Indian Journal of Fertilisers **17** (11) : 1206-1214, November, 2021

Nano Fertilizers for Sustainable Crop Production, Higher Nutrient Use Efficiency and Enhanced Profitability

Yogendra Kumar, Tarunendu Singh, Ramesh Raliya and K.N. Tiwari
Indian Farmers Fertiliser Cooperative Limited, New Delhi

Received : 20/09/2021 Accepted : 28/10/2021

Abstract

Nano fertilizers hold potential to fulfil plant nutrition requirements, ensure farmers profitability and impart sustainability to crop production systems without compromising on crop yields. Nanotechnology employs nanomaterials in the range of 1 nm to 100 nm; particles in this range have unique characteristics having effective interaction at target sites. IFFCO has indigenously innovated at its Nano Biotechnology Research Centre (NBRC), Kalol, Gujarat and introduced nano fertilizers *viz*., Nano urea –liquid (nano N), nano zinc (Zn), and nano copper (Cu). These have been branded as IFFCO NANO UREA, IFFCO NANO ZINC, and IFFCO NANO COPPER. These are in sync with OECD Testing Guidelines (TGs) and Guidelines for Testing of NAIPs and Food Products released by the Department of Biotechnology, Government of India. Their efficacy was evaluated on the basis of multi-location-multi-crop trials under varying crop seasons, both by the research institutes and also on the progressive farmers' fields. Harvested produce of crops applied with IFFCO nano-urea, nano-zinc, and nano-copper have been found to be fit for consumption. Foliar sprays of the nano fertilizer at critical crop growth stages either alone or in combination have been found to increase crop yields even at reduced levels of application of their conventional analogues. IFFCO nano urea (liquid) has been notified under FCO, 1985 and commercial production has started. This paper reviews the efficacy and benefits of these nano fertilizers in increasing the nutrient use efficiency (NUE) and crop productivity, and sustainability and profitability of major crop production systems.

Key Words: Nano fertilizer, nano urea-liquid, nano zinc, nano copper, nutrient use efficiency, sustainability, profitability

Introduction

Chemical fertilizers contribute to over 40% of our agriculture food grain production (Stewart and Roberts, 2012). However, their indiscriminate and imbalanced application has environmental and ecological consequences. Losses of nutrients from agricultural fields due to leaching (NO_3) and gaseous emissions (NH_3 and N_2O) have been the leading causes of environmental pollution and one of the factors responsible for climate change. Nitrogen use efficiency in the range of 20-50% is affecting the sustainability of our agriculture production systems. This fact has been of great concern for the scientists, policy makers, industry and the farming community of the country. Nanotechnology, which utilizes nanomaterials of less than 100 nm size, has emerged as an innovative science to develop concentrated sources of plant nutrients having higher-absorption rate, utilization efficacy, and minimum losses. Nanotechnology-based fertilizers are made by encapsulating or developing plant nutrients in its nanoforms and ultimately delivering them as nano-sized emulsions. Nanoscale nutrients can effectively enter the plant leaves, trigger nutrient pathways and achieve higher nutrient use efficiency (NUE) than their bulk counterparts resulting into better crop production with lesser environment footprint. Nano fertilizers have benefits in terms of application and small requirement by mass volume, slow / control release mechanism, reduction in transportation and application cost, and cause comparatively low salt accumulation in soil *vis-à-vis* conventional fertilizers. These effectively meet crop nutrient requirement with increased bioavailability of nutrients in the plant system and also in the root rhizosphere.

Foliar applied nano fertilizers increase NUE and nutritional quality of crops through bio-fortification. These nanoscale nutrients have desired particle shape, particle size, particle purity, composition, concentration, stability, poly dispersity index (PDI) value, pH and crystal phase. They are bioavailable and within the scientific limits of application as per their desired content in plants thus, fulfilling plant nutritional requirement as a fertilizer. Nanoscale nutrients when sprayed on plant leaves, are taken by two mechanisms: one - direct uptake or stomatal uptake and second is by surface absorption. Due to ultra-small particle size, such nutrients can rapidly be taken by the plants and as a consequence minimize the nutrient losses. Inside the plant cell, these nutrients slowly release the active nutrient component which involves itself in the plant's cellular metabolism for their growth and development. Therefore, it is critical to develop nanotechnology-based nano fertilizers that are available for ready uptake by the plants.

Nanotechnology is a possible route for sustainably and precisely attaining these objectives for which scientists are actively researching-nanoparticles for use in plant science and agriculture. A number of inorganic, organic and composite nanomaterials have

yogendrakumar@iffco.in

been tested on various plants to assess their potential impact on plant growth, development and productivity. The influence of nanoparticles on plants depends greatly on the intrinsic properties (size, shape, surface area, surface charge, etc.) and extrinsic nano bio interactions of the nanoparticles.

At nano scale, physical and chemical properties of nano fertilizers are dynamic and different from their counterpart. Due to higher surface area to volume size ratio and nano size, these have high availability and absorption capacity. It facilitates better uptake from soil or leaves, resulting in production of more photosynthates; root and shoot biomass required for healthy crops.

