrients | Improve solubility and dispersion of insoluble nutrients in soil, reduce soil absorption and fixation, and increase the bioavailability. | Less bioavailability to plants due to large particle size and less solubility |
| Nutrient uptake efficiency | Might increase fertilizer efficiency and uptake ratio of the soil nutrients in crop production and save fertilizer resource | Bulk composite is not available for roots and decrease efficiency. |
| Controlled-release modes | Release rate and release pattern of nutrients for water-soluble fertilizers might be precisely controlled through encapsulation in envelope forms | Excess release of fertilizer may produce toxicity and destroy ecological balance of soil |
| Effective duration of nutrient release | Nano Fertilizer can extend effective duration of nutrient supply of fertilizers into soil | Used by the plants at the time of delivery, the rest is converted into insoluble salts in the soil |
| Loss rate of fertilizer nutrients | Reduce loss rate of fertilizer nutrients into soil by leaching and/or leaking | High loss rate by leaching, rain off and drift. |

### 1.4.2 Controlled Release and Smart Delivery of Nutrients:

A Smart nutrient Delivery System (SDNS) comprises several factors or their combinations such as time-regulation, precise targeting, highly managing, remotely controlled/pre-programmed, and other multifunctional characteristics to overcome biological and physical barriers for the successful targeted release of needed nutrients.

Nano-encapsulated nutrients should be engineered to exhibit all essential features such as optimal concentration, stability, solubility, time-controlled release triggered by specific stimuli, improved targeted functionality, and reduced environmental toxicity, with a safe and convenient delivery method to prevent the need for repeated applications.

There are various methods available for implementing this delivery system.

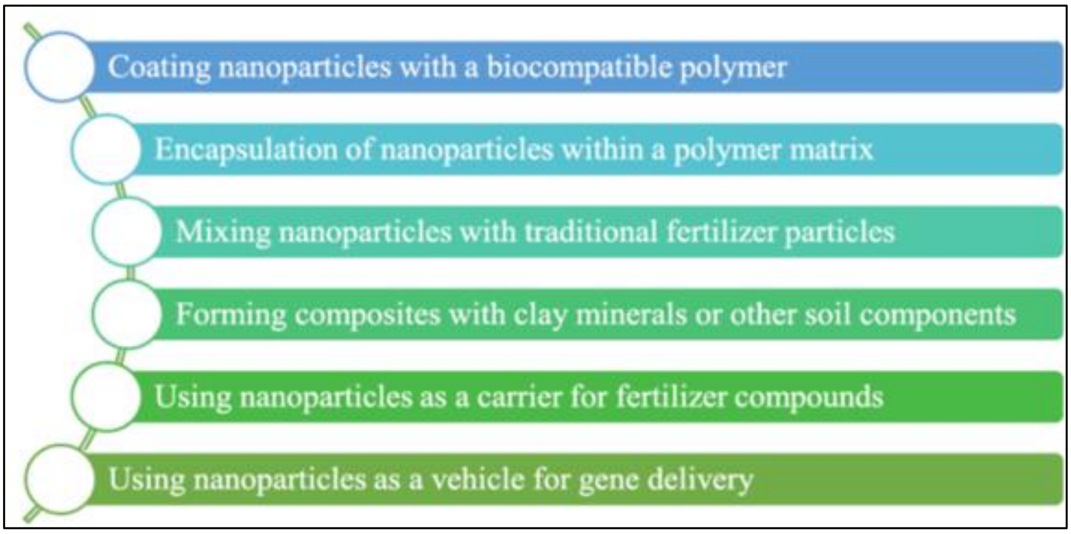


**Figure 1.13: Several Smart delivery systems for commercial NF production (Yadav *et al*., 2023)**

**A. Mechanism of Controlled Release:**

Various mechanisms for the release of coated fertilizers have been proposed and are still being refined. Liu and Shaviv introduced the **multi-stage diffusion model** to explain this process.

According to this model, when coated fertilizer is applied and irrigated, water seeps into the coating, causing the solid fertilizer core to absorb moisture and partially dissolve.

As a result, osmotic pressure builds up inside the granule, leading to two possible outcomes: **Catastrophic Release** (Failure Mechanism) or **Diffusion Release**.

