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Nitrogen Management Strategies for Enhancing its use Efficiency and Environmental Performance of Indian Agriculture

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Abstract

Although, the food grain production showed remarkable increase with increase in fertilizer N use over the time, the average global N use efficiency (NUE) is quite low (0.460). Thus, the rest of the N input (54%) into cropland contributes towards environmental air and water pollution. Over the 60% of N pollution is estimated to originate from crop production. United General Assembly has proposed the NUE as an indicator for assessing the progress made in achieving Sustainable Development Goals. Sustainable N Management Index (SNMI) approach can be used to assess the environmental performance of agriculture at country and global level. Global NUE should be raised to 0.70 by 2050 while achieving the crop production targets to reduce the N waste to desired level. India is the 3rd largest fertilizer consumer after USA and China. It is necessary to increase the average NUE of Indian agriculture to 0.70 to achieve the global NUE target by 2050. Therefore, the current status of NUE and SNMI was assessed at country level as well as in different states of India during the last 10 years (2010-11 to 2019-20) in the present study to identify crop production constraints of low NUE and to suggest crop-specific and state-specific N management strategies. The mean NUE at country level was very low which varied from 0.451 in 2015-16 to 0.527 in 2017-18. The low NUE resulted in huge N surplus (Nsur) which actually contributes to environmental pollution varied from 13.45Tg in 2017-18 to 15.8Tg in 2015-16. The lower NUE and higher Nsur led to the relatively higher SNMI during the last 10 years which is directly proportional to the environmental pollution. Mean NUE of the last 10 years of 32 states and union territories showed the highest NUE of 0.878 in Nagaland and the lowest in Puducherry (0.196). The NUE and environmental performance of Indian agriculture increases at international level only when the environmental performance of agriculture and NUE of different states and UTs would improve. The 32 states and UTs under assessment were divided into 5 groups based on the NUE and fixed the target increase in NUE by 2050 for each group to achieve overall NUE of 0.70 at country level. In each group the major constraints responsible for low NUE were identified and suggested the measures to improve NUE to target level.

Keywords: Nitrogen use efficiency; N surplus; Sustainable nitrogen management index; Environmental performance

Highlights:

a) The current status of nitrogen use efficiency (NUE) and Sustainable N management index (SNMI) of Indian Agriculture was assessed at country level as well as in different states of India during the last 10 years (2010-11 to 2019-20) to identify crop production constraints of low NUE and to suggest crop-specific & state-specific N management strategies.

b) The 10-year mean NUE of Indian agriculture was very low (0.487) with a mean SNMI of 0.542. The poor NUE left about 51.3% of total N applied to croplands as N surplus in soils which leads to environmental pollution. The normalized SNMI value varied from 56.55 in 2015-16 to 64.28 in 2017-18 with a mean of 60.29. There is a need to enhance the NUE of Indian agriculture to the projected global NUE of 0.700 by the year 2050 to raise the environmental performance of Indian agriculture to global level.

c) Mean NUE of the last 10 years of 32 states and union territories of India showed the highest NUE of 0.878 in Nagaland and the lowest in Puducherry (0.196). The states were categorized into 5 groups based on the NUE. The crop production constraints responsible for low NUE were identified in each group and the crop specific & state specific measures were suggested to raise NUE to desired level so that the country level goal could be achieved by 2050.

Introduction

To feed the expected 10 billion people by 2050, the world food production needs to increase by 56% comparing to the base year of 2010. The food production should increase without expanding the agricultural land as there exists a 593 million-hectare land gap between global agricultural land area in 2010 and expected agricultural expansion by 2050. Among the plant nutrients, nitrogen (N) is a critical element for crop growth and consequently an important determinant of food supply. About 48% of world's population depending on food produced arising from the use of N inputs [1]. Thus, the N inputs for crop production have increased rapidly accounting for about 85% of total anthropogenic N inputs to the global N cycle in 2010. Agriculture thereby became the major driver of the global N cycle. Although, the food grain production showed remarkable increase with increase in fertilizer use particularly N over the time, the N use efficiency (NUE) is quite low (46% global average NUE) depending upon the crop /cropping system, crop variety, soil type, climate, extent of irrigation, agronomic management, weather aberrations etc. Thus, the rest of the N input (about 54%) contributes towards environmental air and water pollution [2]. Over the 60% of N pollution is estimated to originate from crop production. In monetary terms, reactive N (Nr) pollution is estimated to cause damages in the magnitude of 0.3-3% of global gross domestic product (GDP) [3].

NUE is the fraction of all N inputs [fertilizers, organic manures, biological N fixation (BNF), N deposition] that is harvested as crop products [1]. Improving NUE is one of the most effective means of increasing crop productivity while decreasing environmental pollution. United General Assembly has proposed the NUE as an indicator for assessing the progress made in achieving Sustainable Development Goals. NUE measures the efficiency of N use in agricultural production and it is usually considered to be positively related to the environmental performance of agricultural production. However, using only NUE to rank country's performance under the Sustainable Development Goal 2 (SDG2) could be problematic due to two reasons: (i) Generally NUE should be between 0 to 1, with values between 0.5 and 0.9 indicating efficient N use and low N losses. But NUE may become greater than 1 when the crop system is mining the soil N which degrades soil fertility and lowers crop yield in the long-term, and (ii) NUE is usually high when both N inputs and crop yields are low which is not compatible with achieving the first part of SDG2 of reducing hunger [4]. Therefore, they have proposed the sustainable nitrogen management index (SNMI) to provide a more comprehensive measurement of the environmental performance of the agricultural production. SNMI considers both the types of efficiencies in crop production i.e., NUE and land use efficiency (Crop yield, N yield) in a one-dimensional ranking score.

Currently, after China and United States, India rank third for fertilizer N consumption in the world and first in the South Asia. In India, the fertilizer consumption increased from 0.74 million tonnes (Tg) N, 0.25Tg P_2O_5 and 0.11Tg K_2O (total 1.1Tg) in 1966-67 to 18.9Tg N, 7.4Tg P_2O_5 and 2.6Tg K_2O (total 28.9Tg) in 2019-20, respectively with the corresponding increase in food grain production from 74.2Tg in 1966-67 to 296.6Tg in 2019-20 [5]. Soil fertility maps of India showed that about 95% soils in 1976, 90% soils in 2002 and 93% in 2011 were low to medium in available N [6]. So N fertilizers have been playing key role along with other deficient major, secondary and micronutrients in increasing food grain production. Although, the food grain production showed remarkable increase with increase in fertilizer use particularly N over the time, the N use efficiency (NUE) is quite low (30-50%) depending upon the crop/cropping system, crop variety, soil type, climate, extent of irrigation etc. [7]. Thus, the rest of the N input (about 50-70%) contributes towards environmental air and water pollution, climate change, biodiversity loss and ozone depletion making India a hot spot for the deposition of N species. Overall, N management is closely related to at least nine Sustainable Development Goals, including those focusing on food supply and pollution. Environmental Performance Index 2020 (EPI2020) has ranked India at 108 with normalized SNMI score of 34.7 in agriculture out of 180 countries [8].