IFFCO has successfully innovated and developed nano urea – liquid (nano nitrogen), nano zinc and nano copper at its Nano Biotechnology Research Centre (NBRC) Kalol, Gujarat. These nanoscale products utilise the benefit of dynamics of shape, size, surface area and bioassimilation. Globally, nano fertiliser trials had not been done on country-wide farm fields and generalisations are largely based on localized trials, pot or polyhouse study. It is for the first time that large scale field trials on nano fertiliser *i.e.* nano urea – liquid (nano N), nano zinc and nano copper have been undertaken by IFFCO in all the agro climatic zones of the country. IFFCO-nano fertilizers were evaluated through multi-location, multi-crop, 'On station' trials under National Agriculture Research System (NARS). 11,000 'On farm' trials were conducted on progressive farmers' fields covering 94 crops across the country since 2019. Efficacy, crop productivity and profitability of IFFCO nano fertilizers [nano urea – liquid (nano N), nano Zn and nano Cu] in terms of better nutrient use efficiency, sustainable crop production and benefit cost ratio are discussed in the paper. Due to the manifold increase in surface area, their work efficiency was high. An extensive characterization of IFFCO nano fertilizers has also been undertaken by IFFCO – NBRC at Kalol. These nano fertiliser products were evaluated for biosafety – bio toxicity as per OECD testing guidelines (TGs) and "Guidelines for Evaluation of Nano-Based-Agri-Input & Food products in India 2020" released by the Department of Biotechnology (DBT), Government of India which are harmonized as per international guidelines.

Photo 1. Bottles of Nano Urea- Liquid (Nano Nitrogen) (500 mL), Nano Zinc (250 mL) and Nano Copper (250 mL)

Materials and Methods

IFFCO's Nano Fertilizers

Nano fertilizers like nano urea – liquid (nano N), nano zinc and nano copper, as displayed in **Photo 1** have been manufactured by IFFCO with indigenous research and development. These nano material formulations were characterized for their morphology by transmission electron microscopy (TEM) (test method: ISO 21363:2020), hydrodynamic size (test method: ASTM E3247-20), and zeta potential (test method: ISO13099-1) by dynamic light scattering, pH by pH meter (test method: ASTM E70-07), and viscosity by rotational viscometer (test method: ASTM D2196-10). Elemental concentration of nano nitrogen was obtained as total nitrogen percentage by weight using the test method, ASTM D3590-02. Similarly, Zn concentration in the nano zinc formulation was estimated using inductively coupled plasma – mass spectroscopy (ICP-MS) using the test method ASTM D8110-17. Nano fertilizers were characterized and diluted with an effective concentration of nano nitrogen as 100 ppm, nano zinc as 20 ppm, and nano copper as 10 ppm. The diluted nano formulations were mixed just before the use. The nano formulations were foliar-sprayed on the plant leaves two to three times during the life cycle of the plant at critical growth stages.

Nano Urea – Liquid (Nano N)

IFFCO nano urea (liquid) has been notified under Fertiliser (Inorganic, Organic or Mixed) (Control) Order 1985 (FCO, 1985), Government of India. As per specifications of IFFCO nano urea – liquid (nano

Table 1. Specifications of IFFCO Nano Urea (Liquid) as per Clause 20 D of FCO, 1985

S. No.	Parameters	Specifications
1	Total nitrogen (% by wt.)	1-5
2	Particle size in nanometer (nm) in one dimension (minimum 50 % of the material)	
	a) Physical particle size	20-50
	b) Hydrodynamic particle size	20-80
3	Zeta potential in mV (+/- scale)	> 30
4	Viscosity in cps	5-30
5	pH	4.5-6.0

nitrogen), the particle size is less than 100 nm **(Table 1)**. It contains 4% N and has a shelf-life of about 2 years. It has a zeta potential > 30 and is stable. Nano urea – liquid (nano nitrogen) is sprayed @ 2 – 4 mL L^{-1} of water depending on the crop nitrogen requirement, crop canopy development, and amount of water required for the standing crop. It is sprayed at critical crop growth stages when crop canopy is suitably developed for proper intake of foliar nutrients. First spray of nano urea is undertaken at 30-35 days after germination or 20-25 days after transplanting and the second spray at one week before flowering. Number of sprays and spray concentration were synchronised as per the crop N requirement.

Nano Zinc and Nano Copper

IFFCO nano zinc and IFFCO nano copper are applied @ 2 mL L^{-1} of water. Nano zinc contains 1% Zn and nano copper contains 0.8% Cu in nano form. These are applied at critical crop growth stages when the zinc requirement is more or at a time when the crop may be experiencing its stress. One spray of nano zinc should be done 30-35 days after germination or 20-25 days after transplanting and one spray of nano copper should be done one week before flowering. Combined spray of nano urea, nano zinc and nano copper can also be done by mixing the product.

IFFCO nano fertilizers can be applied to most of cereals, millets, pulses, legumes, oilseeds, vegetables and fruit crops. Biosafety–biotoxicity studies of nano fertilizers [Nano Urea – liquid (Nano Nitrogen), Nano Zinc and Nano Copper] were undertaken as per "Guidelines for Evaluation of Nano-Based-Agri-Input & Food Products in India -2020" released by Department of Biotechnology, Government of India. These have been evaluated by NABL-accredited and GLP-certified laboratories **(Table 2)** and are reported to be safe for the user and for the environment.

