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Nanofertilizers for Increasing Nutrient Use Efficiency, Yield and Economic Returns in important Winter Season Crops of Uttar Pradesh

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Abstract

Nanofertilizers are gaining importance in agriculture in increasing crop yields, enhancing nutrient use efficiency, and reducing excessive use of chemical fertilizers. Results of 730 field demonstrations conducted in different districts of Uttar Pradesh by IFFCO on farmers' fields with 12 crops proved that with the use of nano-nitrogen (Nano-N), the quantity of urea being applied by the farmers to supply nitrogen to their crops can be successfully reduced to half. The yields obtained with 50% less nitrogen as compared to the N applied under farmers fertilizer practice (FFP) and applying 2 sprays of Nano-N in standing crops gave yields higher than FFP in most of the crops tested in these demonstrations. Apart from this, effect of Nano-Zn and Nano-Cu was also evaluated. As the deficiencies of micronutrients are not universal like N, positive responses to these nanofertilizers depended on the magnitude of the deficiency of specific nutrient [zinc (Zn) or copper (Cu)] and the nature of the crops. This paper describes the results of 730 on-farm trials conducted on 12 important crops grown during winter season of 2019-20.

Key words: Nanofertilizers – nanofertilizers, Nano-N, Nano-Zn, Nano-Cu, crop responses to nanofertilizers, wheat, pulses, oilseeds, potato, tomato, garlic, amaranthus, nutrient use efficiency, economic returns.

Introduction

Sustainable agriculture, food availability and nutritional security are among the key sustainable development goals of the century. However, food security is now a challenging issue for the rising population due to the limited available resources with progressive climate change throughout the world. Human population is constantly on the rise making it a must to produce more food. As per UN estimates, planet Earth will inhabit about 9.6 billion people by 2050 AD (UNDESA, 2015). This burgeoningly rising world population calls for commensurate increase in agricultural productivity to satisfy the food needs of its inhabitants. Geometrically multiplying multi-nutrient deficiencies in soils are causing significant losses to farmers (both yield and economic); deterioration in nutritional quality of grains for food and feed also hurting the end-consumers.

Conventional fertilizers offer nutrients in chemical forms that are not often fully accessible to plants. Additionally, inversion of these chemical fertilizers to sparingly soluble forms in soil is the reason for the very low utilization of most of the added macronutrients. These problems make it imperative to go in for the repeated use of fertilizers. It is fairly well known that the yields of many crops have begun to drop as a result of imbalanced fertilization and decrease in soil organic matter. In addition to the irreparable damage that the excess use of chemical fertilizers causes to the soil structure and mineral cycles, excessive (often indiscriminate) and imbalanced application of fertilizers spoils the soil microflora, plants, and consequently, the food chains across ecosystems, leading to heritable mutations in future generations of consumers. Heavy use of nitrogen (N) and phosphorus (P) fertilizers has become the major anthropogenic factor leading to world-wide eutrophication problems in freshwater bodies and coastal ecosystems (Correll 1998; Conley et al. 2009). To deal with such situation, it is very important to develop smart materials that can systematically release nutrients to specific targeted sites in plants which could be beneficial in controlling their deficiencies in agriculture, while keeping intact the natural soil structure. Such a strategy has a potential to contribute to clean the environment through controlled release of nutrients through site-targeted delivery, reduction in toxicity, and enhanced nutrient utilization of delivered fertilizers. Nanofertilizers possess unique features which enhance plants' performance in terms of ultrahigh absorption, increase in production, rise in photosynthesis, and significant expansion in the leaves' surface area. Besides, the controlled release of nutrients contributes in preventing eutrophication and pollution of water resources. Replacement of traditional fertilizer by nanofertilizer is beneficial as upon application, it releases nutrients into the soil steadily and in a controlled way, thus preventing the water pollution (Naderi and Danesh-Shahraki 2013; Moaveni and Kheiri, 2011).

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Table 1. Treatment details

T1	Farmer's Fertilizer Practice (FFP)
T2	(FFP-50% N) + 2 sprays of Nano-N
T3	FFP + 2 sprays of Nano-Zn
T4	FFP + 2 sprays of Nano-Cu
T5	(FFP-50% N) + 1spray of Nano-N + 1 spray of Nano-Zn + 1 spray of Nano-Cu

Picture 1. IFFCO Nanofertilizers tested in this investigation

The world's largest and wholly owned by cooperatives, Indian Farmers Fertiliser Cooperative Ltd. (IFFCO) has introduced its nanotechnology-based products *i.e.*, Nano-N, Nano-Zn and Nano-Cu for initial testing as part of its efforts to cut usage of chemical fertilizers and boost farmers' income. In view of paucity of information on performance of nanofertilizers (Nano-N, Nano-Zn and Nano-Cu), this investigation was undertaken to evaluate the effect of foliar sprays of these nanofertilizers on yield and economic returns of 12 important crops grown during winter season in Uttar Pradesh and the results of the study are presented in this paper.

Materials and Methods

Of the 1100 demonstrations conducted on farmers' fields with 19 crops in different districts of Uttar Pradesh during *rabi* 2019-20, 730 demonstrations on 12 crops were successfully harvested. The crops were sown in the months of November and December 2019 with 5 treatments, details of which are presented in **Table 1**. Nanofertilizers namely, Nano-N, Nano-Zn and Nano-Cu (**Picture 1**) had nutrient concentrations of 25000, 5000 and 2000 mg L^{-1}, respectively. Four mL of these liquid fertilizers were added in 1L of water and for one acre 500 mL of nanofertilizers were added to 125 L of water and sprayed as per treatments detailed in **Table 1**. The first spray was done three weeks after full germination in each crop and the second spray was made 10-15 days after 1st spray or 5 weeks after full germination. The field was kept weed-free as far as practical according to means and will of the farmers. Plant protection measures were adopted as per need of the crop. The crops were harvested at full maturity and the yield data were recorded from the net plot area harvested.

Results and Discussion

Data emanating from 730 demonstrations with respect to economic yield, the range and mean of responses, additional yields and economic returns recorded over FFP are given in **Table 2**. Crop-wise results are described in following paragraphs.

Wheat (Triticum aestivum*)*

Mean effects of nanofertilizers on grain yield of wheat under different treatments, additional yield and economic return over FFP are summarised in **Table 2** and **Figure 1** and crop performance under the influence on nano-fertilizers *vis-à-vis* FFP in two demonstrations is depicted in **Pictures 2** and **3**. The lowest and highest grain yields under different nano treatments varied from 2,490 to 2,617 kg ha^{-1} and 6,165 to 6,875 kg ha^{-1}, respectively; mean yields were in the range of 4,354 to 4,779 kg ha^{-1}. Grain yield under T2 [(FFP-50% N) + 2 sprays of of Nano-N] was the

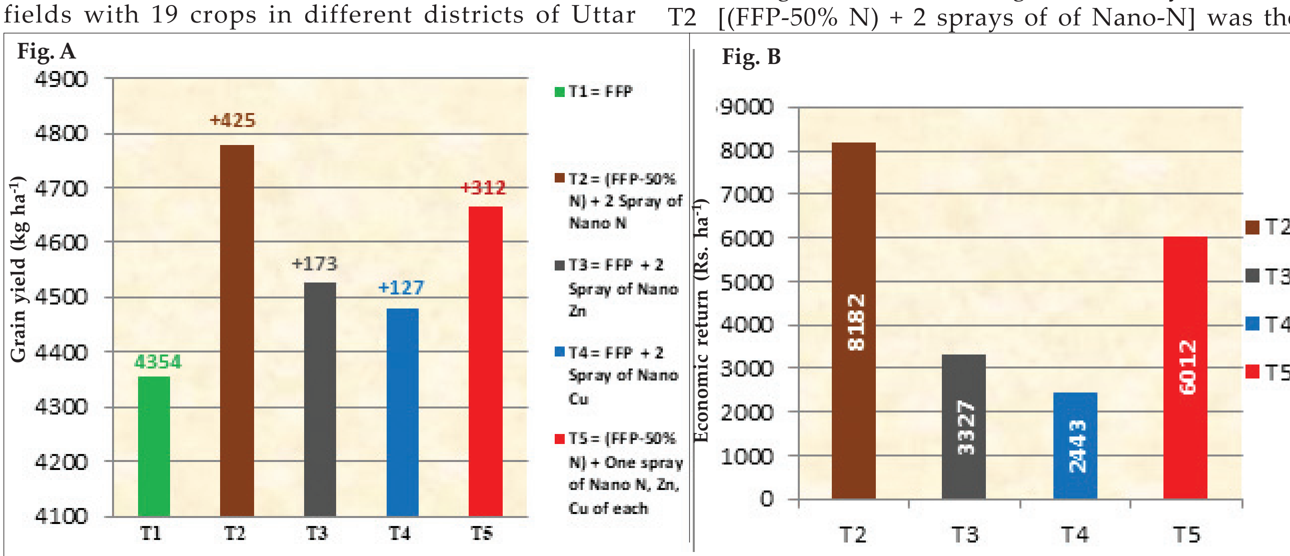

Figure 1. Mean effect of IFFCO nanofertilizers on grain yield of wheat and economic returns (No. of trials - 431)