Meeting 2050 food demand of 107Tg N yr^{-1} projected by the FAO [9] while reducing N surplus from the current 100Tg N yr^{-1} to a global limit of 50Tg N yr^{-1} requires the broad increase in NUE. There is a need to increase the global average NUE from the current 0.46 to 0.70 while increasing the N yield from 74Tg N yr^{-1} to 107Tg N yr^{-1} to achieve the global surplus target [1]. The average increase in global NUE could be achieved if average NUE rose to 0.75 in EU and USA, to 0.6 in China and rest of Asia and to 0.70 in other countries including sub-Saharan Africa. Since India is the third largest fertilizer N consumer and hot spot of N deposition, enhancing the NUE in agriculture to 0.7 by 2050 not only helps India to raise its environmental performance of agriculture, crop productivity and profitability but also leads to achieve global and regional N surplus targets.

Nitrogen lost to the environment could be mitigated by 41% if it's allocation is optimized among the regions [10]. Even greater mitigation is possible if N resources can be efficiently reallocated on sub-regional basis. The combined effect of all mitigation actions can lower global Nr losses to 95Tg Nr in 2050. Therefore, there is a need to assess the environmental performance of agriculture at country level as well as at state or regional level within each country to understand the current environmental performance of country and state considering the global targets of food production, NUE and N Surplus and to implement crop specific and location specific N management strategies to reduce N pollution while achieving food grain production targets. In the current study, the environmental performance of Indian agriculture in terms of N yield, NUE and SNMI at country level during the last 10 years was assessed for global comparison. The environmental performance of agriculture of different states of India were also assessed to understand the current position of each state and to

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identify major constraints and to suggest state-specific and crop specific N management strategies for achieving NUE targets.

Materials and Methods

Computation of N_{yield} and nitrogen use efficiency (NUE)

Major nitrogen (N) inputs into the agriculture include fertilizer N application (N_{fer}), Manure N application (N_{man}), biological N fixation (N_{fix}), and atmospheric deposition (N_{dep}). Total N input is the sum of fertilizer N consumed in India/year, contribution from BNF/year, Manure N/year, and atmospheric deposition of N (both dry and wet deposition)/year. In case of atmospheric N deposition, N deposited over net sown area (139.22-141.34m ha) in each year was computed at the rate of 14.15kg N ha^{-1} which include both wet and dry deposition in India [11]. The N input into the gross cropped area (182.57-191.32m ha) through the biological N fixation in each year was computed at the rate of 27.54kg N ha^{-1} [12]. The N input into the gross area of cropland in each year through manure application was computed at the rate of 22.89kg N/ha [13]. After these computations, total N input was expressed in terms of Tg N yr^{-1} as well as kg N ha^{-1} yr^{-1}. Fertilizer N input into crop lands each year for different states and whole country was obtained from Fertilizer Statistics (2010-11 to 2019-20) [14].

Major N outputs from agricultural soils are total N removed by crops (N yield) including any part of the crop that is removed from the field. Total N removed (N yield) by different crops from soils was computed on the basis of total N removal (grain + straw) per specified economic yield (Table 1). For this purpose, year-wise production data of different crops in different states and India was collected from a publication of Agricultural Statistics at a Glance [15]. The difference between the N inputs and outputs is lost to the environment or remains in soil (N_{sur}). The major assumption is that the long-term (e.g., over a decade) the average change of N in soil is negligible and is small relative to the annual N input, then we can assume that N surplus is a reasonable index of N lost to the environment over the long term [1].

Table 1: Average N removal by different crops grown in India [14,19].

S. No.	Crop	Economic Yield (t ha^{-1})	Total N removed (kg ha^{-1})
1	Rice	3	84
2	Wheat	3	125
3	Jowar	2.5	65
4	Bajra	2.5	65
5	Maize	5	170
6	Other cereals	1.7	36
7	Gram	1.5	91
8	Other pulses	1.08	81
9	Groundnut	2	170
10	Other oil seed crops	1	54.6
11	Cotton	1	43.2
12	Jute	1	35.2
13	Sugarcane	88	180
14	Fruits	1	4.5
15	Vegetables	1	3.6
16	Tea	1	178.3
17	Coffee	1	129
18	Rubber	1	30

$$N_{sur} = \left(N_{fer} + N_{man} + N_{fix} + N_{dep}\right) - N_{yield}$$

Nitrogen Use Efficiency (NUE) also called the N recovery ratio is the ratio of N yield to N input (NUE= N yield/N input).

The N input, N yield, SNMI and Normalized score of SNMI were computed for whole India as well as different states of India for the last 10 years (2010-11 to 2019-20) to evaluate the environmental performance of Indian Agriculture using SNMI as an indicator.

Computation of sustainable nitrogen management index (SNMI)

The agricultural Sustainable Nitrogen Management Index (SNMI) is defined to make a more comprehensive measurement of the environmental performance of the agricultural production. Here, the SNMI is defined based on two important efficiency terms in crop production, namely Nitrogen Use Efficiency (NUE) and Land Use Efficiency (N Yield) [4].

NUE is defined as the fraction of all nitrogen inputs (fertilizers, manures, N fixation, N deposition) that is harvested as crop

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products [4]. Usually, NUE should be between 0~1. NUE measures the efficiency of nitrogen (N) use in agricultural production, and it is usually considered to be positively related to the environmental performance of agricultural production. However, directly using only NUE to rank country's performance under the Sustainable Development Goal 2 (SDG2) could be problematic. Therefore, SNMI was defined considering both types of efficiencies in crop production, namely NUE and land use efficiency (crop yield, *N Yield*).