Multi-location multi-crop on-station and on-farm trials of IFFCO nano fertilizers were conducted for studying the impact of these fertilizers on sustainability of crop production, nutrient use efficiency, and farmers' profitability (**Photo 2**). Research and farmer field trials have been undertaken by IFFCO for last more than 4 seasons on 13 crops at 43 locations (on-station) and on 94 crops across 21 states (on-farm) since 2019. Trials were continued during *Kharif* 2021-22 too in all the agro-climatic regions of India. Treatments were varied as per the research programme of IFFCO and the participating institute(s), depending upon the crop N requirement and testing facilities available at the research institutes. Graded levels of nitrogen (100 %, 75%, 50%, No N-control) or replacement levels based on split or top-dressed application of N fertilizers like urea (33% replacement, 50% replacement, 66% replacement or 100% replacement) were tested with single, double or triple spray of either single nano fertilizer or combination of nano urea-liquid (nano N), nano zinc and nano copper. Randomised block design (RBD) or CRBD, split plot with 3 replications were undertaken. All the standard analysis and estimation procedures, statistical designs, standard recommended doses of fertilizers (RDFs) for crops as per agro-climatic location, and stage of fertilizer application (basal, top-dressing) were adopted. Plant protection, weed control and

Table 2. Safety, biosafety and toxicity – Studies of IFFCO nano fertilizers by NABL* Accredited GLP certified laboratories.**

Tests conducted by IFFCO as per DBT# & OECD* Guidelines**

Human Health Safety
Dermal toxicity – IATA for skin corrosion and irritation (OECD TG 404); Skin Absorption Study (OECD TG 428); Eye Irritation Investigation (OECD TG 437); Inhalation Toxicity Study of Nanoparticles (OECD TG 433); Genotoxicity Study (OECD TG 473); Cytotoxicity Study (MTT & Neutral Red Assay)

Aquatic / Ecological - Environment Safety, Toxicity
Inhibition test in fresh water alga (OECD TG 201); Immobilization test in Daphnia (OECD TG 202); Toxicity in tropical fish (OECD TG 203); Fish embryo toxicity study (OECD TG 236); Earthworm reproduction study (OECD TG 222); Stability test of the nanomaterials (OECD TG 318); Soil – water leaching – spray on soil (OECD 312); Packaging compatibility test (OECD, ENV/JM/MONO (2019)12)

Rhizosphere, Contamination and Toxicity Studies
Toxicity on Microbes (FCO 1985 & DBT); Microbial Contamination study (FCO 1985 & DBT); Toxicity on mice and chicken (OECD 407 & DBT)

Stability and Trophic Transfer
NMR analyses of nitrogen; Plant uptake studies **(DBT)** ***Food Toxicity, Nutritional Value and Human Safety***
Nutritional analyses **(FSSAI@)**

Symbols' description
*NABL – National Accreditation Board for Testing and Calibration Laboratories
**GLP - Good Laboratory Practices
*** OECD- Organization of Economic Cooperation and Development
# DBT – Department of Biotechnology, Government of India
@ FSSAI- Food Safety & Standards Authority of India

Photo 2. On-station and On-farm trials of IFFCO nano fertilizers conducted on research farms and farmers' fields across India

irrigation were undertaken as per the need of crop. Growth and yield attributes, grain and straw yield, soil analysis, root studies, microbial studies, quantitative and qualitative analysis of physiological and biochemical traits were selectively undertaken. Foliar sprays of nano fertilizers were undertaken through hand/battery - operated knapsack sprayers with flat fan or cut nozzles for complete coverage of leaves. Spray was repeated wherever rain occurred within 12 hours of the application of spray. Foliar spray was done during morning or evening hours when there is no dew. Precautions were exercised by the operator. He protected himself by covering his body and wearing hand gloves and face mask while spraying nano fertilizers.

Results and Discussion

IFFCO has introduced nano urea (liquid) nitrogen to address low or declining use efficiency of nitrogen. Nano urea – liquid (Nano Nitrogen) utilises the dynamics of shape, size, surface area and better assimilation. Its application enhances plant metabolic processes, promotes meristematic activities; ensures higher apical growth and leaf photosynthetic area, triggers enzymes, and induces mechanisms/pathways inside the plant for achieving the desired N levels in amino acids/ protein content, chlorophyll content, nucleic acid, photosynthates, etc.

Precise and targeted application of nitrogen through foliar application of nano urea – liquid (nano nitrogen) reduces urea losses; increases nutrient uptake efficiency; and addresses environmental issues of soil, air and water pollution. It results in better crop harvest with lesser nitrogen application per unit area thus, leading to better farm economics. Spraying of nano urea – liquid (nano nitrogen) meets 100 ppm N requirement of crop at critical growth stages and triggers positive crop response, fulfils its nutritional requirement and also improves nutrient availability in the rhizosphere. When sprayed on leaves, nano urea – liquid (nano nitrogen) fertilizer easily gets absorbed and also enters through stomata due to its nano size (<100 nm). It is distributed to other plant parts through phloem translocation and metabolically assimilated as per the plant's need. Nano urea contains nanoscale nitrogen particles (18-30 nm) which have more surface area (10,000 times over 1 mm urea prill) and number of particles (55,000 nano urea – liquid (Nano nitrogen) particles over 1 mm urea prill by mass volume). Nano urea – liquid (nano nitrogen) particles with pore size (20 nm) can easily penetrate through cell wall and reach up to plasma membrane. Large size particles (20 - 50 nm) can penetrate through stomatal pores. These are also transported via phloem cells through plasmodesmata (40 nm diameter) to other plant parts. These can bind to carrier proteins through aquaporin, ion channels, and through endocytosis and metabolized inside the plant cell. Primary aim of nano zinc and nano copper nanofertilizers is to substitute their conventional fertilizer analogues which have use efficiency between 2-5 %, increase crop productivity, and enhance its quality through agronomic fortification. Furthermore, nano zinc also helps plant to take up more phosphorus, leads to better