Table 2. Effect of IFFCO nanofertilizers on economic yield of 12 crops

S. No.	Crop (Data in parenthesis are number of trials)		Farmer's Fertilizer Practice (FFP)	(FFP - 50% N) + 2 sprays of Nano- N	FFP + 2 sprays of Nano-Zn	FFP + 2 sprays of Nano-Cu	(FFP - 50% N) + 1 spray of Nano-N + 1 spray of Nano-Zn + 1 spray of Nano-Cu
1	Wheat (431)	Lowest yield (kg ha^{-1})	2,504	2,617	2,510	2,490	2,575
		Highest yield (kg ha^{-1})	6,165	6,650	6,250	6,200	6,875
		Mean yield (kg ha^{-1})	**4,354**	**4,779**	**4,527**	**4,481**	**4,666**
		Response over FFP(kg ha^{-1})	-	425	173	127	312
		Per cent increase over FFP	**-**	**9.76**	**3.97**	**2.92**	**7.17**
		Net return over FFP (Rs. ha^{-1})	-	8,182	3,327	2,443	6,012
2	Field Pea (26)	Lowest yield (kg ha^{-1})	1,560	1,850	1,670	1,620	1,650
		Highest yield (kg ha^{-1})	3,313	3,473	3,400	3,433	3,478
		Mean yield (kg ha^{-1})	**2,092**	**2,270**	**2,165**	**2,146**	**2,185**
		Response over FFP(kg ha^{-1})	-	178	73	54	93
		Per cent increase over FFP	**-**	**8.50**	**3.48**	**2.59**	**4.44**
		Net return over FFP (Rs. ha^{-1})	-	3,576	1,474	1,082	1,873
3	Lentil (5)	Lowest yield (kg ha^{-1})	625	680	665	660	650
		Highest yield (kg ha^{-1})	2,019	2,056	2,032	2,038	2,024
		Mean yield (kg ha^{-1})	**1,677**	**1,715**	**1,696**	**1,696**	**1,689**
		Response over FFP(kg ha^{-1})	-	38	19	19	12
		Per cent increase over FFP	**-**	**2.26**	**1.11**	**1.13**	**0.72**
		Net return over FFP (Rs. ha^{-1})	-	1,795	893	912	576
4	Amaranthus (3)	Lowest yield (kg ha^{-1})	2,453	2,760	2,515	2,490	2,675
		Highest yield (kg ha^{-1})	2,740	3,075	2,825	2,840	2,990
		Mean yield (kg ha^{-1})	**2,626**	**2,927**	**2,683**	**2,677**	**2,825**
		Response over FFP(kg ha^{-1})	-	301	57	51	199
		Per cent increase over FFP	**-**	**11.45**	**2.17**	**1.94**	**7.58**
		Net return over FFP (Rs. ha^{-1})	-	15,033	2,833	2,533	9,950
5	Mustard (44)	Lowest yield (kg ha^{-1})	425	492	456	462	480
		Highest yield (kg ha^{-1})	2,427	3,355	2,533	2,416	2,394
		Mean yield (kg ha^{-1})	**1,708**	**1,837**	**1,750**	**1,738**	**1,755**
		Response over FFP(kg ha^{-1})	-	129	42	30	47
		Per cent increase over FFP	**-**	**7.55**	**2.46**	**1.75**	**2.75**
		Net return over FFP (Rs. ha^{-1})	-	5,724	1,871	1,352	2,077
6	Potato (187)	Lowest yield (kg ha^{-1})	13,250	15,000	14,000	14,000	16,000
		Highest yield (kg ha^{-1})	61,200	64,300	61,800	61,800	62,700
		Mean yield (kg ha^{-1})	**32,298**	**35,414**	**33,568**	**33,824**	**34,798**
		Response over FFP(kg ha^{-1})	-	3,116	1,270	1,526	2,500
		Per cent increase over FFP	**-**	**9.65**	**3.93**	**4.72**	**7.74**
		Net return over FFP (Rs. ha^{-1})	-	31,165	12,702	15,259	24,997
7	Green Pea (12)	Lowest yield (kg ha^{-1})	7,500	8,000	7,500	7,500	9,000
		Highest yield (kg ha^{-1})	12,266	13,654	13,626	13,454	14,021
		Mean yield (kg ha^{-1})	**9,484**	**10,247**	**10,097**	**9,935**	**10,143**
		Response over FFP(kg ha^{-1})	-	763	613	451	659
		Per cent increase over FFP	**-**	**8.05**	**6.46**	**4.75**	**6.94**
		Net return over FFP (Rs. ha^{-1})	-	30,524	24,521	18,033	26,346
8	Tomato (5)	Lowest yield (kg ha^{-1})	23,000	30,500	29,310	31,000	30,250
		Highest yield (kg ha^{-1})	40,270	42,920	41,925	40,100	40,800
		Mean yield (kg ha^{-1})	**30,354**	**35,534**	**34,297**	**34,930**	**34,470**
		Response over FFP(kg ha^{-1})	-	5,180	3,943	4,576	4,116
		Per cent increase over FFP	**-**	**17.07**	**12.99**	**15.08**	**13.56**
		Net return over FFP (Rs. ha^{-1})	-	51,800	39,430	45,760	41,160

Table 2. Continued....

9	Cauliflower (4)	Lowest yield (kg ha^{-1})	29,500	30,670	29,880	30,450	29,660
		Highest yield (kg ha^{-1})	33,490	36,752	34,468	36,200	34,205
		Mean yield (kg ha^{-1})	**32,276**	**34,521**	**33,030**	**34,019**	**32,870**
		Response over FFP(kg ha^{-1})	-	2,245	754	1,743	594
		Per cent increase over FFP	**-**	**6.96**	**2.34**	**5.40**	**1.84**
		Net return over FFP (Rs. ha^{-1})	-	22,450	7,540	17,425	5,938
10	Cabbage (2)	Lowest yield (kg ha^{-1})	28,400	30,640	29,500	27,410	26,980
		Highest yield (kg ha^{-1})	33,550	34,440	33,970	34,230	33,450
		Mean yield (kg ha^{-1})	**30975**	**32540**	**31735**	**30820**	**30215**
		Response over FFP(kg ha^{-1})	-	1,565	760	-155	-760
		Per cent increase over FFP	**-**	**5.05**	**2.45**	**-0.5**	**-2.45**
		Net return over FFP (Rs. ha^{-1})	-	15,650	7,600	-1,550	-7,600
11	Garlic (6)	Lowest yield (kg ha^{-1})	7,000	7,800	7,300	7,350	7,400
		Highest yield (kg ha^{-1})	9,458	9,875	9,483	9,320	9,568
		Mean yield (kg ha^{-1})	**8,295**	**8,870**	**8,797**	**8,451**	**8,817**
		Response over FFP(kg ha^{-1})	-	575	502	156	522
		Per cent increase over FFP	**-**	**6.93**	**6.05**	**1.88**	**6.29**
		Net return over FFP (Rs. ha^{-1})	-	28,750	25,104	7813	26,104
12	Chilli (5)	Lowest yield (kg ha^{-1})	7,000	7,700	7,300	7,500	7,200
		Highest yield (kg ha^{-1})	9,000	9,900	9,500	9,600	9,300
		Mean yield (kg ha^{-1})	**8,000**	**8,800**	**8,420**	**8,560**	**8,300**
		Response over FFP(kg ha^{-1})	-	800	420	560	300
		Per cent increase over FFP	**-**	**10**	**5.25**	**7**	**3.75**
		Net return over FFP (Rs. ha^{-1})	-	16,000	8,400	11,200	6,000