Catastrophic release occurs when the osmotic pressure exceeds the membrane's resistance threshold, causing the coating to burst and the core to be rapidly released.

This typically happens with fragile coatings like sulfur. On the other hand, polymeric coatings such as polyolefin utilize the diffusion release mechanism.

The core is gradually released through the intact membrane via diffusion as the membrane is capable of withstanding pressure buildup.

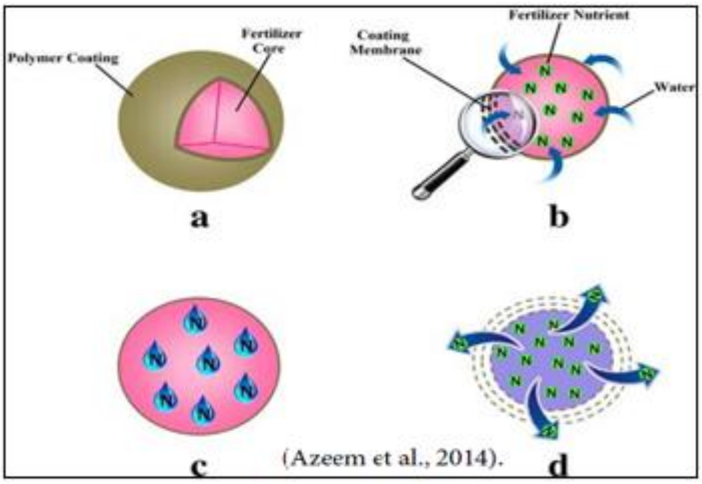


**Figure 1.14: Control Release Mechanism from Nano fertilizer**

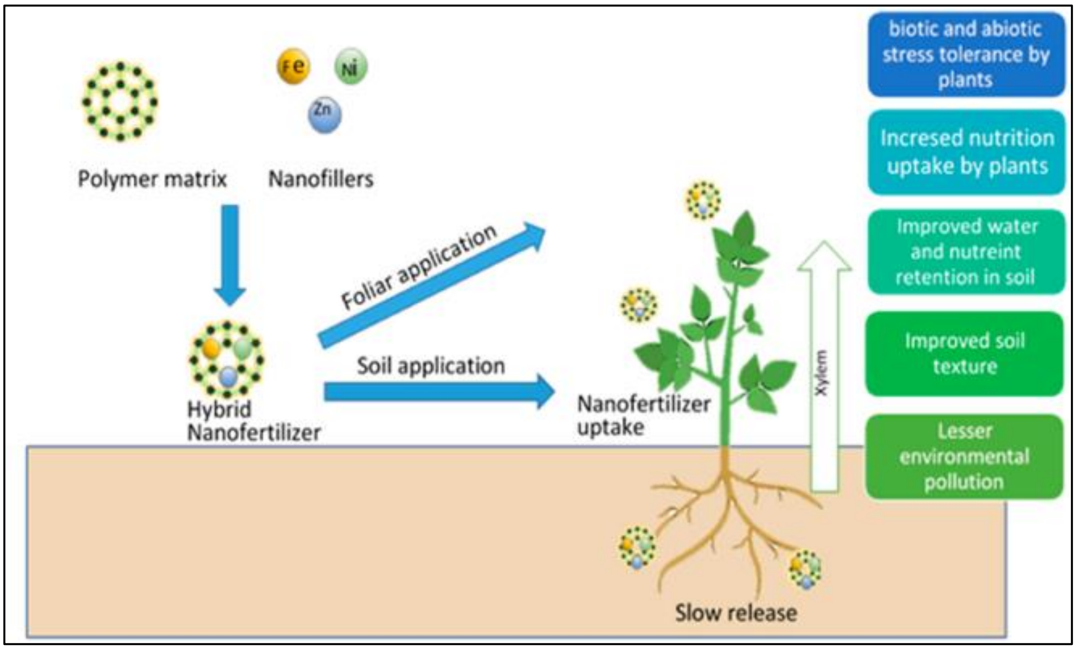


**Figure 1.15: Smart Nutrient Delivery System (SNDS)**

## B. Role of Controlled Release Fertilizers in Enhancing Fertilizer Use Efficiency (FUE):

The Fertilizer Use Efficiency (FUE) measures the potential of an applied fertilizer to increase productivity and utilization of nutrients in the soil/plant system. FUE indices are used to assess the effectiveness of nitrogen (N), phosphorus (P), and potassium (K) fertilization. Nitrogen is the most important nutrient in crop production, so most scientific research focuses on improving Nutrient Use Efficiency (NUE) (Barlog, 2023).