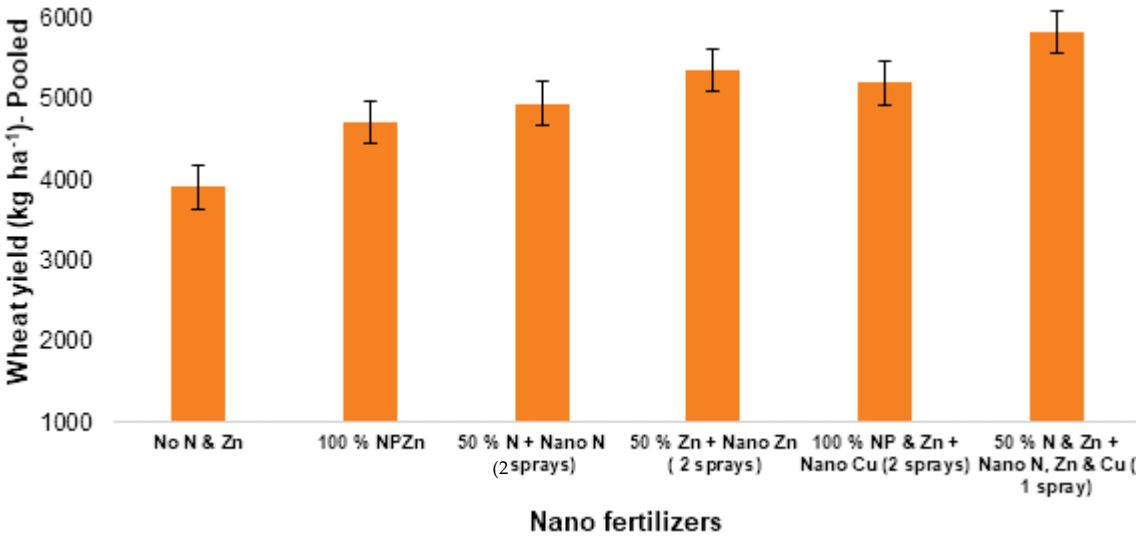

Figure 1. Effect of nano fertilizers on wheat grain yield at Regional Research Station, Anand during *rabi* seasons of 2019-20 and 2020-21

physiological growth, and brings uniformity in shape and size of fruits. Similarly, nano copper builds innate immunity of crops against harmful fungal and bacterial pathogens which affects their overall growth and development. When nano zinc and nano copper are sprayed on the leaves because of small size these can be easily absorbed by the plant either directly or through stomatal openings. On entering through the leaves, these are distributed to plant parts through phloem translocation and metabolically assimilated as per the plant's need. Data received from different research institutes/state agriculture universities largely confirmed the performance of nano fertilizers. Variability occurred due to soil conditions, fertility status, human error and crop type. Results confirm that NUE can be improved by synchronizing the nutrient availability as per the need of the crops. Here, foliar application of nano fertilizers at critical growth stages of crops can provide opportunity for improving nutrient utilisation, arresting/minimising nutrient losses from the crop production system (Liu and Lal, 2015; Preetha and Balakrishnan, 2017; Raliya et al., 2018; Kumar et al., 2020a,b, 2021; Lahari et al., 2021).

Crop-wise and cropping system-wise results are summarised as below:

Maize – Wheat and Mustard – Pearl Millet Cropping Systems

Results of field experiments conducted at the Regional Research Station, Anand, Gujarat during 2019-20 and 2020-21 on wheat (cv. GW 451) demonstrated that application of 50% N along with foliar application of nano nitrogen at tillering stages (25 DAS), nano zinc (at 38 DAS) and nano copper (at 53 DAS) significantly increased the grain yield (5,813 kg ha^{-1}) and straw yield (6,933 kg ha^{-1}) (**Figure 1**). Application of nanofertilizer did not change the electrical conductivity, pH, organic carbon, available major nutrients (N, P_2O_5 and K_2O) as well as DTPA extractable micronutrients (Fe, Mn, Cu) in soil after harvest of wheat crop. The experimental soil was classified as Typic Haplustept having loamy sand soil texture, slightly alkaline (8.01) in reaction (pH:1:2 H_2O). Organic carbon and available N contents were low. Available K_2O and available P_2O_5 were medium in status.

In experimental trials conducted under *kanhar* (Vertisols) soils at the Research Farm of IGKVV, Raipur during *rabi* 2019-20 and 2020-21 on performance of wheat (cv. GW-366), application of 2 sprays of nano nitrogen (tillering and before flowering) with 50% N + 100% PKZn increased the yield of wheat crop and saved 50% on N as the yields obtained with this treatment were at with those of 100% RDF. Response of nano nitrogen is also likely to be influenced by the initial nutrient status of the soil. Soil was neutral in reaction, low in organic carbon and available nitrogen, medium in available potassium, but all the micronutrients were above the critical level of their deficiencies. As reflected in yield and yield attributes, wheat variety WH-711 responded well to nano urea – liquid (nano nitrogen) fertilizer application at CCSHAU, Hisar farm during *kharif* 2019-20. Application of 75% NPK with 2 sprays of nano nitrogen at 27 days after sowing (DAS) and 44 DAS produced wheat grain yield statistically at par with that obtained with 100% RDF, suggesting on 25% saving on N-fertilizer.

A field experiment was conducted at University Farm of GBPUAT, Pantnagar on wheat (cv. HD 2967) in *rabi* 2020-21 in a sandy loam soil (pH 6,29; EC 0.26 dS m^{-1})

having 0.86% organic carbon and 220.4 kg ha^{-1}, 20.2 kg ha^{-1}, and 200.8 kg ha^{-1} available N, available P and available K, respectively. Results revealed that the foliar sprays of nano nitrogen formulation in wheat at 27 and 44 days after sowing along with 100% fertilizer N gave numerically additional yield of 188 kg ha^{-1} over 100% fertilizer N alone. Two foliar sprays of nano nitrogen with 75% and 50% fertilizer N resulted in 181 and 245 kg ha^{-1} more grain yield than the 75 and 50% fertilizer N alone application.