Picture 2. Comparative performance of FFP (T1) and FFP-50% N + 2 sprays of Nano-N (T2) with wheat crop after one spray in the demonstration conducted in Deoria district

Picture 3. Comparative performance of FFP (T1) and FFP-50% N + 2 sprays of Nano-N (T2) with wheat crop in the demonstration conducted in Budaun district

Picture 4. Comparative performance of FFP + 2 sprays of Nano-Zn (T3) and (FFP-50% N) + 2 sprays of Nano-N (T2) with amaranthus crop in the demonstration conducted in Lucknow district

highest (4,779 kg ha^{-1}) with additional increase of 425 kg ha^{-1} over FFP, giving 9.76% increase. The economic return over FFP was also highest under T2 (Rs. 8,182 ha^{-1}) and second in order was under T5 [(FFP-50% N) + one spray of Nano- N, Zn, Cu each)]. As compared to FFP, the economic return with T3 (FFP + 2 sprays of Nano-Zn) and T4 (FFP + 2 sprays of Nano-Cu) were Rs. 3,327 and Rs. 2,443 ha^{-1}, respectively.

***Field Pea* (Pisum sativum)**

Data presented in **Table 2** and **Figure 2** show that the lowest yields of pea ranged from 1,560 to 1,850 kg ha^{-1} while the highest yield varied between 3,313 and 3,478 kg ha^{-1} under different treatments, highest yield being with T_5 and lowest with FFP. Mean yields ranged from 2092 to 2270 kg ha^{-1}. Yield under T2 [(FFP-50% N) + 2 sprays of Nano-N)] was highest (2,270 kg ha^{-1}), producing additional yield of 178 kg ha^{-1} over FFP which exhibited an increase of 8.50%. Economic return over FFP was also highest with T2 (Rs. 3,576 ha^{-1}) followed by T5 [(FFP-50% N) + one spray of Nano- N, Zn, Cu each)], T3 (FFP + 2 sprays of Nano-Zn) and T4 (FFP + 2 sprays of Nano-Cu), respectively. Economic returns with T5, T3 and T4 were Rs. 1,873, 1,474 and 1,082 ha^{-1}, respectively.

***Lentil* (Lens culinaris)**

As depicted in **Table 2** and **Figure 3**, the lowest grain yield of lentil as influenced by different treatments ranged from 625 to 680 kg ha^{-1} and the highest yield varied from 2,019 to 2,056 kg ha^{-1}. Mean grain yield under different treatments varied between 1677 and 1715 kg ha^{-1}, being highest under T2 and the lowest under FFP showing a per cent increase of 2.26. Yield under T2 [(FFP-50% N) + 2 sprays of Nano-N)] was the highest (1,715 kg ha^{-1}) with additional yield of 38 kg ha^{-1} over FFP. The economic return over FFP was also highest with T2 (Rs. 1,795 ha^{-1}) followed by T4 (Rs. 912 ha^{-1}), T3 (Rs. 893 ha^{-1}), and T5 (Rs. 576 ha^{-1}).

***Amaranthus* (Amaranthus sp. *L.*)**

Comparative performance of the amaranthus crop under Nano-N and FFP in the field is shown in **Picture 4**. Data from the field trials are presented in **Table 2** and **Figure 4.** Perusal of data shows that the lowest seed yield of amaranthus ranged from 2453 to 2760 kg ha^{-1} while the highest yield varied between 2740 to 3075 kg ha^{-1}; it was highest under T2 and lowest under FFP. Mean seed yield ranged from 2,626

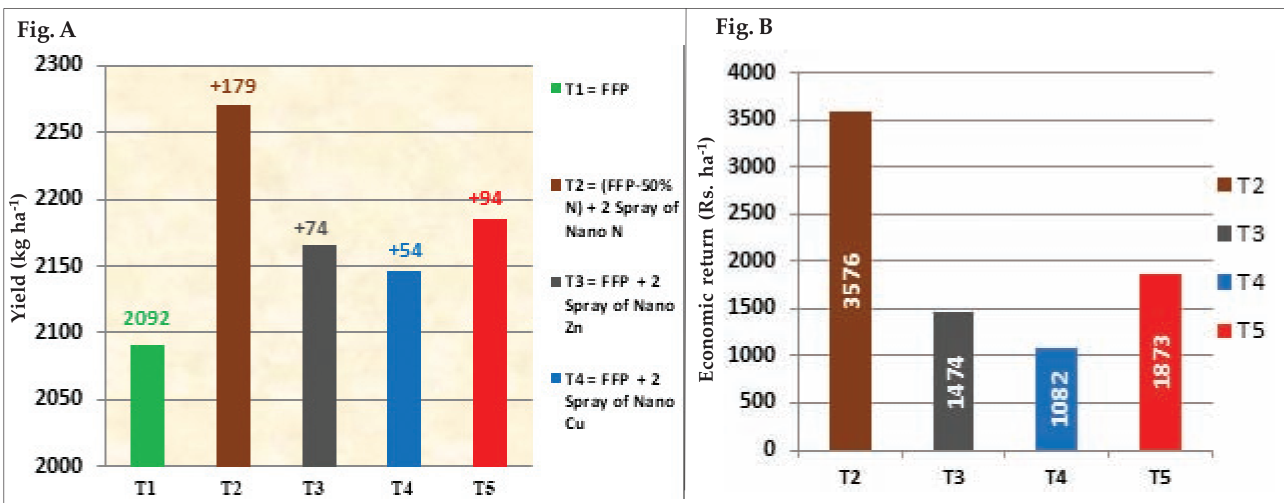

Figure 2. Mean effect of IFFCO nanofertilizers on yield of field pea and economic returns (No. of trials - 26)

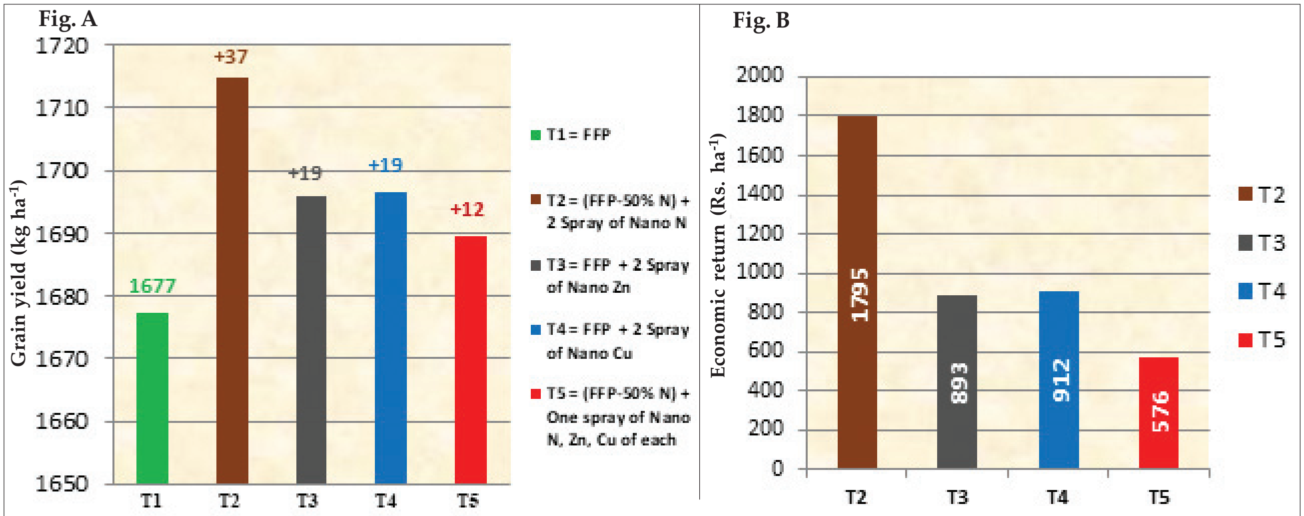

Figure 3. Effect of IFFCO nanofertilizers on grain yield of lentil and economic returns (No. of trials - 5)