In India, the average Nutrient Use Efficiency (NUE) from chemical fertilizers such as urea ranges from 20 to 50% for rice. Currently, it is assumed that the recovery of nitrogen from applied fertilizers is at a low level of just 30–50% (Fixen *et al*., 2015). The use of coated fertilizers helps in delayed and synchronized release of nutrients, preventing:

i. Leaching losses of nutrients

ii. Volatilization losses of nutrients

iii. Fertility erosion of nutrients

iv. Excessive application of fertilizers

Zhang *et al*., 2016 also reported that Controlled-release fertilizers have played significant roles in increasing grain yield and N use efficiency and decreasing N losses of rice. In the agriculture sector, innovation is a common subject.

## 1.5 Nano Diammonium Phosphate (Nano DAP):

The use of Nano DAP (diammonium phosphate) in fertilizers is a recent and noteworthy innovation.

These tiny particles make traditional diammonium phosphate fertilizer extremely easy to apply by shredding it to a size that is imperceptible to the human eye and suspending it in a liquid carrier.

Despite their size, these small particles are revolutionizing agriculture. Nano-DAP fertilizers hold significant promise for the future of agriculture, offering intriguing and valuable potential to enhance agricultural productivity while safeguarding the environment.

Foliar spray can effectively address a crop's immediate nitrogen requirements, but the use of Nano-scale materials can enhance fertilizer efficiency significantly. According to Lal R. (2008), Nano fertilizers, also known as nutrient vectors, are created using Nano-scale raw material substrates ranging from 1-100 nm.

These Nano fertilizers can manipulate materials at the atomic, molecular, and macromolecular levels. Due to their large surface area, Nanoparticles can retain a substantial amount of nutrients and release them gradually and steadily over an extended period.

This capability allows crops to absorb the necessary nutrients more efficiently, mitigating the drawbacks associated with specialized fertilizer inputs (Kothari *et al*., 2019). Nano urea and DAP fertilizers have been developed for the first time globally at the IFFCO Nano Biotechnology Research Centre (NBRC) in Kalol, Gujarat, using proprietary patented technology.


**Figure 1.16: Nano DAP bottle (IFFCO)**

### 1.5.1 Chemical Structure and Components:

The Nano DAP formulation contains both nitrogen (8.0% N w/v) and phosphorus (16.0% P2O5 w/v), making it an excellent source of bioavailable N and P for all crops. The particles of Nano DAP (Liquid) are smaller than 100 Nanometers (nm), giving them a higher surface area to volume ratio.

This unique characteristic allows the formulation to easily reach the seed surface, stomata, and other plant apertures. The Nano nitrogen and phosphorus clusters in Nano DAP are functionalized using biopolymers and other excipients. Improved Nano DAP dispersion and assimilation throughout the plant system results in higher seed vigor, chlorophyll content, photosynthetic efficiency, and seed quality (https://www.iffco.in/en/Nano-dap-liquid) (IFFCO, 2023).

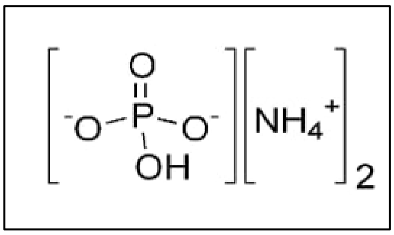

**Figure 1.17: Chemical Structure of DAP**

### 1.5.2 IFFCO Nano DAP:

IFFCO Nano DAP is an efficient source of readily available nitrogen (N) and phosphorus, helping to compensate for any deficiencies in these nutrients in existing crops. The Nano DAP formulation contains 8.0 percent N (w/v) and 16.0 percent phosphorus (w/v). Nano DAP (Liquid) has an advantage in terms of surface area to volume (nm) due to its particles being smaller than 100 nm.