An experiment was conducted at the Research Farm of ICAR- IARI, Pusa to assess the performance of nano fertilizers under maize-wheat and pearl millet-mustard cropping systems starting with effect from *rabi* 2019-20. Nano fertilizers were applied through foliar sprays along with the graded N doses. Soils of the experimental farm site were sandy loam and mildly alkaline (pH 8.22) and non-saline (EC 0.24 dS m^{-1}). Top soil (0-15 cm) contained 0.58% organic C; 272 kg ha^{-1} available N, 22.3 kg ha^{-1} available P, 311 kg ha^{-1} available K, and 0.84 mg kg^{-1} DTPA-extractable Zn. Response of nanofertilizers was recorded in control plot block and in graded fertilizer block in both mustard and wheat **(Figures 2** and **3**). It was observed through the application of nanofertilizers (alone or in combination) with graded doses of fertilizers that the fertilizer N dose by up to 25% in wheat and 50% in mustard could be substituted by the two sprays of nano nitrogen. Application of 2 sprays of nano nitrogen reduced the recommended N dosage by 50%. Application of 3 sprays of nano N + nano Zn + nano Cu alternately with 50% N and 50% Zn also led to a significant increase in yield which was statistically at par with RDF. These results are in consonance with those obtained at MPUAT, Udaipur; RARI, SKNAU, Jobner, Rajasthan; and BAU, Ranchi, Jharkhand.

Paddy (Rice)

Nano fertilizer trials conducted at the Research Farm of IGKVV, Raipur on rice (cv. Rajeshwari) during *kharif* 2020 showed at par yield in treatment receiving 2 foliar sprays of nano urea – liquid (nano nitrogen) with 50% saving of nitrogen with 100% RDF. Maximum grain yield (5,848 kg ha^{-1}) was observed in treatment receiving 2 sprays of nano zinc.

Application of foliar spray of nano N, nano Zn, and nano Cu fertilizers was found to be effective in terms of improving growth and yield of paddy (cv. IR-30864) – *kharif* 2020 at Mandya Farm of UAS, GKVK, Bengaluru. Significantly higher yield (6.39 t ha^{-1}) and B:C ratio was recorded in the treatment receiving 50% N, 0% Zn and 100% PK + alternate sprays of nano N, nano Zn, and nano Cu while at par yield (6.34 t ha^{-1}) and B:C ratio (2.82) was recorded in RDF. Results of the experiment conducted at Assam Agricultural University on rice cv. Ranjit during *kharif* 2020-21 revealed a positive impact of nano fertilizers on

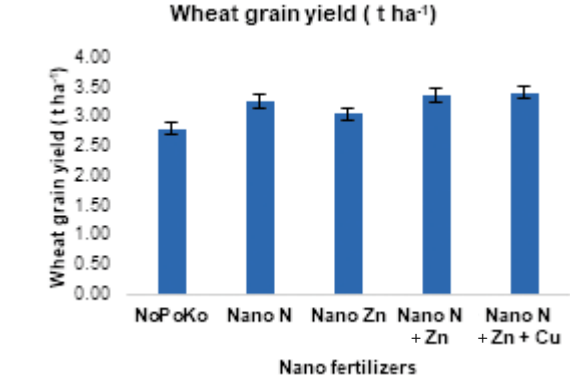

Figure 2. Effect of nano N, nano Zn and nano Cu in absence of fertilizer NPK on the grain yield of wheat (Error bars indicate SEM± (n=3))

growth of rice crop as compared to the control. Treatment with RDF (50% N + 100% PK) + 2 sprays of Nano N recorded 5.30 t ha^{-1} yield over 4.26 t ha^{-1} in RDF. Experimental trials were conducted at University of Agricultural and Horticultural Sciences, Shimoga on paddy (cv. Jyoti) during summer 2019-20 under drip irrigation. Maximum yield of 3,164 kg ha^{-1} and B:C ratio of 2.53 was recorded in treatment T_5 (50% N and 2 sprays of Nano N) while yield under RDF was 2,775 kg ha^{-1}.

Maize and Pearl Millet

Foliar application of nano particles as an alternative to soil application was found to be effective in enhancing yield and benefit-cost ratio in maize (Hybrid N-6240) during summer seasons of 2019-20 and 2020-21 at UAS, Raichur, Karnataka (Ajith Kumar et al., 2021). Among the different combinations of nano fertilizers with recommended dose of fertilizers, the treatment T_{11} [50% N, 100% PK, 0% Zinc + 2 sprays of nano N (4 mL L^{-1}) mixed with IFFCO Sagarika (2 mL L^{-1})] showed significant effect on the growth and yield parameters with

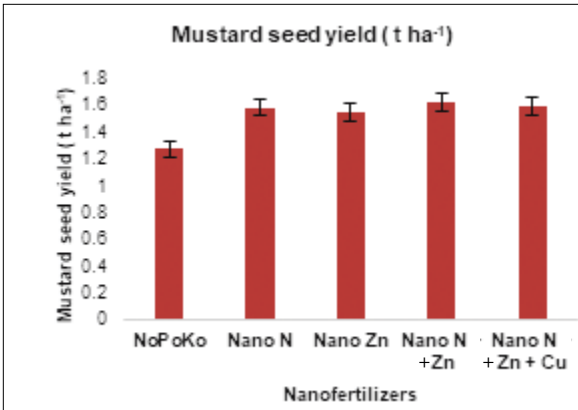

Figure 3. Effect of nano N, nano Zn and nano Cu in absence of fertilizer NPK on the seed yield of mustard (Error bars indicate SEM± (n=3))

maximum yield of 5,890 kg ha^{-1} and highest B:C of 2.99. Treatment T_{10} [50% N, 100% PK, 0% zinc + 2 sprays of nano N (4 mL L^{-1}) mixed with nano Zn (2 mL L^{-1}) and nano Cu (2 mL L^{-1})] was found superior with regard to management of Turcicum leaf blight disease with minimum of 18.20% severity.