SNMI of a country is derived as

$$SNMI_{co} = \sqrt{\left(1 - NYield^{*}_{co}\right)^{2} + \left(1 - NUE^{*}_{co}\right)^{2}}$$

Where,

$$NYield^{*}_{co} = NYield_{co} / NYield_{ref} \quad if \quad NYield_{co} \le NYield_{ref}$$
$$NYield^{*}_{co} = 1 \quad if \quad NYield_{co} > NYield_{ref}$$

$NYield^{*}_{co}$ is Nitrogen yield of a country on 0-1 scale computed as Nitrogen yield of the country $(NYield_{co})$ in kg ha^{-1} yr^{-1} divided by global reference $(NYield_{ref})$ of 90kg ha^{-1} yr^{-1} [1,2].

$$NUE^{*}_{co} = NUE_{co} \quad if \quad (NUE_{co} \le 1)$$
$$NUE^{*}_{co} = 1 - (NUE_{co} - 1) \quad if \quad (NUE_{co} > 1)$$

NUE^{*}_{co} is Nitrogen Use Efficiency of a country on 0-1 scale

After computing SNMI for all countries based on NUE and N yield, relative score of a country on a scale of 0-100 is calculated using the following normalization method.

$$SNMI^{N}_{co} = \left[\frac{(SNMI_{Max} - SNMI_{co})}{(SNMI_{Max} - 0)}\right]100$$

Where,

$SNMI^{N}_{co}$ is normalized SNMI of a country.

$SNMI_{Max}$ is maximum SNMI among the countries under evaluation.

Zero is the lowest possible SNMI which is ideal and set as target.

SNMI is inversely related to sustainability or environmental performance whereas normalized SNMI is directly proportional to sustainability or environmental performance. High normalized SNMI score indicate relatively high sustainability or better environmental performance.

After computing SNMI based on NUE and N yield, Normalized SNMI Score for India on a scale of 0-100 was calculated using the following normalization method.

$$\left[(Max - India\ score) / (Max - Min)\right]100$$

The Environmental Performance Index 2020 (EPI2020) provides a data-driven summary of the state of sustainability around the world [8]. EPI2020 ranked 180 countries on environmental health and ecosystem vitality using 32 performance indicators across 11 issue categories. Max was the SNMI of 180th rank country in EPI2020. As it is not available from the documents, worst SNMI (99th percentile) of 1.3641 was used in place of Max and zero was taken as Min (best SNMI) while computing normalized SNMI score at country level [8].

States of India was also be evaluated for SNMI in a similar fashion by replacing country (co) with state (s) in the formula. While computing normalized SNMI of a state, maximum SNMI score among the states in each year under evaluation was used for $SNMI_{Max}$.

Limitations

a) The variation in the contribution from the BNF and organic manure to the N input from year to year might be due to the slight variation in the gross cropped area from year to year. The gross cropped area varied from 182.86m ha in 2012-13 to 189.44m ha in 2016-17.

b) Reference N Yield Target (90kg N ha^{-1}): India has achieved self-sufficiency in food grains production. Food grains demand projections [16] made for 2020 were achieved by 2019-20 [17]. Nutritional security should follow the food security. In view of this a modest target of 90kg N ha^{-1} yr^{-1} is considered a reasonable reference yield for computing SNMI. Food grains demand projected for India (assuming 7% growth in GDP) for 2050 is 375-380Tg which calls for an N yield of about 105kg N ha^{-1} yr^{-1} [18]. The N yield target of 90kg N ha^{-1} yr^{-1} would be incrementally enhanced at the rate 1 per two years so that the target for 2050 becomes 105kg N ha^{-1} yr^{-1}. Thus, the global reference N yield of 90kg N ha^{-1} yr^{-1} is also relevant to Indian agriculture [1,4].

c) Major N outputs from agricultural soils are total N removed by crops (N yield) including any part of the crop that is removed from the field. Total N removed (N yield) by different crops from soils has been computed on the basis of total N removal (grain + straw) per specified economic yield [14,19]. The N removed from soil per specified economic yield target were computed by Swarup et al. [19] from 3-year or more old field experiments and are being used widely in Indian research papers.

Results

NUE and SNMI at country level during the last 10 years

Total N input into Indian cropland during the last 10 years (2010-11 to 2019-20) increased from 28.03Tg to 30.5Tg with a steep in the input by 3.5% in 2018-19 and 8.8% in 2019-20 over that of 2010-11 (Table 2). The N input fluctuated around the 28Tg during 2010-11 to 2017-18. Majority of the contribution to total N input was from the fertilizer N which varied from 59% in

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2010-11 to 61% in 2019-20. The contribution of biological nitrogen fixation (BNF) of total input varied from 17.27% in 2019-20 to 18.53% in 2012-13. Organic manures application contribution to total N input varied from 14.36% to 15.34% during the last 10 years. The atmospheric deposition of N on the net sown area varied from 1.97Tg yr^{-1} to 2.00Tg yr^{-1}. This variation was observed due to the slight variation in the net sown area from 139.9m ha in 2010-11 to 141m ha in 2019-20.

Table 2: N input, N removal (yield or harvest), N surplus and NUE in India during the last 10 years.

Year	N input (Tg yr^{-1})				Total N Input		Total N Removal or N Yield		N Surplus		NUE	SNMI	Worst SNMI	Normalized SNMI Score
	Fertilizer N	Manure N	BNF-N	Atmospheric Deposition N	Tg yr-1	Kg ha^{-1} yr^{-1}	Tg yr^{-1}	kg ha^{-1} yr^{-1}	Tg yr^{-1}	kg ha-1yr^{-1}				
2010-11	16.6	4.28	5.15	2	28.03	149.79	13.03	69.64	14.99	80.15	0.465	0.581	1.3641	57.41
2011-12	17.3	4.26	5.13	1.99	28.68	153.99	13.43	72.11	15.25	81.88	0.468	0.568	1.3641	58.39
2012-13	16.82	4.18	5.03	1.98	28.21	154.27	13.39	73.24	14.82	81.03	0.475	0.557	1.3641	59.15
2013-14	16.75	4.32	5.2	2	28.27	149.62	14.03	74.23	14.24	75.39	0.496	0.533	1.3641	60.89
2014-15	16.95	4.25	5.11	1.98	28.29	152.39	13.12	70.69	15.17	81.7	0.464	0.577	1.3641	57.67
2015-16	17.37	4.26	5.12	2	28.75	155.3	12.95	69.97	15.8	85.33	0.451	0.593	1.3641	56.55
2016-17	16.74	4.34	5.22	1.98	28.28	149.28	14.33	75.64	13.95	73.64	0.507	0.518	1.3641	61.99
2017-18	16.96	4.31	5.18	1.97	28.42	150.96	14.97	79.53	13.45	71.43	0.527	0.487	1.3641	64.28
2018-19	17.64	4.26	5.13	1.99	29.02	155.92	14.85	79.79	14.17	76.13	0.512	0.501	1.3641	63.25
2019-20	18.86	4.38	5.27	1.99	30.5	163.87	15.42	82.84	15.08	81.04	0.505	0.501	1.3641	63.28

The N yield (Total N removal by crops) varied from 12.95Tg in 2015-16 to 15.42Tg in 2019-20. The NUE was very low which varied from 0.451 in 2015-16 to 0.527 in 2017-18. The low NUE resulted in huge N surplus (N_{sur}) which actually contributes to environmental pollution. The N_{sur} varied from 13.45Tg in 2017-18 to 15.8Tg in 2015-16 which may be due to variation in the crop production. The lower NUE and higher N_{sur} led to the relatively higher SNMI during the last 10 years which varied from 0.487 in 2017-18 to 0.593 in 2015-16 which is directly proportional to the environmental pollution. Higher the SNMI higher will be the environmental pollution. The normalized SNMI is directly proportional to NUE and inversely proportional to the SNMI. The highest normalized SNMI was observed in 2017-18 and the lowest in 2010-11 which indicates that the environmental performance of Indian agriculture in terms of SNMI is increasing over the last 10 years.