Its unique qualities allow it to readily enter stomata, the exposed surface, and other plant openings. Nano DAP utilizes biopolymers and other excipients to functionalize the Nano nitrogen and phosphorus clusters.

The enhanced spread ability and digestion of Nano DAP throughout the plant system results in higher seed vigor, greater chlorophyll, improved photosynthetic efficiency, better quality, and increased crop yields (IFFCO, 2023).

### 1.5.3 Coromandel Nano DAP:

A high-end product developed and produced internally; Nano DAP is built on state-of-the-art Nanotechnology. It is a unique liquid fertilizer solution containing Nanoparticles of diammonium phosphate (DAP). It offers supplies of phosphorus and nitrogen, two crucial basic minerals required for crop development and growth.

Nano DAP's wide surface area and small size (100 nm) allow it to be readily absorbed by plant leaves. Innovative Nano-formulation yields benefit such as enhanced crop growth and productivity, less environmental impact, and increased farmer profitability (Nano DAP- Coromandel. 2023).

**Table 1.2: Application of IFFCO Nano DAP**

| Sr. No. | Method | Application Rate | Water Quality |
|---|---|---|---|
| 1 | Seed treatment | 3-5 ml per Kg of seeds | |
| 2 | Root/Tuber/Sett Treatment | 3-5 ml per litre of water | |
| 3 | Foliar Spray | 2-4 ml per litre of water | At the good foliage stage (Tillering/ Branching) and 2$^{nd}$ spray at per-flowering/ Late Tillering stage |
| 4 | Knapsack Sprayers | 2-3 caps (50-75 ml) per 15-16-liter tank | 8-10 tanks normally cover 1 acre crop area |

| Sr. No. | Method | Application Rate | Water Quality |
|---|---|---|---|
| 5 | Boom/ Power Sprays | 3-4caps (75-100ml) per 20-25 litre tank | 4-6 tanks normally cover 1 acre crop area |
| 6 | Drones | 250-500 ml per tank of 10-20-liter volume | To cover 1-acre area |

## Features of Coromandel Nano DAP:

a. Nano DAP is an opalescent white aqueous Nano fertilizer designed for foliar application.
b. It contains DAP Nanoparticles with a concentration of 2% nitrogen (N) and 5% phosphorus pentoxide ($P_2O_5$) by weight per volume (w/v).
c. Due to its diminutive dimensions and expansive surface area, it maximizes nutrient utilization efficiency.
d. Nano-formulated DAP is optimal for systemic absorption within plants.
e. It incorporates top-quality stabilizers to enhance product effectiveness and longevity.

**Table 1.3 Application of Coromandel Nano**

| Pack Size | Dosage per Acre | Number of Sprays | |
|---|---|---|---|
| 1 litre | 500 ml | Two sprays | |
| | | a | Vegetative state (4-5 weeks after crop sown/transplant) |
| | | B | Before the flowering stage of the crop |

## 1.5.4 Environmental Benefits:

The incredible benefits of Nano DAP are:

**a. Nutrient Powerhouse Delivery:** Nano DAP's ultrafine particles boast a vast surface area, facilitating enhanced nutrient absorption by plants, and ultimately promoting robust growth and increased yields.

**b. Environmental Friendliness:** Unlike conventional fertilizers, which pose risks to groundwater, Nano DAP significantly mitigates these concerns, offering a more eco-conscious option for farmers.

**c. Cost Efficiency:** Despite its advanced technology, Nano DAP proves to be a cost-saving solution for farmers. With amplified yields and minimized fertilizer wastage, it translates to long-term financial gains.

**d. Advocating Sustainable Agriculture:** Nano DAP aligns seamlessly with the principles of sustainable agriculture. By obviating the need for chemical fertilizers and advocating prudent nutrient management, it contributes to environmentally conscious farming practices.