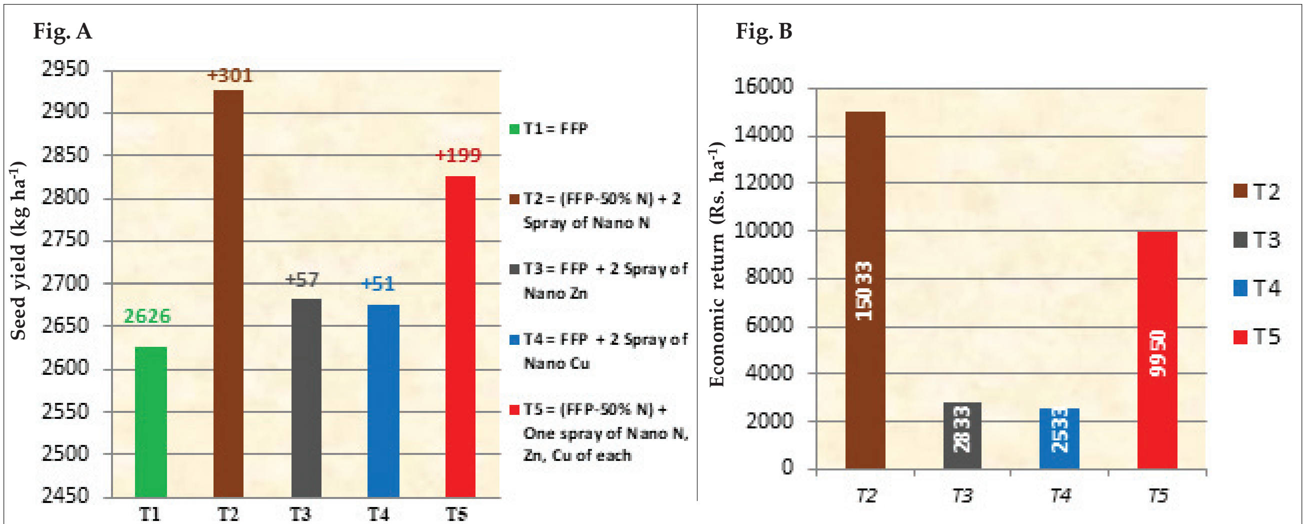

Figure 4. Effect of IFFCO nanofertilizers on seed yield of amaranthus and economic returns (No. of trials – 3)

to 2,927 kg ha^{-1}. Seed yield was highest under T2 [(FFP-50% N) + 2 sprays of Nano-N)] with additional yield of 301 kg ha^{-1} over FFP (2,626 kg ha^{-1}), showing an increase of 11.45%. The economic return over FFP was also highest under T2 (Rs. 15,033 ha^{-1}) followed by T5, T3 and T4**.**

Mustard (Brassica campestris *L.*)

Crop performance of mustard under Nano-N treatment *vis-à-vis* FFP is shown in **Picture 5**. Data presented in **Table 2** and depicted through **Figure 5** shows that the lowest seed yield of mustard ranged

Picture 5. Comparative performance of FFP (T1) and (FFP-50% N) + 2 sprays of Nano-N (T2) with mustard crop in the demonstration conducted in Bulandshahar district

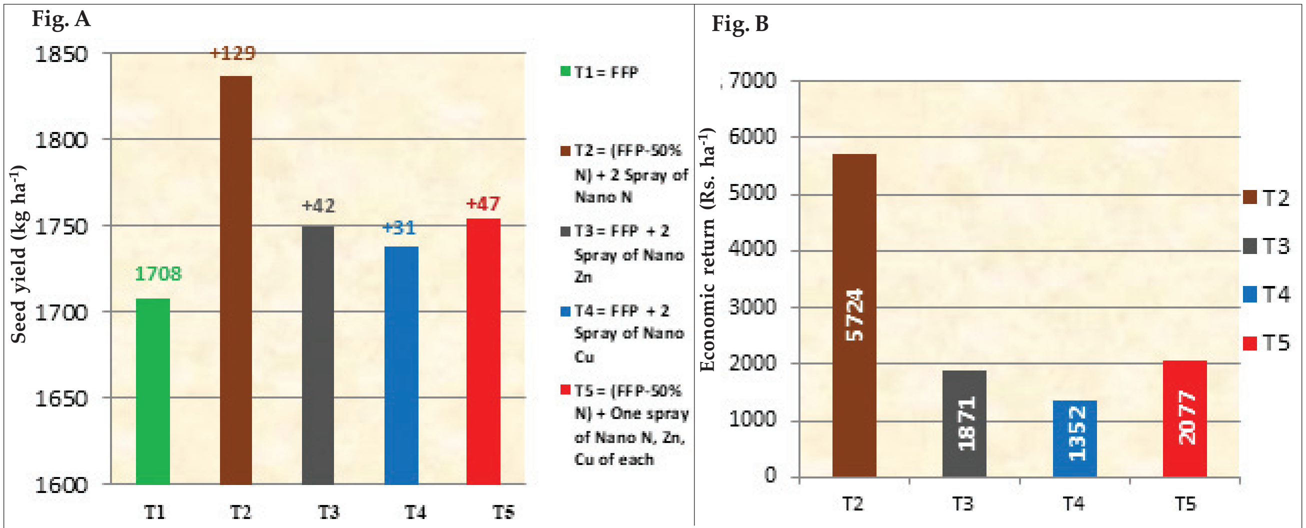

Figure 5. Effect of IFFCO nanofertilizers on seed yield of mustard and economic returns (No. of trials – 44)

Picture 6. Comparative performance of (FFP-50% N) + 2 sprays of Nano- N (T2) and FFP + 2 sprays of Nano-Zn (T3) with potato in Auraiya district

from 425 to 492 kg ha^{-1} while the highest yield varied between 2,427 and 3,355 kg ha^{-1} under different treatments, being highest under T2 and the lowest with FFP. Mean seed yield were in the range of 1,708 to 1,837 kg ha^{-1}. Seed yield under T2 [(FFP-50% N) + 2 sprays of Nano-N] was highest (1,837 kg ha^{-1}) producing additional 129 kg seed ha^{-1} over FFP (1,708 kg ha^{-1}); per cent increase was 7.55. The economic return over FFP was also highest with T2 (Rs. 5,724 ha^{-1}) followed by T5 (Rs. 2,077 ha^{-1}), T3 (Rs. 1871 ha^{-1}), and T4 (Rs. 1,352 ha^{-1}).

Potato (Solanum tuberosum *L.*)

Performance of potato crop under application of nanofertilizer is shown in **Picture 6**. As per summarized data presented in **Table 2** and **Figure 6**, the lowest and highest tuber yields of potato under different treatments varied from 13,250 to 16,000 kg ha^{-1} and 61,200 to 64,300 kg ha^{-1}, respectively; mean yields were in the range of 32,298 to 35,414 kg ha^{-1}. The yield under T2 [(FFP-50% N) + 2 sprays of Nano-N] was highest (35,414 kg ha^{-1}); it was 3,116 kg ha^{-1} higher than that obtained under FFP. Economic return over FFP was also highest under T2 (Rs. 31,165 ha^{-1}) and second in order was under T5 [(FFP-50% N) + one spray of Nano- N, Nano-Zn, Nano-Cu each) (Rs. 24,997 ha^{-1}). Over FFP, the economic returns under T4 and T3 were Rs. 15,259 ha^{-1} and Rs 12,702 ha^{-1}, respectively.