NUE and SNMI in different states of India during the last 10 years

In India, improved technologies are being demonstrated and promoted in villages by state governments through *Krishi Vigyan Kendras* (KVK) (Farmers' Science Centres), State department of agriculture, State Agricultural Universities (SAUs) etc. So, it is essential to assess the current status of NUE and constraints in each state to identify regional and crop-specific technologies for implementation on farmers' fields. At present, India has 28 states and 8 union territories (UTs) out of which the environmental performance in terms of SNMI was assessed for all 28 states and 4 union territories during the last 10 years (2010-11 to 2019-20) (Table 3, Figure 1). The remaining 4 union territories (Chandigarh, Dadra Nagar Haveli and Daman Diu, Ladakh and Lakshadweep) were not considered as there was no consistency in data availability and further their contribution to the agriculture production is also very minimal. Year-wise data on N input, N yield, N surplus, NUE, SNMI, normalized SNMI, gross and net sown area for all 32 states is furnished in supplementary information (Table S1-S9). The 10-year average total N input into agriculture was the highest in Uttar Pradesh followed by Madhya Pradesh, Rajasthan, Maharashtra, Gujarat, Punjab and the lowest in Goa depending upon the gross cropped area (Table 3). The N input per unit area showed that the highest N input was in Puducherry (541.64kg ha^{-1} yr^{-1}) followed by Punjab, Haryana, Telangana etc. and was lowest in Sikkim (59.58kg N ha^{-1} yr^{-1}). The average N yield varied from 2.354Tg yr^{-1}

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in Uttar Pradesh to 0.0006Tg N yr^{-1} in Andaman & Nicobar Islands (A&N Islands). The N yield per hectare varied from 148.8kg N ha^{-1} yr^{-1} in Punjab to 33.09kg N ha^{-1} yr^{-1} in Mizoram depending upon the productivity of different crops. The N_{sur} which depends on N input and N yield showed that it varied from 2.31Tg N yr^{-1} in Uttar Pradesh to 0.0009Tg N yr^{-1} in A & N Islands. But when N_{sur} expressed per unit area, it varied from 446.61kg N ha^{-1} yr^{-1} in Puducherry to 7.77kg N ha^{-1} yr^{-1} in Nagaland. As expected, contrary to the trend of N_{sur}, the highest NUE of 0.878 was observed in Nagaland and the lowest was in Puducherry (0.196). Generally north-east Indian states such as Arunachal Pradesh, Assam, Meghalaya, Nagaland, Tripura recorded higher NUE of more than 0.700. The SNMI which is inverse proportion to the trend of NUE, varied from 0.234 in Assam to 0.869 in Mizoram. But the contribution of north-east states to Indian agriculture production is very less and out of 32 states and UTs, 14 states contribute almost 91% of the Indian agricultural production. Among these 14 major agriculture states, the SNMI was the lowest in Punjab and highest in Maharashtra state (Figure 2). In Punjab, the highest N yield (148.8kg N ha^{-1} yr^{-1}) and moderate NUE (0.604) resulted in the lowest SNMI (0.395) with normalized SNMI score of 54.52 with the 3rd rank among the 32 states and UTs studied. The normalized SNMI score varied from 73.11 in Assam with 1st Rank to 7.21 in Puducherry with 31st rank and further worst to 0 in Mizoram indicating the poorest environmental performance of Puducherry and Mizoram agriculture due to the highest N input and lowest NUE. Among the 14 major agriculture states, as expected Punjab has got the best rank of 4th with normalized SNMI value of 54.52 followed by West Bengal (5th Rank), Madhya Pradesh (6th Rank), Tamil Nadu (7th Rank) and the poorest rank (30th) in Maharashtra. The status of NUE vis-a-vis the environmental performance of these major states needs to be improved during next few decades by 2050 as per the FAO suggestions [5].

Table S1: Total N input (Tg yr^{-1}) into agriculture in different states during the last 10 years.