## 1.6 Effect of Nano Fertilizers on Growth, Yield, Nutrient Uptake, and Soil Microbiology on Crop:

### 1.6.1 Growth Attributes:

In the condition that received 75% RNP as baseline + Nano urea & DAP spray @ 1.5 ml l-1 each at 30 and 45 DAS, there were noticeably more leaves per plant (11.8, 12.1, and 8.9 at 60, 90 DAS, and at harvest, respectively). (Maheta *et al*. 2023) and (Rajput *et al*. 2018) both published comparable findings. By increasing the availability of nitrogen and phosphorous through the combined application of chemical and Nano fertilizers, plant height was raised. This was due to the acceleration of photosynthesis, carbohydrate metabolism, protein synthesis, and cell division enzymatic activity. A rise in plant height ed to an increase in internodes and nodes, which in turn produced more leaves. Sorghum leaves and leaf area index rose when 75% RNP was used as a baseline and Nano urea and DAP spray were applied at 1.5 ml l-1 each at 30 and 45 DAS. With comparable leaf area indices of 4.44, 5.21, and 4.45, the leaf area measured at 60, and 90 DAS, and harvest was reported at 30.0, 35.2, and 30 $dm^2$ $plant^{-1}$, respectively. This increase in leaf area is thought to be the result of less rivalry between plants for nutrients, which is made possible by the efficient delivery of nitrogen and phosphate in the right amounts through both conventional and Nano fertilizers, which encourages the growth of more leaves. The leaf area index increased as a result of the increased leaf area. These findings were by (Mallikarjuna 2021).

### 1.6.2 Yield Attributes:

Significantly higher length of earhead (35.9 cm), number of grains earhead-1 (2207), grain weight (57.0 g plant-1), and test weight (29.0 g 1000 grains-1) was recorded by Application of 75% RNP as basal + Nano urea & DAP spray @ 1.5 ml l-1 each at 30 and 45 DAS (Table 1.2). Similar results were reported Sharma *et al*. 2022) and (Chavan *et al*. 2023) Combined application of conventional and Nano fertilizers (Nano urea and DAP) ensured optimum and balanced nutrient availability throughout the crop period especially during the critical stages of crop.

### 1.6.3 Nutrient Uptake and Available Nutrients in Soil at Harvest:

The treatments that received the foliar application of 75% RNP as basal + Nano urea & DAP spray @ 1.5 ml l-1 each at 30 and 45 DAS showed significantly greater uptake of important nutrients, namely nitrogen (133.9 kg ha-1), phosphorous (53.8 kg ha-1), and potassium (109 kg ha-1). The increase in nutrient uptake was due to the use of Nano fertilizers. These fertilizers have a higher surface area and smaller particle size than plant roots and leaves, allowing them to penetrate the plant more deeply and enhance nutrient uptake. These findings are based on the research of Gupta *et al.* (2022).

### 1.6.4 Soil Microbiology:

The prescribed dose of fertilizers (RDF) produced significantly better results in bioassay experiments (bacterial, fungal, actinomycetes population, and dehydrogenase activity) compared to all other treatments, and was comparable to the absolute control. In contrast, bioassay trials with Nano fertilizers resulted in noticeably poorer outcomes. This was due to the increased surface area and smaller size of the Nano particles, which allowed them to enter bacterial cells and affect the growth and development of microorganisms.

Additionally, this broad-spectrum antibacterial treatment could negatively impact beneficial soil microorganisms responsible for breaking down organic matter, potentially affecting long-term soil fertility. The long-term effects of using these Nano-formulations on plant yields and soil fertility may be unfavorable, especially with repeated exposure. This conclusion is supported by the findings of Rajput *et al*. (2018) and Xu *et al.* (2015).

### 1.6.5 Response of Nano Fertilizers on Growth, Yield, and Economics of Kharif Sorghum:

Applying nano fertilizers to sorghum resulted in varied economic outcomes. The highest cultivation cost was observed with the use of 75% RNP as basal, along with nano urea and DAP spray at 1.5 ml/l at 30 and 45 DAS (Rs. 42,330 ha-1). In contrast, the absolute control had the lowest cost (Rs. 27,380 ha-1). However, this higher-cost method yielded the highest gross returns, net returns, and benefit-cost ratios (Rs. 1,26,649 ha-1, Rs. 84,319 ha-1, and 2.99). Similar high returns were achieved with 75% RNP plus nano urea and DAP spray at 3.0 ml/l at 30 DAS, and the recommended fertilizer dose. The absolute control, with inadequate nutrient supply, had significantly lower gross returns, net returns, and benefit-cost ratios (Rs. 59,843 ha-1, Rs. 32,013 ha-1, and 2.15), resulting in reduced yields. Conversely, conventional fertilizers combined with nano fertilizers ensured adequate nutrient supply, leading to higher yields and returns. These findings align with studies by Rawat (2017) and Sankar *et al.* (2020).