Foliar application of nano N, nano Zn and nano Cu significantly increased the yield attributing characters *viz.,* plant height, days to silking, number of cobs per plant, number of seeds per cob, cobs per plot; ear length (cob); ear girth; test weight and root biomass in experiments conducted on maize during *kharif* 2020-21 at AAU, Anand, Gujarat. Experiment conducted at RARI, SKNAU, Durgapura during *kharif* 2020-21 also confirmed that foliar feeding of nano N + nano Zn in pearl millet (*bajra*) crop could be an efficient method for maximizing yield under semi-arid conditions of Rajasthan. Application of nano N + nano Zn in combination with 50% of recommended dose of traditional nitrogenous fertilizers (urea) and zinc sulphate may provide an effective solution to enhance the crop growth and productivity.

Cotton

Efficacy of nanoparticles on growth, yield parameter and foliar diseases of cotton was evaluated at Main Experimental Station (MES), UAS, Raichur, Karnataka during 2020-21 on cotton (hybrid RCH-659). It was observed that application of nano fertilizers *viz*., nano Urea – liquid (nano nitrogen) (@ 4 mL L^{-1}) and nano Zn and nano Cu (@ 2 mL L^{-1}) in combination with 50% soil application of fertilizers is an attractive alternative to the soil application of fertilizers for better growth and development. It was found to be effective in enhancing yield as well as provided higher B:C ratio. First foliar spray of recommended nanoparticles at 45 DAS and the second spray at 65 DAS to cotton were given. Maximum yield of 2,434 kg ha^{-1} of seed cotton was recorded under the treatment receiving 50% N, 100% PK and 0% Zn application along with 2 sprays of nano N @ mL L^{-1} mixed with Sagarika @ 2 mL L^{-1} followed by treatment receiving combined spray of nano fertilizers (nano N, nano Zn and nano Cu) with a yield of 2,333 kg ha^{-1}; this yield was 23% (441 kg) more than the yield of 1892 kg ha^{-1} recorded in the RDF plot.

Onion and Tomato

In an experimental trial conducted on onion (N-2-4-1) under drip-fertigation at MPKV, Rahuri during 2019-20, 2 sprays of nano N increased the crop yield even at 50% reduced dose of nitrogen (urea) over RDF. Significantly superior yield of onion (38.92 t ha^{-1}) was obtained in treatment T_{11} (drip irrigation with 75% RDN and Zn; 100% RD of PK + 3 foliar sprays of nano N, Zn and Cu) over all other treatments. Application of 50% RDN along with 2 sprays of nano N gave higher yield over 100% RDF and was at par with the best treatment. Nutrient availability showed improvement with the foliar application of nano fertilizers [nano urea – liquid (nano N), nano Zn and nano Cu].

Similarly, in experiments conducted with nano fertilizer in hybrid tomato (Ayushman) under drip fertigation during *kharif*/summer 2019-20 at MPKV, Rahuri, availability and uptake of nutrients was found to be improved with foliar sprays of nano N, Zn and Cu over other treatments. Significantly, maximum yield of tomato (70.48 t ha^{-1}) was recorded in treatment T_9 (100 % RDF + 2 sprays of Nano Cu) receiving 2 sprays of nano copper followed by treatment T_8 (68.41 t ha^{-1}) which received 2 sprays of nano Zn along with 50% reduction in application of conventional zinc fertilizers. Treatment T_9 also recorded highest B:C ratio of 4.34.

Summary of the results on application of nano urea – liquid (nano N) across locations revealed that two foliar applications at critical growth stages of crops like rice, wheat, maize, tomato, cucumber and capsicum led to a reduction in the application rate of fertilizer-N and also caused increase in the yield in range of: 3-23% in wheat, 5-11% in tomato, 3-24% in paddy/rice, 2-15% in maize, 5% in cucumber, and 18% in capsicum (**Table 3)**. Foliar application of nano urea, thus, increased the number of effective tillers, enhanced the growth and raised the biomass yield (both grain and straw yields) in most of the crops at different locations. Economic benefits (BCR or ROI) of nano fertilizer application have to be seen from the perspective of extra yield achieved along with reductions in fertilizer usage as well as direct and indirect benefits in terms of reduction in the environmental (soil-air-water) pollution.

Farmer Field Trials (FFTs) with IFFCO Nano Fertilizers

More than 11,000 FFTS were undertaken by IFFCO along with some trials in close coordination with ICAR-KVKs during *rabi* 2019-20. Results of 9073 successful trials on different crops indicated yield increase of 8% with 50% less application of top-dressed urea by the farmers.