S. No.	State	2010-11	2011-12	2012-13	2013-14	2014-15	2015-16	2016-17	2017-18	2018-19	2019-20	Mean
1	Arunachal	0.0191	0.0202	0.0202	0.0203	0.020564	0.0202	0.018393	0.0204	0.0192	0.0192	0.019776
2	Assam	0.3757	0.383	0.3838	0.3826	0.39	0.404	0.389095	0.3863	0.4264	0.4078	0.392874
3	Bihar	1.3792	1.4644	1.6113	1.4324	1.494886	1.7362	1.544928	1.5973	1.6696	1.6925	1.562271
4	Jharkhand	0.1959	0.2821	0.2881	0.2512	0.274675	0.3076	0.326511	0.309	0.3212	0.3295	0.288579
5	Manipur	0.0299	0.0315	0.0285	0.0339	0.037154	0.0371	0.036235	0.0393	0.0408	0.0355	0.034989
6	Meghalaya	0.0181	0.083	0.0185	0.0193	0.017618	0.0164	0.016655	0.0159	0.0161	0.0161	0.023767
7	Mizoram	0.0089	0.009	0.0091	0.0121	0.012434	0.0109	0.011786	0.0142	0.0141	0.0136	0.011612
8	Nagaland	0.026	0.0279	0.0287	0.0297	0.03027	0.0305	0.03138	0.0317	0.0311	0.0302	0.029745
9	Odisha	0.6925	0.7039	0.7012	0.7049	0.705791	0.7003	0.677614	0.6795	0.7053	0.7052	0.697621
10	Sikkim	0.0075	0.0069	0.007	0.0069	0.006227	0.0065	0.0067	0.0072	0.0071	0.0071	0.006913
11	Tripura	0.0297	0.0328	0.0364	0.0341	0.032542	0.0349	0.039852	0.0348	0.0337	0.0351	0.034389
12	West Bengal	1.2124	1.3606	1.3577	1.2397	1.297232	1.3925	1.325918	1.2864	1.3358	1.3449	1.315315
13	Haryana	1.3368	1.3895	1.3805	1.3034	1.371803	1.3985	1.373988	1.4171	1.4789	1.4277	1.387819
14	HP	0.0961	0.0964	0.0976	0.0965	0.097121	0.0994	0.098241	0.0976	0.0976	0.0982	0.097476
15	J&K	0.1532	0.1534	0.1574	0.1488	0.147224	0.1591	0.149869	0.1604	0.1509	0.1545	0.153479
16	Punjab	1.8353	1.8505	1.9196	1.7959	1.785073	1.8803	1.822503	1.7604	1.8254	1.7758	1.825078
17	UP	4.4056	4.5436	4.8247	4.4531	4.658646	4.4079	4.407514	4.7222	4.9604	5.2668	4.665046
18	Uttarkhand	0.192	0.2034	0.2	0.2094	0.214675	0.245	0.235881	0.2226	0.2047	0.1935	0.212116
19	Delhi	0.0042	0.0038	0.0045	0.0055	0.010404	0.0072	0.009598	0.0079	0.0118	0.0145	0.00794
20	Andhra	2.8167	2.7744	2.5898	2.9633	1.506897	1.448	1.400168	1.3385	1.3444	1.3965	1.957867
21	Telangana**	0	0	0	0	1.161295	1.1967	1.275794	1.2614	1.2383	1.4061	1.256598
22	Karnataka	1.7565	1.8964	1.5602	1.6351	1.690975	1.7077	1.546841	1.5544	1.6135	1.7296	1.669122
23	Kerala	0.2106	0.2273	0.2152	0.2313	0.190125	0.1994	0.165558	0.2276	0.1511	0.1643	0.198248
24	Tamil Nadu	0.9529	1.0006	0.8491	0.8693	0.924914	1.0109	0.799652	0.8368	0.8592	0.8844	0.898777
25	Puducherry	0.0207	0.016	0.0127	0.0133	0.009255	0.0089	0.008704	0.0089	0.0078	0.0081	0.011436
26	A&N Islands	0.0016	0.0016	0.0016	0.0011	0.001126	0.0006	0.001134	0.0008	0.0044	0.0006	0.001456
27	Gujarat	1.9471	1.9293	1.6389	1.8646	1.869668	1.7349	1.79662	1.9561	1.7661	1.981	1.848429

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28	MP	2.2727	2.3944	2.4674	2.613	2.550849	2.6977	2.7948	2.7707	2.9149	3.0722	2.654861
29	Chhattis-garh	0.6811	0.716	0.742	0.7213	0.741517	0.7601	0.761747	0.6938	0.666	0.7559	0.723946
30	Maharash-tra	3.0987	2.9574	2.6971	2.9945	2.908509	2.8091	2.932484	2.8519	2.6996	2.8883	2.883759
31	Rajasthan	2.1936	2.1657	2.1241	2.1611	2.106937	2.2593	2.234206	2.0831	2.3404	2.6048	2.227324
32	Goa	0.0084	0.0089	0.0085	0.0075	0.007049	0.0064	0.0065	0.0058	0.0056	0.0051	0.006975
**Telangana state was formed in the year 2014-15.											

Table S2: Total N yield (removal) (Tg yr-1) into agriculture in different states during the last 10 years.

S. No.	State	2010-11	2011-12	2012-13	2013-14	2014-15	2015-16	2016-17	2017-18	2018-19	2019-20	Mean
1	Arunachal	0.0124	0.0145	0.0144	0.015	0.016071	0.0137	0.013329	0.0138	0.0139	0.0143	0.01414
2	Assam	0.293	0.2874	0.3093	0.3045	0.311472	0.3179	0.308405	0.3215	0.3265	0.323	0.310298
3	Bihar	0.4582	0.6054	0.6797	0.5784	0.575264	0.6167	0.683099	0.717	0.6945	0.6185	0.622676
4	Jharkhand	0.0967	0.1729	0.193	0.1837	0.197298	0.1714	0.23521	0.249	0.1924	0.2122	0.190381
5	Manipur	0.0223	0.0251	0.0163	0.0212	0.019544	0.0198	0.022239	0.0275	0.0215	0.0184	0.021388
6	Meghalaya	0.01	0.0106	0.0112	0.0139	0.015502	0.0156	0.013269	0.0154	0.0127	0.0158	0.013397
7	Mizoram	0.0038	0.0044	0.0037	0.005	0.005228	0.0049	0.004795	0.0047	0.0048	0.0049	0.004622
8	Nagaland	0.0234	0.0247	0.0258	0.028	0.0288	0.0249	0.025948	0.0266	0.0261	0.0264	0.026063
9	Odisha	0.2882	0.2561	0.3058	0.3143	0.33038	0.2513	0.331362	0.2729	0.3037	0.3219	0.297594
10	Sikkim	0.005	0.0045	0.0045	0.0045	0.004361	0.0041	0.004486	0.0046	0.0046	0.0046	0.004525
11	Tripura	0.0254	0.0259	0.0267	0.0275	0.028803	0.0308	0.031638	0.313	0.0308	0.0313	0.057184
12	West Bengal	0.6954	0.7266	0.7631	0.7797	0.770646	0.8085	0.795491	0.8069	0.8696	0.8691	0.788504
13	Haryana	0.7235	0.7712	0.7173	0.7428	0.662661	0.7058	0.74915	0.7238	0.8118	0.7883	0.739631
14	HP	0.06347	0.0637	0.064	0.0682	0.063439	0.0712	0.075396	0.0657	0.0658	0.0682	0.06691
15	J&K	0.071	0.0732	0.0769	0.0793	0.056209	0.0757	0.071622	0.0715	0.0855	0.0773	0.073823
16	Punjab	1.0559	1.0862	1.082	1.1236	1.009429	1.065	1.078063	1.19	1.1919	1.1369	1.101899
17	UP	2.209	2.348	2.3589	2.3076	1.924654	2.0604	2.397118	2.5487	2.6733	2.716	2.354367
18	Uttarkhand	0.0853	0.0866	0.087	0.0831	0.077332	0.0808	0.086459	0.0878	0.088	0.0889	0.085129
19	Delhi	0.0074	0.0063	0.0058	0.0046	0.004463	0.0046	0.004543	0.0044	0.0043	0.0043	0.005071
20	Andhra	0.9567	0.8231	0.9321	0.973	0.490708	0.525	0.499165	0.6194	0.5181	0.6185	0.695577
21	Telangana	0	0	0	0	0.336912	0.2607	0.383606	0.4111	0.3853	0.4665	0.37402
22	Karnataka	0.7411	0.6298	0.6019	0.6801	0.681444	0.6285	0.57515	0.6652	0.6355	0.721	0.655969
23	Kerala	0.0717	0.0737	0.0714	0.0735	0.069294	0.068	0.066522	0.0691	0.0764	0.0703	0.070992
24	Tamil Nadu	0.4832	0.5845	0.3994	0.5257	0.544869	0.5757	0.318528	0.5449	0.5252	0.5656	0.50676
25	Puducherry	0.0023	0.0019	0.0022	0.0021	0.002307	0.0018	0.001575	0.0017	0.0023	0.0021	0.002028
26	A&N Islands	0.001	0.0011	0.0009	0.0005	0.000463	0.0004	0.000399	0.0005	0.0003	0.0005	0.000606
27	Gujarat	0.8623	0.8855	0.6018	1.0544	0.811597	0.7114	0.791105	0.9199	0.6816	0.9975	0.83171
28	MP	1.1432	1.4309	1.644	1.4595	1.765191	1.7584	2.000574	1.9946	1.967	1.8797	1.704307
29	Chhattis-garh	0.2575	0.2489	0.2819	0.2751	0.283474	0.2525	0.342878	0.2389	0.2846	0.2738	0.273955
30	Maharash-tra	1.1845	0.9989	0.9824	1.1647	0.89568	0.7536	1.186386	1.0896	1.0143	1.117	1.038707
31	Rajasthan	1.1467	1.0819	1.0945	1.0814	1.0966	1.0784	1.185141	1.2154	1.3274	1.4143	1.172169
32	Goa	0.0051	0.0058	0.0055	0.0049	0.004448	0.0036	0.003952	0.0035	0.0034	0.003	0.00432