Green pea (Pisum sativum)

Lowest yields of green pea (green pods) under different treatments of nanofertilizers ranged from 7,500 to 9,000 kg ha^{-1} and the highest yields varied between 12,266 and 14,021 kg ha^{-1}. (**Table 2** and **Figure 7**). Perusal of data shows that the mean yields were in the range of 9,484 to 10,247 kg ha^{-1}, with highest yields being under T2 and the lowest under FFP. Green pod yield under T2 [(FFP-50% N) + 2 sprays of Nano-N) of 10,247 kg ha^{-1} was 763 kg ha^{-1} more than that under FFP (9,484 kg ha^{-1}); this was 8.05% increase. The economic return over FFP was also highest under T2

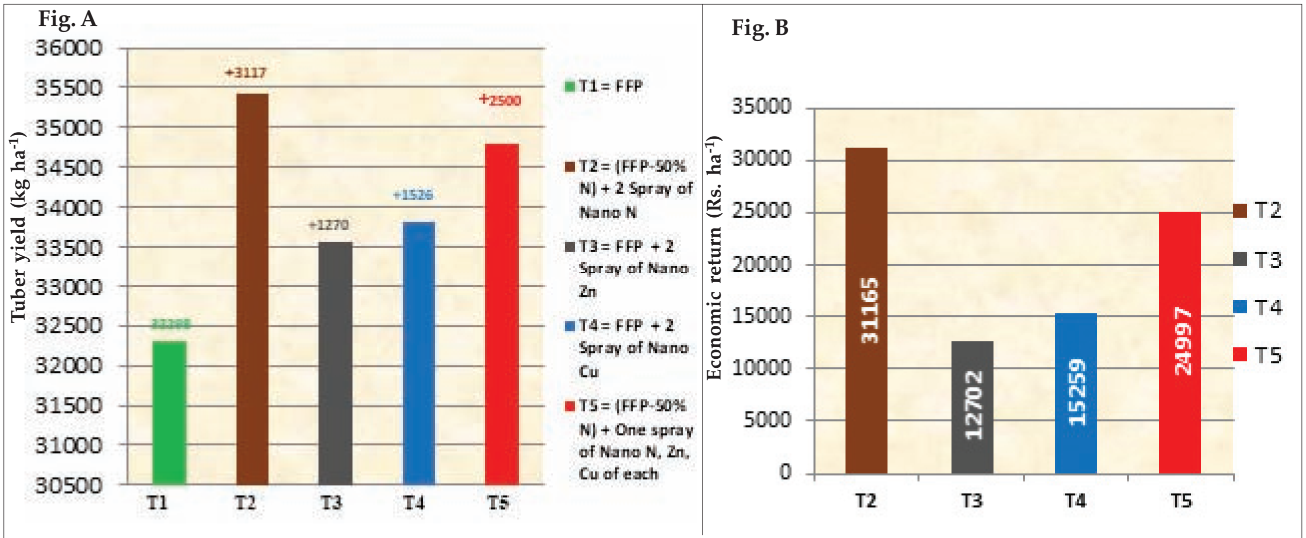

Figure 6. Effect of IFFCO nanofertilizers on tuber yield of potato and economic returns (No. of trials – 187)

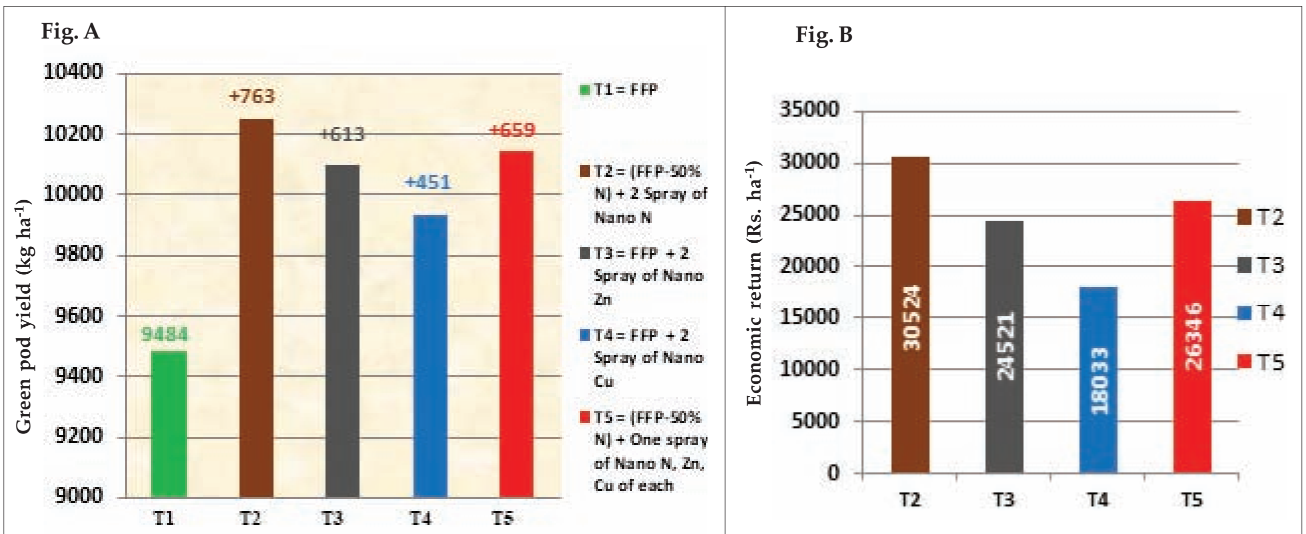

Figure 7. Effect of IFFCO nanofertilizers on green pod yield of green pea and economic returns (No. of trials - 12)

(Rs. 30,524 ha^{-1}) followed by T5 (Rs.26,346 ha^{-1}), T3 (Rs.24,521 ha^{-1}), and T4 (Rs.18,033 ha^{-1}).

Tomato (**Solanum lycopersicum** *L.)*

The lowest fruit yields of tomato ranged from 23,000 to 30,500 kg ha^{-1} and the highest yields varied between 40,270 and 42,920 kg ha^{-1} under different treatments; yields were highest with T2 and the lowest with FFP (**Table 2 and Figure 8**). The mean fruit yields were in the range of 30,354 and 35,534 kg ha^{-1}. Fruit yield under T2 [(FFP-50% N) + 2 sprays of Nano-N) was highest (35,534 kg ha^{-1}); additional tomato fruit of 5,180 kg ha^{-1} over FFP (30,354 kg ha^{-1}), which amounted to 17.07% was harvested with application of Nano-N. The economic return over FFP was also highest with T2 (Rs. 51,800 ha^{-1}) followed by T4 (Rs. 45,760 ha^{-1}), T5 (Rs. 41,160 ha^{-1}), and T3 (Rs. 39,430 ha^{-1}). Fruit quality was also superior with application of nano-fertilizer (**Picture 7**).

Cauliflower **(Brassica oleracea var. botrytis)**

The lowest and highest curd yield of cauliflower under different treatments ranged from 29,500 to 30,670 kg ha^{-1} and 33,490 to 36,752 kg ha^{-1}, respectively; mean curd yield was in the range of 32,276 to 34,521 kg ha^{-1}, being highest in T2 [(FFP-50% N) + 2 sprays of Nano-N]and the lowest in FFP with additional yield of 2,245 kg ha^{-1} over FFP. The economic return over FFP was also highest with T2 (Rs.22,450 ha^{-1}) and decreased in magnitude under T4 (Rs. 17,425 ha^{-1}), T3 (Rs 7,540 ha^{-1}), and T5 (Rs. 5,938 ha^{-1}). Mean effect of nanofertilizers on curd yield of cauliflower under