Mean effects of nano fertilizers on grain yield of wheat under different treatments, additional yields and economic returns over FFPs with respect to 480 farmer field demonstrations conducted in Rajasthan state are presented in **Figure 4.** The lowest and highest grain yields as influenced by different nano- treatments varied between 2,250 and 2,400 kg ha^{-1}, and 6,410 and 6,875 kg ha^{-1}, respectively; the mean yields were in the range of 4,330 to 4,628 kg ha^{-1}. The grain yield

Table 3. Effect of foliar application of nano urea–liquid (nano N) on different crops in "on-station' trials across India

S. No.	Location/State	Crop	Season	Yield in RDF plot (t ha^{-1})	Yield in 50% N and nano N (2 sprays) plot (t ha^{-1})
1	Annamalai, Tamil Nadu	Capsicum	*Rabi* 2019-20	16.30	19.21
2	Bengaluru, Karnataka	Cucumber	*Rabi* 2019-20	120.10	126.60
3	Telangana	Maize	*Kharif*/Summer 2019-20	6.63	6.75
4	Raichur, Karnataka	Maize	*Kharif*/Summer 2019-20	5.08	5.83
5	Raichur, Karnataka	Maize	*Kharif* 2020-21	4.74	4.94
6	Bengaluru, Karnataka	Maize	*Kharif* 2020-21	8.31	9.14
7	Shimoga, Karnataka	Paddy	*Kharif*/Summer 2019-20 & 2020-21	2.78	3.16
8	Jorhat, Assam	Rice	*Kharif* 2020-21	4.26	5.30
9	Bengaluru, Karnataka	Rice	*Kharif* 2020-21	5.26	5.42
10	Shimoga, Karnataka	Tomato	*Kharif*/Summer 2019-20	64.66	72.07
11	Rahuri, Maharashtra	Tomato	*Kharif*/Summer 2019-20	60.89	63.90
12	Anand, Gujarat	Wheat	*Rabi* 2019-20 & 2020-21	4.70	4.82
13	Ranchi, Jharkhand	Wheat	*Rabi* 2019-20	3.43	4.22
14	Udaipur, Rajasthan	Wheat	*Rabi* 2019-20	4.42	5.31
15	Jaipur, Rajasthan	Wheat	*Rabi* 2019-20	4.82	5.55
16	Ayodhya, Uttar Pradesh	Wheat	*Rabi* 2019-20	3.20	3.94

under T_5 (FFP-50% N) + one spray of each of nano N, nano Zn and nano Cu) was highest (4,628 kg ha^{-1}) with additional increase of 298 kg ha^{-1} over FFP and per cent increase of 6.97. The economic return over FFP was also highest with T_5 (Rs. 5,727 ha^{-1}) and second in order was T_2 (FFP-50% N + 2 sprays of nano N). As compared to FFP, the economic return with T_3 (FFP + 2 sprays of nano Zn) and T_4 (FFP + 2 sprays of nano Cu) were Rs. 3,080 ha^{-1} and RS. 2,791 ha^{-1}, respectively.

Data on grain yield, additional grain yield and economic returns of mustard with respect to 70 farmer field trials conducted in Rajasthan is presented in **Figure 5.** Results showed that the lowest yields varied in a very narrow range from 1,100 to 1,200 kg ha^{-1} and so did the highest yields which ranged from 4,200 to 4,600 kg ha^{-1}. The mean grain yield under different treatments varied between 2650 and 2890 kg ha^{-1} being highest under T_5 and the lowest under FFP with per cent increase of 9.91. The additional yield under T_5 over FFP was 240 kg ha^{-1} followed by T_3 (185 kg ha^{-1}), T_2 (100 kg ha^{-1}) and T_4 (10 kg ha^{-1}). Economic returns over FFP were also highest with T_5 (Rs. 10,620 ha^{-1}) followed by T_3 (Rs. 8,186 ha^{-1}), T_2 (Rs. 4,425ha^{-1}), and T_4 (Rs. 443 ha^{-1}).

Conclusions

Application of nanotechnology is increasing in every sphere of human life. In crop production, it provides an opportunity of developing/refining innovative and need-based nutrient application. It offers reduced cost of agri-inputs as well as enhanced efficiency of fertilizers with minimal losses to the environment. Reactive N pollution (NO_3^-, NH_4^+, N_2O) has emerged

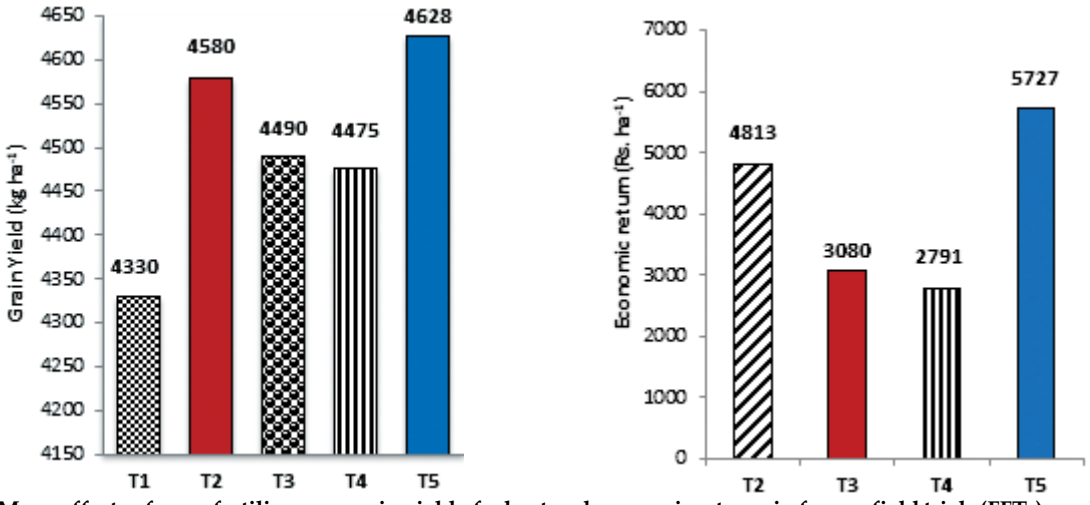

Figure 4. Mean effects of nano fertilizers on grain yield of wheat and economic returns in farmer field trials (FFTs) conducted in Rajasthan (No. of trials – 480) (Source: Kumar et al., 2020b)