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Table S3: N surplus (Tg yr^{-1}) in agriculture in different states during the last 10 years.

S. No.	State	2010-11	2011-12	2012-13	2013-14	2014-15	2015-16	2016-17	2017-18	2018-19	2019-20	Mean
1	Arunachal	0.0067	0.0057	0.0058	0.0053	0.004493	0.0064	0.005063	0.0066	0.0052	0.0049	0.005616
2	Assam	0.0827	0.0956	0.0745	0.0781	0.078576	0.0861	0.08069	0.0648	0.0999	0.0847	0.082567
3	Bihar	0.921	0.8589	0.9315	0.854	0.919623	1.1195	0.861829	0.8803	0.9751	1.074	0.939575
4	Jharkhand	0.0992	0.1091	0.0951	0.0675	0.077377	0.1363	0.091301	0.06	0.1288	0.1173	0.098198
5	Manipur	0.0076	0.0063	0.0122	0.0127	0.01761	0.0173	0.013996	0.0118	0.0193	0.017	0.013581
6	Meghalaya	0.0081	0.0076	0.0073	0.0054	0.002116	0.0008	0.003386	0.0004	0.0033	0.0003	0.00387
7	Mizoram	0.0051	0.0047	0.0055	0.0072	0.007205	0.0061	0.006991	0.0095	0.0092	0.0087	0.00702
8	Nagaland	0.0025	0.0032	0.0029	0.0016	0.001488	0.0055	0.005432	0.0051	0.0049	0.0037	0.003632
9	Odisha	0.4042	0.4477	0.3954	0.3906	0.375411	0.449	0.346252	0.4066	0.4016	0.382	0.399876
10	Sikkim	0.0025	0.0024	0.0024	0.0024	0.001866	0.0024	0.002214	0.0025	0.0025	0.0025	0.002368
11	Tripura	0.0043	0.0069	0.0096	0.0066	0.003739	0.004	0.008214	0.0035	0.0028	0.0037	0.005335
12	West Bengal	0.517	0.6339	0.5946	0.46	0.526586	0.584	0.530428	0.4795	0.4662	0.4757	0.526791
13	Haryana	0.6133	0.6182	0.6632	0.5606	0.709142	0.6928	0.624838	0.6934	0.667	0.6394	0.648188
14	HP	0.0326	0.0327	0.0336	0.0283	0.033682	0.0282	0.022845	0.0319	0.0319	0.03	0.030573
15	J&K	0.0821	0.0802	0.0805	0.0695	0.091015	0.0833	0.078247	0.0888	0.0654	0.0772	0.079626
16	Punjab	0.7794	0.7643	0.8376	0.6723	0.775644	0.8153	0.74444	0.5703	0.6335	0.6389	0.723168
17	UP	2.1966	2.1955	2.4657	2.1455	2.733992	2.3475	2.010395	2.1736	2.2871	2.5507	2.310659
18	Uttarkhand	0.1067	0.1168	0.1129	0.1263	0.137343	0.1642	0.149422	0.1348	0.1167	0.1046	0.126977
19	Delhi	-0.0032	-0.0024	-0.0013	0.0009	0.005941	0.0026	0.005055	0.0035	0.0074	0.0102	0.00287
20	Andhra	1.8599	1.9513	1.6577	1.9903	1.016189	0.923	0.901003	0.7191	0.8263	0.778	1.262279
21	Telangana	0	0	0	0	0.824383	0.936	0.892188	0.8503	0.853	0.9395	0.882562
22	Karnataka	1.0154	1.2667	0.9583	0.955	1.009531	1.0792	0.971691	0.8892	0.978	1.0087	1.013172
23	Kerala	0.1389	0.1536	0.1438	0.1577	0.120832	0.1314	0.099035	0.1585	0.0747	0.094	0.127247
24	Tamil Nadu	0.4696	0.4161	0.4496	0.3436	0.380045	0.4352	0.481124	0.2918	0.334	0.3188	0.391987
25	Puducherry	0.01841	0.014	0.0105	0.0112	0.006949	0.007	0.00713	0.0071	0.0055	0.0059	0.009369
26	A&N Islands	0.0006	0.0005	0.0006	0.0006	0.000663	0.0001	0.000735	0.0003	0.0041	7.76E-05	0.000828
27	Gujarat	1.0848	1.0438	1.0371	0.8102	1.058071	1.0234	1.005515	1.0362	1.0844	0.9835	1.016699
28	MP	1.1295	0.9635	0.8233	1.1534	0.785658	0.9393	0.794191	0.7761	0.9478	1.1926	0.950535
29	Chhattisgarh	0.4236	0.4671	0.4601	0.4462	0.458043	0.5075	0.41887	0.4549	0.3814	0.4821	0.449981
30	Maharashtra	1.9141	1.9585	1.7147	1.8297	2.012829	2.0555	1.746098	1.7622	1.6853	1.7713	1.845023
31	Rajasthan	1.0469	1.0837	1.0296	1.0797	1.0104	1.1809	1.049064	0.8677	1.013	1.1905	1.055145
32	Goa	0.0032	0.0031	0.003	0.0027	0.0026	0.0028	0.0025	0.0022	0.0022	0.0021	0.00264

Table S4: N surplus (kg ha^{-1} yr^{-1}) in agriculture in different states during the last 10 years.