### 1.6.6 Impact of Nano-DAP on Growth and Development of Cabbage:

According to Rameshaiah *et al*. (2015), Solanki *et al*. (2015), and Siddiqui *et al.* (2015), Nano fertilizers have a larger surface area, higher incorporation capacity, and controlled release in targeted areas. Diammonium phosphate (DAP), widely used for its beneficial physical properties and high N (18%) and P2O5 (46%) content, would be even more advantageous in Nano form.

### A. Plant Spread (cm):

The use of Nano-DAP on the leaves likely facilitated the immediate absorption of nitrogen (N) and phosphorus (P) by the crops. This, in turn, enhanced tissue differentiation, cell proliferation, and cell elongation. Studies on cabbage by Nath (2000) and Sumanth (2019) support this conclusion. Furthermore, similar results in cabbage were observed by Chamuah *et al*. (2023) and Silva *et al*. (2021).

### B. Leaf Area (sq cm):

The crop treated with Nano DAP at 30 and 60 days after planting, T7 (50% P, 100% N & K + FS of n-DAP @ 2 ml/lir. at 25°C) had the largest leaf area (88.33 and 183.70 sqm). On the other hand, T4 (100% RD of N & K (130:0:80 kg/ha) + Seedling root-dip treatment of n-DAP @ 5 ml/lir.) had the smallest leaf area, measuring 27.40 sqm at 30 DAT and 54.69 sq cm at 60 DAT. The difference in leaf areas of various treatments may be due to the different fertilizer doses applied, leading to varying synergistic effects.

### C. Leaf Fresh Weight (g):

The highest leaf fresh weight at 30 and 60 DAT was documented in T7 (50% P, 100% N & K + foliar spray of Nano-DAP at 2 ml/lir. at 25-30 DAT) (4.40 g), and T11 (50% P, 100% N & K + soil treatment at 5ml/lir. + foliar spray of Nano-DAP at 2 ml/lir. at 25-30 DAT) (10.61 g), respectively.

### D. Root Fresh Weight (g):

Regarding root fresh weight, the highest root fresh weight was achieved in T7 (50% P, 100% N & K + foliar spray of Nano-DAP at 2 ml/lir. at 25-30 DAT) (7.24 g), while the lowest was observed in T4 (100% recommended dose of N & K (130:0:80 kg/ha) + seedling root-dip treatment of Nano-DAP at 5 ml/lir.) (3.74 g) at 30 DAT. The recent study clearly shows that enhancing the growth characteristics of cabbage heads was achieved by using Nano-DAP at different levels as a spray on the leaves and as a seedling root dip treatment. This is because Nano-DAP greatly reduces the number of applications needed. Therefore, it can be used as a cost-effective and environmentally friendly alternative to traditional inorganic fertilizers, both in terms of quantity and cost.

## 1.6.7 Nutrient Uptake of Pigeon Pea as Influenced by Foliar Spray of Nano-DAP:

At 45 and 60 DAS, significantly greater quantities of N, P, and K were found in the seed (2.46%, 1.07%, and 1.63% N, P, and K, respectively) and in the stalk (0.55%, 0.58%, and 0.78% stalk N, P, and K, respectively) in the treatment receiving 100% RDF with Nano-DAP spray @ 4 ml l-1. At 45 and 60 DAS (2.40%, 0.98%, and 1.61% N, P, and K, respectively), as well as in the stalk (0.52%, 0.52%, and 0.76% N, P, and K, respectively), it is comparable to 100% RDF with Nano-DAP spray @ 2 ml l-1. The foliar application of Nano-DAP, which both holds nitrogen and decreases nitrogen loss, is the cause of the increase in nitrogen content. Additionally, there may be synergistic interactions between nitrogen and phosphorus that further enhance nitrogen concentration. Nanoparticles potentially permeate pigeon pea leaves via stomata and disperse throughout the plant. Nano-DAP primarily addresses challenges such as leaching, immobilization, and limited nutrient availability. It facilitates direct nutrient supply to plants, particularly nitrogen and phosphorus. Corresponding findings were reported by Sharma *et al.* (2022). The elevation in phosphorus levels attributed to the Nano-DAP application could be attributed to its small diameter of 25-50 nm, enhancing the total surface area and safeguarding phosphorus from fixation, thus ensuring a controlled nutrient release and prolonged availability.