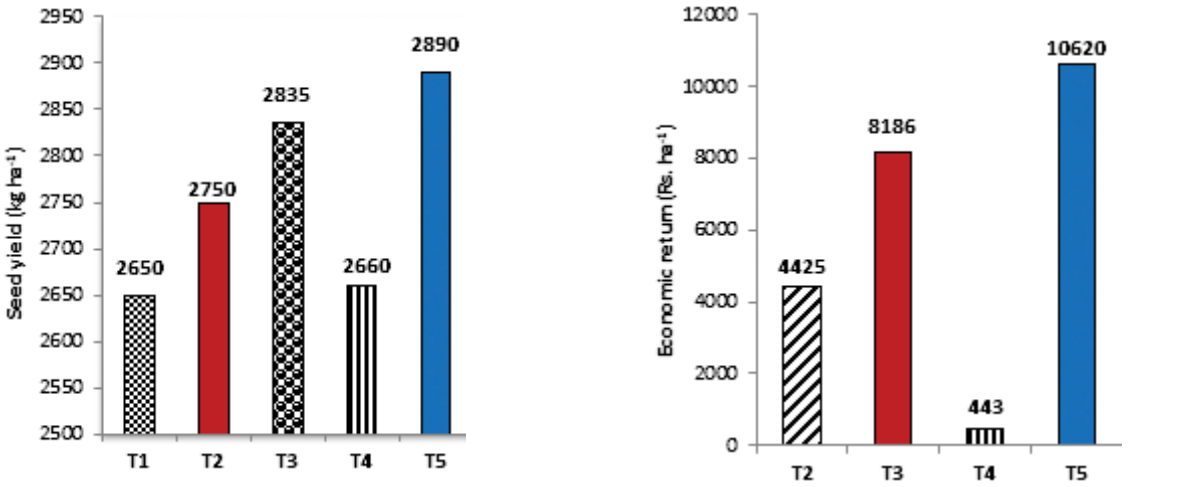

Figure 5. Mean effects of nano fertilizers on seed yield of mustard and economic returns (No. of trials – 70) (Source: Kumar et al., 2020b)

as a major factor responsible for environment pollution, and the same is being targeted globally for rational reduction. Excessive N application in agriculture through bulk chemical fertilizers has to be reduced in a phased manner for ensuring healthy environment and sustaining soil-crop-atmospheric biodiversity.

Nanotechnology, as one of the innovative solution, offers definitive advantage in terms of size, shape, quantity and efficacy of nano scale formulations. Through, nano agri-inputs nutritional requirement of crops can effectively be met through targeted, stage-wise and slow-release application without disturbing the agri-ecology. These also trigger nutrient pathways and address the constraints faced by crops in assimilation and absorption of nutrients from soils. Application of nano fertilizers enhances bioavailability of nutrients by triggering the alternative pathways and enzymes inside the plant system, increases the root biomass and rhizospheric microbial population. Synchronization of application of nano fertilizers with crop demand is a sustainable strategy. Nano fertilizers have to be viewed in totality as a package addressing the practical crop nutrient solutions in the light of constraints at the field level. It is high time that nano fertilizers for major, secondary and micronutrients as well as their composite combination products be accepted as an informed effective solution to overcome the contemporary challenges faced by modern day intensive agriculture.

Acknowledgement

Authors are thankful to the Scientists of ICAR Research Institutes, State Agricultural Universities, ICAR-Krishi Vigyan Kendras (KVKs) and the field officers of IFFCO for conducting on-field nano fertilizer experiments across the country.

References

Ajith Kumar, K., Kumar, Y., Savitha, A.S., Ajayakumar, M.Y., Narayanaswamy, C., Raliya, R., Krupashankar, M.R. and Bhat, S.N. 2021. Effect of IFFCO nanofertilizer on growth, grain yield and managing turcicum leaf blight disease in maize. *International Journal of Plant and Soil Science* **33(16)**, 19-28.

Kumar, Y., Tiwari, K.N., Nayak, R.K., Rai, A., Singh, S.P., Singh, A.N., Kumar, Y., Tomar, H., Singh, T. and Raliya, R. 2020b. Nano fertilizers for enhancing nutrient use efficiency, crop productivity and economic returns in winter season crops of Uttar Pradesh. *Indian Journal of Fertilizers* **16**, 772-786.

Kumar, Y., Tiwari, K.N., Singh, T., Sain, N.K., Laxmi, S., Verma, R. Sharma, G.C. and Raliya, R. 2020a.Nano fertilizers for enhancing nutrient use efficiency, crop productivity and economic returns in winter season crops of Rajasthan. *Annals of Plant and Soil Research* **22**, 324-335.

Kumar, Y., Tiwari, K.N., Singh, T. and Raliya, R. 2021. Nano fertilizers and their role in sustainable agriculture. *Annals of Plant and Soil Research* **23**, 238-255.

Lahari, S., Hussain, S.A., Parameswari, Y.S. and Sharma, K.H.S. 2021. Grain yield and nutrient uptake of rice as influenced by the nano forms of nitrogen and zinc. *International Journal of Environment and Climate Change.* **11(7)**, 1-6.

Liu, R. and Lal, R. 2015. Potentials of engineered nanoparticles as fertilizers for increasing agronomic production. *Science of the Total Environment* **514**, 131-139.

Preetha, P.S. and Balakrishnan, N. 2017. A review of nano fertilizers and their use and functions in soil. *International Journal of Current Microbiology and Applied Sciences* **6**, 3117-3133.

Raliya, R., Saharan, V., Dimkpa, C. and Biswas, P. 2018. Nano fertilizers for precision and sustainable agriculture: current status and future perspectives. *Journal of Agricultural and Food chemistry* **66,** 6487-6503.