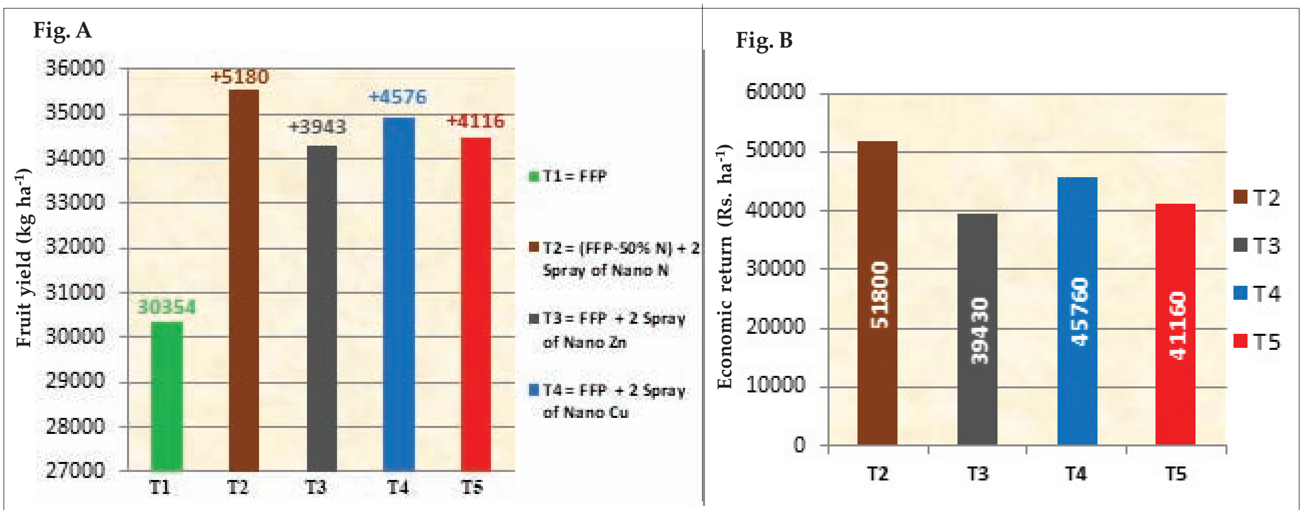

Figure 8. Effect of IFFCO nanofertilizers on fruit yield of tomato and economic returns (No. of trials – 5)

Picture 7. A view of tomato produce obtained under different treatments in demonstration conducted in Ayodhya district

different treatments, additional yield and economic return over FFP have been summarised in **Table 2** and **Figure 9.**

Cabbage (Brassica oleracea var. capitata)

Data summarised in **Table 2** and **Figure 10** showed that the lowest yield of cabbage ranged from 28,400 to 30,640 kg ha^{-1} while the highest yield varied between 33,550 and 34,440 kg ha^{-1} under different treatments. Values were highest and lowest with T2 and FFP, respectively. Mean yields were in the range of 30,215 to 32,540 kg ha^{-1}. Yield under T2 (FFP-50% N) + 2 Spray of Nano N) was the highest (32,540 kg ha^{-1}). It gave additional yield of 1,565 kg ha^{-1} over FFP (30975 kg ha^{-1}); this increase amounted to 5.05% over FFP. The economic return over FFP was also highest with T2 (Rs.15,650 ha^{-1}).

Garlic (Allium sativum)

The lowest bulb yield of garlic ranged from 7,000 to 7,800 kg ha^{-1} and the highest value varied between 9,458 and 9,875 kg ha^{-1} under different treatments **(Table 2** and **Figure 11)**. Bulb yields were highest with T2 and lowest with FFP . Mean bulb yields were in the range of 8,295 to 8,870 kg ha^{-1} with additional yield of 575 kg ha^{-1} over FFP (8,295 kg ha^{-1}), the per cent increase being 6.93. The economic return over FFP was also highest with T2 (Rs. 28,750 ha^{-1}) followed by T5 (Rs. 26,104 ha^{-1}), T3 (Rs. 25,104 ha^{-1}), and T4 (Rs. 7,813 ha^{-1}).

Chilli (Capsicum frutescens)

As shown in **Table 2** and **Figure 12**, lowest yields of chillies ranged from 7,000 to 7,700 kg ha^{-1} while the highest yield varied between 9,000 and 9,900 kg ha^{-1}

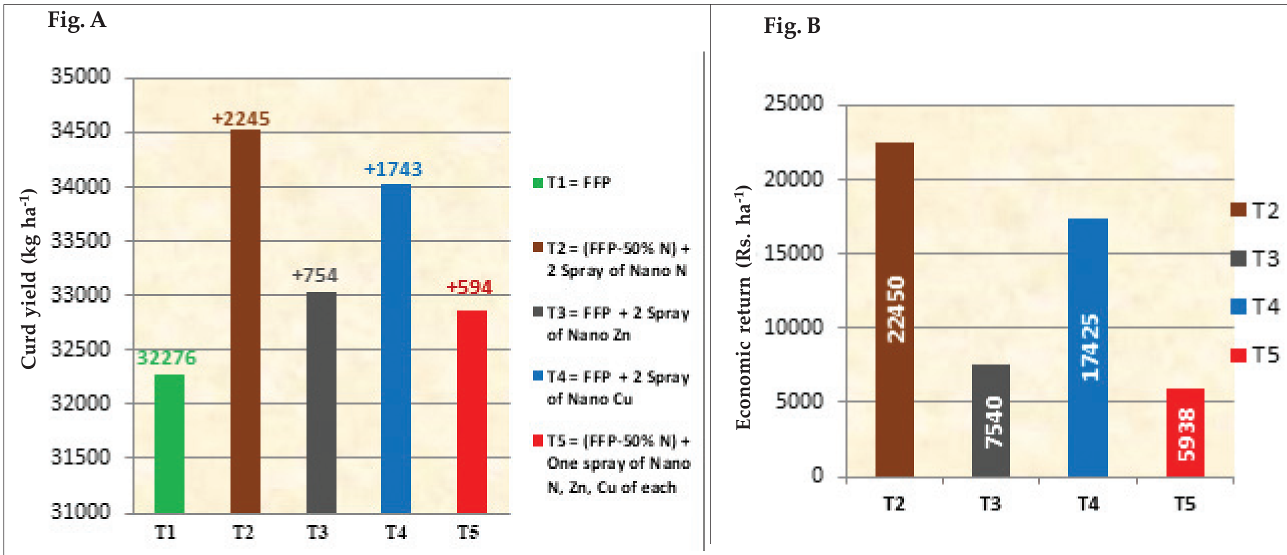

Figure 9. Effect of IFFCO nanofertilizers on curd yield of cauliflower and economic returns (No. of trials – 4)

under different treatments; highest and lowest chilli yields were recorded with T2 and FFP, respectively. Mean chilli yields were in the range of 8,000 to 8800 kg ha^{-1}. Treatment T2 (FFP-50% N) + 2 Spray of Nano N) produced additional chillies 800 kg ha^{-1} over FFP, which was 10% more than that produced under FFP. The economic return over FFP was also highest under T2 (Rs.16,000 ha^{-1}) followed by T4 (Rs. 11,200 ha^{-1}), T3 (Rs. 8,400 ha^{-1}), and T5 (Rs. 6,000 ha^{-1}).

Discussion

In the perspective of sustainable agriculture, application of nanotechnology in agriculture is considered as one of the important approaches to enhance crop production and feed the world's fast-growing population (Lal, 2008). According to recent studies, nanotechnology has the possibility to revolutionize agricultural systems (Manjunatha et al., 2016) enabling slow and controlled release of nutrient for the plants' benefit, and ultimately increasing the amount of crop production with low environmental impact (Scott and Chen, 2013). A paradigm shift from the traditional ways of crop production to technologies that could increase agricultural productivities with required nutrients, cost effective and efficient resource use that guarantees nutrient security, uplifts the value of production, boosts farmers' economy, delivers agri-value chain and supports pollution free environment is therefore, the need of the day (Subramanian and Tarafdar, 2011). Nanotechnology seems to be the alternative that could revolutionize this field of agriculture which has the