S. No.	State	2010-11	2011-12	2012-13	2013-14	2014-15	2015-16	2016-17	2017-18	2018-19	2019-20	Mean
1	Aruna chal	21.8609	17.1897	17.5904	15.6715	13.03767	22.1358	17.32537	20.8575	16.5308	15.5382	17.77378
2	Assam	21.5883	25.0951	19.4595	20.5783	20.4132	22.2143	20.80628	17.1204	25.8569	22.8279	21.59602
3	Bihar	116.8391	103.082	110.8899	106.8275	110.348	135.3102	104.1687	108.2995	120.7043	139.2171	115.5686
4	Jhar khand	49.2722	37.6039	30.6628	22.8195	23.89977	35.7228	23.93138	15.4504	37.4074	34.4145	31.11846
5	Mani-pur	19.3416	16.1588	40.9468	31.5557	42.87384	39.2344	31.77333	27.2431	45.1138	52.5211	34.67625
6	Megha laya	36.9629	35.0153	33.0509	23.1603	8.767372	3.1583	13.5454	1.7412	13.4559	1.389	17.02466

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7	Mizoram	49.7423	34.8447	47.0215	47.6887	46.57596	40.6882	46.85967	63.9116	62.6558	58.2469	49.82353
8	Nagaland	6.4202	7.3842	6.556	3.499	3.192517	11.3539	11.09221	10.3342	10.2688	7.6432	7.774423
9	Odisha	61.4932	70.9341	61.5211	59.994	57.64896	72.6053	55.99063	68.4004	67.3655	63.147	63.91002
10	Sikkim	19.6143	20.8937	20.8781	20.8906	18.31499	21.6135	19.89827	20.8903	21.2917	21.1129	20.53984
11	Tripura	12.0854	18.4442	25.4242	16.7673	9.2639	9.1742	18.75871	8.1359	6.6108	8.7285	13.33931
12	West Bengal	60.6977	70.2594	65.1809	49.0721	56.95655	62.3604	56.64002	51.9631	47.9304	48.1895	56.92501
13	Haryana	98.8316	97.7774	108.662	93.2068	115.8606	110.5808	99.73633	109.9288	102.5322	98.053	103.517
14	HP	29.4821	29.5207	30.1766	25.7521	31.26748	25.4335	20.61108	30.2329	29.9884	28.9047	28.13696
15	J&K	59.1755	52.7104	57.1602	49.2427	64.21633	62.2533	58.44975	65.5888	49.3519	60.513	57.86619
16	Punjab	105.2137	102.652	112.5905	90.8363	104.3854	111.8595	102.1347	76.1291	84.2857	87.0756	97.71626
17	UP	90.8133	89.2023	100.4045	86.8109	109.8797	92.3086	79.05139	86.7521	92.6442	101.3858	92.92528
18	Uttarkhand	77.0248	84.681	82.8998	98.1736	102.7512	129.9481	118.2605	107.9731	94.6208	86.9864	98.33193
19	Delhi	-45.6912	-38.1113	-21.3835	29.8018	196.7234	76.0731	148.5396	104.483	223.1762	306.0716	97.96826
20	Andhra	135.5924	153.9608	128.3	145.64	149.811	141.4576	138.089	108.8361	125.5656	118.8887	134.6141
21	Telangana	0	0	0	0	152.6201	164.0981	156.4171	145.175	153.0793	156.9223	154.7186
22	Karnataka	86.5848	118.3339	91.1968	87.6366	93.03157	102.9938	92.73081	83.6292	91.7657	93.5222	94.14254
23	Kerala	110.1427	123.0885	115.0475	119.8582	107.5182	114.0998	86.01048	132.0456	76.4453	78.8452	106.3102
24	Tamil Nadu	98.8529	85.4706	107.9063	68.4265	75.04328	100.8214	111.465	59.6789	69.6909	61.5422	83.8898
25	Puducherry	719.119	623.9102	468.3575	571.057	330.8993	388.0649	391.7397	343.7058	260.6682	277.9977	437.5519
26	A&N Islands	29.214	26.5515	33.6955	69.4795	78.92824	21.396	111.7086	56.0744	672.1316	12.2914	111.1471
27	Gujarat	97.6756	87.6956	107.7445	72.971	105.3737	101.7329	99.94981	100.2474	112.6934	93.3682	97.94521
28	MP	53.7127	43.4992	35.5677	49.1135	32.62353	36.2884	30.6809	30.2764	37.94	47.9238	39.76261
29	Chhattisgarh	73.0035	80.2767	77.1616	75.5786	76.45443	83.4975	68.9078	77.049	67.0113	84.2135	76.31539
30	Maharashtra	80.7674	89.7484	79.8183	79.4217	90.46629	90.5496	76.91894	80.8633	80.766	78.8911	82.8211
31	Rajasthan	49.641	54.8168	57.0447	56.0154	56.20125	60.2798	53.54883	45.2319	50.5275	53.5414	53.68486
32	Goa	50.1788	39.5433	39.3232	49.4629	48.5233	64.45	51.72	49.2175	51.326	53.3891	49.71341

Table S5: N yield (kg ha-1 yr-1) in agriculture in different states during the last 10 years.

S. No.	State	2010-11	2011-12	2012-13	2013-14	2014-15	2015-16	2016-17	2017-18	2018-19	2019-20	Mean
1	Arunachal	39.9746	44.128	43.4381	44.144	46.6328	46.9512	45.6088	43.9094	44.0466	45.0348	44.38683
2	Assam	76.5046	75.4003	80.8127	80.2106	80.91753	81.9673	79.52378	84.8828	84.4841	87.0284	81.17321