This observation aligns with the findings of Satyashraya *et al*. (2022). Additionally, the interaction between nitrogen and phosphorus leads to a synergistic effect, resulting in increased potassium concentrations in grains and stalks, as similarly noted by Merghanya *et al*. (2019).

### 1.6.8 Effect of Nano-Phosphorus Formulation on Growth, Yield, and Nutritional Quality of Wheat under Semi-Arid Climate;

The application of foliar Nano-phosphorus (NP) significantly increased panicle number per plant, panicle length (cm), and 1000 seed weight (g). The highest values, 5.67, 12.4 cm, and 41.1, were observed in treatment T4 (100% NK + 75% P + 2 foliar sprays of Nano-P at tillering and panicle initiation stages), marking a 35.5%, 34.7%, and 29.15% increase, respectively, over T1 (100% NPK by RDF without foliar Nano-P spray).

This is consistent with findings in rice by Sirisena *et al.* (2013), which attributed increased leaf area and dry matter accumulation to Nano-P supplementation with DAP, improving nutrient availability and metabolic processes. Meena *et al*. (2020) similarly noted improved wheat yield via enhanced metabolic processes and photosynthesis with Nano-P application. Moreover, Nano-P aids nutrient absorption, optimizing plant growth and metabolic activities, augmenting photosynthate accumulation, and translocation to economic plant parts, as evidenced in broad beans by El-Azizy *et al.* (2015). This smart delivery system of Nano-fertilizers enhances nutrient accumulation and growth activity, promising improved crop yields.

The grain and straw yields surpass 100% RDF due to enhanced absorption, interception, and utilization of phosphorus (P) in Nano-P form, facilitating gradual P release during the growth cycle. This leads to heightened photosynthetic rates, culminating in increased biomass accumulation (Adhikari *et al.* 2014). When compared to no Nano-fertilizer, the application of Nano-particle fertilizer led to a higher growth rate of 32.6% and improved seed yield of 20.4% (Liu and Lal, 2014).

## 1.7 Nanotechnology-Based P Fertilizers for Higher Efficiency and Agriculture Sustainability:

The global population is expected to increase, leading to a higher demand for phosphorus (P) fertilizers due to the shift towards meat-centric diets and the growing need for bio-energy crops (Childers *et al*., 2011). However, the use of conventional P fertilizers contributes to eutrophication in surface waters. As a result, regulations, best management practices (BMPs), and remediation technologies have been suggested to reduce P fertilizer usage and prevent runoff into water bodies (Buda *et al.*, 2012). To address this issue, Nano-P fertilizers are being considered as an alternative to traditional P fertilizers in agriculture. This switch is expected to increase agricultural output, improve P utilization efficiency, and enhance surface-water quality. Agriculture accounts for 80–90% of global P demand and is the primary consumer of mined phosphorus (Childers *et al.*, 2011). Additionally, phosphate fertilizers are derived from phosphoric rock, a finite resource with depleting reserves. Given the various issues associated with conventional phosphate fertilizers, Nano fertilizers show promise as a viable alternative.

## 1.8 Conclusion:

Nano-fertilizers like Nano-DAP and Nano-P are revolutionizing agriculture. Their tiny size and controlled release boost plant growth and nutrient uptake in crops like wheat and cabbage. This "smart delivery" reduces fertilizer use, minimizes runoff, and improves efficiency. By lowering application rates and boosting yields, nano-fertilizers offer a cost-effective and environmentally friendly solution for a phosphorus-hungry world. This technology has the potential to enhance food security, agricultural sustainability, and environmental protection.

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