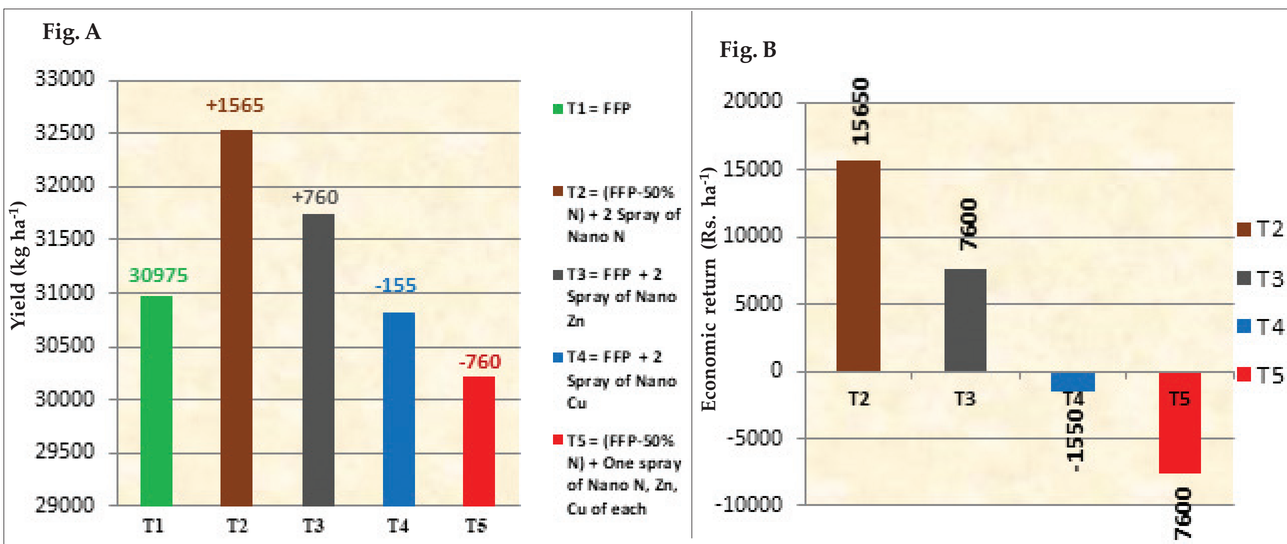

Figure 10. Effect of IFFCO nanofertilizers on yield of cabbage and economic returns (No. of trials – 2)

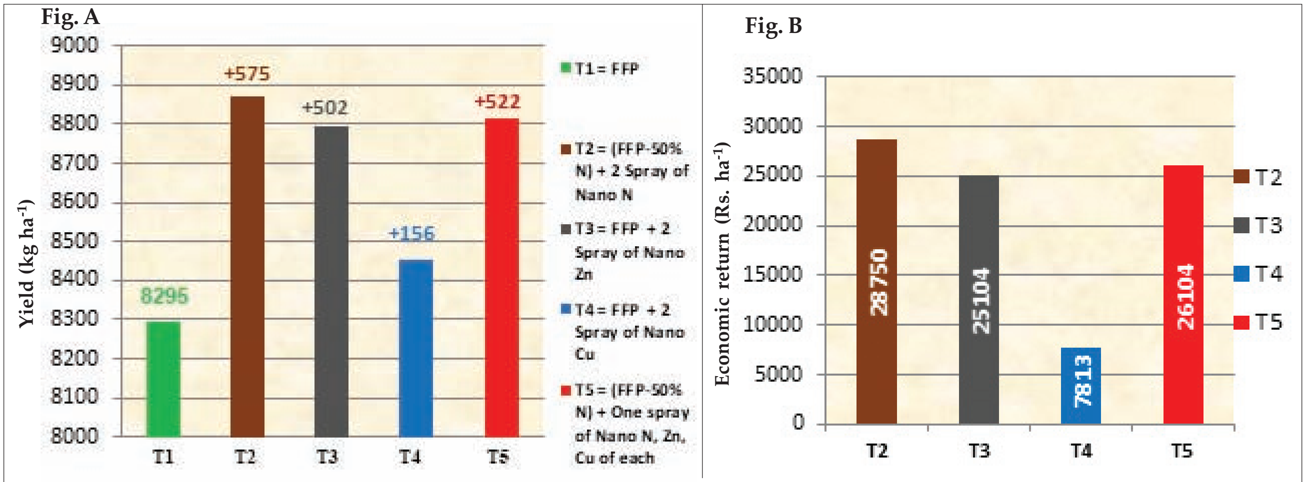

Figure 11. Effect of IFFCO nanofertilizers on bulb yield of garlic and economic returns (No. of trials – 6)

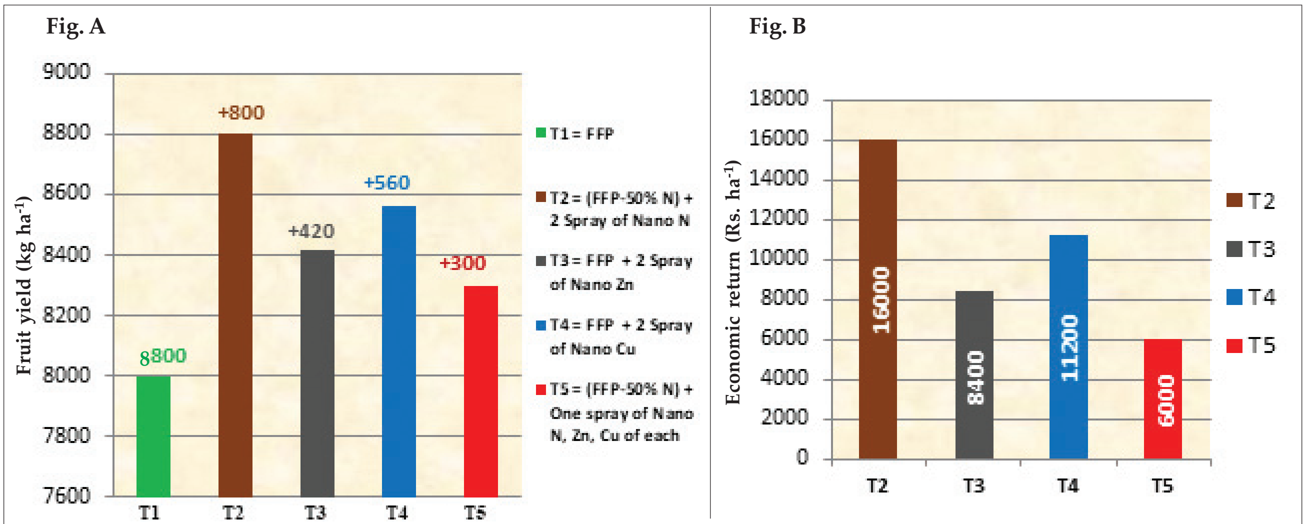

Figure 12. Effect of IFFCO nanofertilizers on yield of chillies and economic returns (No. of trials – 5)

potential to increase food quality, global food production, plant protection, detection of plant and animal diseases, monitoring of plant growth and reduce waste for "sustainable amplification" (Gruère et al. 2011, Frewer et al. 2011, Pérez-de-Luque and Hermosín 2013, Prasad et al. 2014, Biswal et al. 2012, Ditta 2012, Sonkaria 2012).

The purpose of using nanomaterials (NMs) in the field of agriculture is to improve the efficiency and sustainability of agricultural practices by putting less input and generating less waste than conventional products and approaches. Nanoscale science and nanotechnology have the potential to transform the agriculture and food systems (Norman and Hongda, 2013). It has immense potentials in agriculture uprising, high reactivity, better bioavailability, bioactivity and the surface effects of NPs (Gutiérrez et al., 2011). Nanofertilizers or nano-encapsulated nutrients have properties to release nutrients effectively on demand that regulate plant growth and enhance target activity (DeRosa et al., 2010; Nair et al., 2010). With nanofertilizer, there is a slow release of the nutrients, which minimizes leaching of the nutrients among other interesting properties. Nanofertilizers due to their characteristic features have great role in sustainable agriculture (El-Ramady, 2014).

There are so many reports where application of nanofertilizer produced positive effect in terms of good crop yield as well as reduced environmental pollution. Urea modified hydroxyapatite nanoparticle-encapsulated *Gliricidia sepium* nanocomposite exhibited a slow and sustained release of nitrogen over time at three different pH values (Kottegoda et al., 2011). Manikandan and Subramanian (2014) reported that nanoporous zeolite used on N fertilizer might be used as alternate strategy to enhance the effectiveness of N in crop production system. Soil amended with metallic

Cu -Ps significantly increased 15 days' lettuce seedling growth by 40% and 91%, respectively (Shah and Belozerova, 2009). Some focused studies on the characteristics of NPs also revealed that NPs can enter plant cells and transport DNA and chemicals inside the cell (Ambrogio et al., 2013; Ghafariyan et al., 2013; Torney et al., 2007). These studies provide a platform on which we can assume that NPs can also deliver nutrients to the plants as fertilizers. Moreover, nanofertilizers have great impact on the soil as these can reduce the toxicity in the soil and decrease the frequency of fertilizer application (Naderi and Danesh-Shahraki, 2013). DeRosa et al. (2010) reported that in nanofertilizers, nutrients can be encapsulated by NMs, coated with a thin protective film or delivered as emulsions or NPs. Nano and subnano composites control the release of nutrients from the fertilizer capsule (Liu et al., 2006). Thus from the above mentioned findings we can articulate that the use of nanofertilizer leads to an increased efficiency of the micro and macro elements, reduces their toxicity in the soil and reduces the frequency of application of conventional fertilizers.

Nanofertilizers or nano-encapsulated nutrients have properties to release nutrients effectively and chemical fertilizers on demand that regulate plant growth and enhance target activity (Nair et al., 2010). Nanoscale science and nanotechnology have the potential to transform the agriculture and food systems (Norman and Hongda, 2013). Nanotechnology has immense potentials in agriculture uprising, high reactivity, better bioavailability, bioactivity and the surface effects of NPs (Gutierrez et al., 2007). The engineered nanoparticles (ENPs) are able to enter into plants cells and leaves, and can also transport DNA and chemicals into plant cells (Galbraith, 2007; Torney et al., 2007).

Apparently, use of nanofertilizers is the most important application of nanotechnology in agriculture (Agrawal and Rathore, 2014). Nanofertilizers can be applied either through the soil (for uptake by plant roots), or through foliar spray (for uptake through leaves) (O'Neill et al., 2014) or both (Yan et al., 2018). In this connection, carrier delivery systems of nano-fertilizers can synchronize their release with uptake by crops, thus preventing undesirable loss of nutrients to soil (DeRosa et al., 2010). Actual application of delivery system for nanofertilizers came rather recently in agriculture (Joseph and Morrison, 2006; Kuzma and Verhage, 2006; Roco, 2011; Scott and Chen, 2013). Nanofertilizers are designed to make nutrients more available, consequently increasing the nutrient use efciency (Suppan, 2013). Some characteristics of nanoparticles, including the large specic surface area, unique magnetic/optical properties, electronic states, and catalytic re-activity confer nanoparticles better reactivity than the equivalent bulk materials (Agrawal and Rathore, 2014). Regarding N fertilizers, the application of nanotechnology can provide fertilizers that release N when crops need it, eventually leading to increases in N efficiency through decreases in N leaching and emissions and long-term incorporation by soil microorganisms (Naderi and Danesh-Shahraki, 2013; Suman et al., 2010). In previous studies, urea-loaded zeolite chips (Millan et al., 2008) and nanocomposites containing N (Jinghua, 2004) have been used to induce a slow N release and increase plant N uptake. Other materials being used for the same purpose include nutrient sources coated with thin polymer films and nutrients encapsulated inside nanoporous materials (Rai et al., 2012).

Epilogue

Nanotechnology is a powerful tool in agriculture to improve crop growth, yield and quality parameters; increase nutrient use efficiency; reduce wastage of fertilizers; and decrease the cost of cultivation. Nano-fertilizers are very effective for controlled nutrient supply in precision agriculture in synchrony with demand created by plants at different growth stages. Nano-fertilizers have higher surface area mainly due to very small size of particles which provide more sites to facilitate different metabolic processes in the plant system resulting from the production of more photosynthates. Due to higher surface area and very small size they have exceptionally high reactivity with other compounds. They have high solubility in different solvents such as water. Particles size of nano-fertilizers is in the range of 1 to 100 nm which facilitates more penetration of nanoparticles into the plant from applied surface such as soil or leaves. Nano-fertilizer have large surface area and particle size is less than the pore size of root and leaves of the plant which can increase their penetration into the plant from applied surface and improve uptake and use efficiency of the nano-fertilizer. Reduction of particle size results in increased specific surface area and number of particles per unit area of a fertilizer that provide more opportunity to come in contact of nano-fertilizers which leads to more penetration and uptake of the nutrient. It also protects plant from different biotic and abiotic stress. Because of the limitation in arable lands and water resources, the development of agriculture sector is only possible by increasing the resources' use efficiency with the minimum damage to production bed through effective use of modern technologies. Studies show that the use of nano-fertilizers causes an increase in nutrients use efficiency, reduces undesirable toxicities in soil, minimizes the potential negative effects associated with over-dosage and reduces the frequency of the application. Hence, nanotechnology has a high potential for achieving sustainable agriculture, especially in developing countries. The results of these 730 on-farm demonstrations conducted by IFFCO have clearly established that 50% consumption of urea could be reduced by foliar sprays of IFFCO Nano-N. The ongoing researches at the ICAR Institutes and State Agricultural Universities would help in precisely quantifying the magnitude of increase in nutrient uptake, increase in nutrient use efficiency, improvement in soil quality, and finally the agriculture sustainability and environmental protection. On the basis of the findings of this investigation, following action plan is suggested:

- Farmers are fully convinced about the effectiveness of IFFCO Nano-N as is evident from the results of 730 on-farm demonstrations conducted on 12 important *rabi* crops of Uttar Pradesh. Seeing the amazing performance of IFFCO nanofertilizers on their own fields, farmers are now demanding these fertilizers for field application.

- There is a need to create greater awareness among the farmers about efficacy of IFFCO nanofertilizers as shown from the results of mega research projects funded by IFFCO to various research organisations *i.e.*, State Agricultural Universities, ICAR Institutes, Krishi Vigyan Kendras, and the progressive farmers.

- Farmers should be educated about effectiveness and the importance of Nano-N towards arresting increasing demand of urea and its indiscriminate use which in turn is exacerbating nutrient mining, triggering the multi-nutrient deficiencies, reducing the nutrient use efficiency, and multiplying the environmental problems. It is simultaneously increasing the cost of cultivation. IFFCO Nano-N helps in reducing the use of urea to the extent of 50% with higher yields without causing any collateral damage to the environment.

- Pre-season workshops, training programmes, group meetings etc. should be extensively organised using audio-visual aids by the field officers ensuring full participation of the scientists who are involved in the testing of IFFCO nano-fertilizers.

- The innovative farmers who are keen to use and judge the performance of Nano-N fertilizer should be encouraged to conduct on-farm trials by making them available the Nano-N well before the sowing/transplanting of the crop. For the success of this initiative, it is essential and inevitable that the field officers select only those few farmers who have proven ability. These innovative farmers will help in telling the success story of the value of IFFCO nano-N fertilizer in the light of the crop performance they have seen in their own crops and fields.

- Field officers should ensure their own full participation and involvement with the innovative farmers starting from sowing/ transplanting of the crops up to harvesting. This approach will help in creating greater awareness among the farmers about benefits of Nano-N within a short period. These innovative farmers can easily influence the farming community because they are both *local and vocal*. This approach will help in promotion of nano fertilizers on the principle of "*seeing and believing*" at a fast speed.

- Apart from this, IFFCO commits to educate the interested progressive farmers spread across the country and also provide them free sample products and make them use it and get their satisfaction for the technology. Once the farmers get convinced of the technology, their will help in making the nano-products popular. This will trigger the demand for these novel nanofertilizers.

- Crop seminars and "Crop Harvest Day" should invariably be organised at the demonstration sites and "*Success story of nano fertilizers*" should be told in detail by the innovative farmers and the scientists associated with testing programme of IFFCO nanofertilizers.

- Short video films and photographs of important events and activities should be compulsorily developed.

Conclusions

From the foregoing results it is concluded that IFFCO nanofertilizers in general, and Nano-N in particular, will successfully help in reducing the consumption of urea to 50% by applying 2 sprays of Nano-N. Other products *viz.*, Nano-Zn and Nano-Cu would show their effectiveness depending upon the magnitude of deficiencies of these nutrients in soils. As N deficiency in Indian soils is universal and so is the response to applied nano-N. The Government policy and support to promote IFFCO nanofertilizers will transform Indian agriculture and help in maintaining the sustainability of Indian agriculture. For this to happen, the Government on its own initiative should consider giving a green signal to include these IFFCO nanofertilizers in the Fertiliser Control Order in the larger interest of India's farming community.

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