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3	Bihar	58.1276	72.654	80.9094	72.3501	69.02743	74.548	82.56568	88.2175	85.9665	80.1717	76.45379
4	Jhar khand	48.0759	59.5851	62.2365	62.1314	60.94009	44.9183	61.65248	64.0796	55.8644	62.2647	58.17485
5	Mani-pur	56.481	64.3212	54.6273	52.6311	47.5812	44.9961	50.48492	63.4646	50.056	56.7689	54.14123
6	Megha laya	45.7134	48.8084	50.9235	59.6908	64.235	62.4123	53.07423	63.3669	51.4114	63.4417	56.30776
7	Mizo ram	37.2864	32.6704	31.6497	32.9864	33.79628	32.5971	32.13636	31.9561	33.057	32.7869	33.09226
8	Naga land	58.7905	57.162	58.5863	60.9266	61.75025	50.9435	52.98817	53.6302	53.9574	53.894	56.26289
9	Odisha	43.8467	40.5826	47.5864	48.2831	50.73392	40.6359	53.58292	45.9117	50.9513	53.4247	47.55392
10	Sikkim	39.3901	38.8746	38.8345	39.0132	42.81254	36.7762	40.32747	38.5888	38.2549	38.4321	39.13044
11	Tripu-ra	70.8096	69.5467	70.6232	69.932	71.36849	70.4652	72.24937	71.5122	71.3929	73.2907	71.11904
12	West Bengal	81.6404	80.5302	83.6459	83.1864	83.3546	86.3331	84.94391	87.4357	89.3946	88.0317	84.84965
13	Hary-ana	116.5836	121.9797	117.5099	123.4982	108.2664	112.6558	119.5789	114.7481	124.7856	120.8736	118.048
14	HP	57.324	57.5447	57.5021	62.0201	58.8907	64.2261	68.02241	62.1694	61.8907	65.7924	61.53826
15	J&K	51.1742	48.0999	54.5892	56.1425	39.65861	56.5696	53.50144	52.7841	64.4449	60.5913	53.75557
16	Punjab	142.5488	145.8884	145.4308	151.7991	135.8479	146.1142	147.9068	158.8436	158.5779	154.9385	148.7896
17	UP	91.3276	95.3987	96.0566	93.3735	77.35222	81.0174	94.25785	101.7237	108.2885	107.9549	94.6751
18	Uttar khand	61.5834	62.7677	63.8773	64.5693	57.85465	63.9764	68.42799	70.3373	71.3173	73.8849	65.85962
19	Delhi	105.8145	98.9904	95.7176	151.9026	147.7915	135.0982	133.491	130.2454	129.9894	130.1223	125.9163
20	Andh ra	69.7493	64.9408	72.143	71.194	72.34229	80.4631	76.50271	93.7445	78.7374	94.5316	77.43487
21	Telan gana	0	0	0	0	62.37329	45.7053	67.25331	70.1834	69.1532	77.9259	65.4324
22	Karna taka	63.193	58.8346	57.2765	62.4088	62.79734	59.9774	54.88788	62.5665	59.6274	66.8474	60.84168
23	Kerala	56.8575	59.0945	57.0551	55.8833	61.65876	59.0607	57.77336	57.5533	78.2752	58.9125	60.21242
24	Tamil Nadu	101.7124	120.0735	95.8511	104.6797	107.5893	133.3886	73.79534	111.4445	109.5827	109.2046	106.7322
25	Pudu cherry	89.4712	87.1752	97.9852	109.0817	109.8375	99.3894	86.51648	84.2031	109.3947	99.9484	97.30028
26	A&N Is-lands	51.0324	53.287	50.718	55.6469	55.10498	69.6471	60.64591	80.8228	56.7216	86.0408	61.96675
27	Guja-rat	77.6342	74.4016	62.5141	94.9696	80.82724	70.7192	78.6371	88.9963	70.8336	94.7016	79.42345
28	MP	54.367	64.599	71.0199	62.1458	73.29748	67.9289	77.28553	77.8094	78.7351	75.5349	70.2723
29	Chhat-tisgarh	44.3683	42.7784	47.2663	46.5996	47.31623	41.5469	56.40641	40.4617	50.0058	47.839	46.45886
30	Maha-ra shtra	49.988	45.7776	45.7292	50.5531	40.2562	33.1971	52.26253	49.9998	48.6084	49.7472	46.61191
31	Rajas than	54.3735	54.7277	60.6395	56.1011	60.99431	55.0461	60.4948	63.3562	66.2071	63.6069	59.55472

Table S6: Nitrogen Use Efficiency (NUE) in different states during the last 10 years.

S. No.	State	2010-11	2011-12	2012-13	2013-14	2014-15	2015-16	2016-17	2017-18	2018-19	2019-20	Mean
1	Arunachal	0.6465	0.7196	0.7117	0.738	0.781505	0.6796	0.724706	0.678	0.7271	0.7435	0.715021

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2	Assam	0.7799	0.7503	0.8059	0.7958	0.798548	0.7868	0.792622	0.8321	0.7657	0.7922	0.789987
3	Bihar	0.3322	0.4134	0.4218	0.4038	0.384821	0.3552	0.442156	0.4489	0.4159	0.3654	0.398358
4	Jharkhand	0.4938	0.6131	0.6699	0.7314	0.718296	0.557	0.720375	0.8057	0.5989	0.644	0.655247
5	Manipur	0.7449	0.7992	0.5715	0.6252	0.52602	0.5342	0.613737	0.6997	0.526	0.5194	0.615986
6	Meghalaya	0.5529	0.5823	0.6064	0.7204	0.879903	0.9518	0.796676	0.9732	0.7926	0.9786	0.783478
7	Mizoram	0.4284	0.4839	0.4023	0.4089	0.420497	0.4448	0.40681	0.3333	0.3454	0.3602	0.403451
8	Nagaland	0.9015	0.8856	0.8993	0.9457	0.950841	0.8177	0.826902	0.8384	0.8401	0.8758	0.878184
9	Odisha	0.4162	0.3639	0.4361	0.4459	0.468099	0.3588	0.489013	0.4016	0.4306	0.4583	0.426851
10	Sikkim	0.6676	0.6504	0.6503	0.6513	0.700381	0.6298	0.669605	0.6488	0.6424	0.6454	0.655599
11	Tripura	0.8542	0.7904	0.7353	0.8066	0.88511	0.8848	0.793879	0.8978	0.9152	0.8936	0.845689
12	West Bengal	0.5736	0.534	0.562	0.6289	0.59407	0.5806	0.599954	0.6272	0.651	0.6462	0.599752
13	Haryana	0.5412	0.5551	0.5195	0.5699	0.483058	0.5046	0.545238	0.5107	0.5489	0.5521	0.53303
14	HP	0.6604	0.6609	0.6558	0.7066	0.653193	0.7163	0.767457	0.6728	0.6736	0.6948	0.686185
15	J&K	0.4637	0.4771	0.4885	0.5327	0.381792	0.4761	0.4779	0.4459	0.5663	0.5003	0.481029
16	Punjab	0.5753	0.587	0.5636	0.6256	0.565483	0.5664	0.591529	0.676	0.6529	0.6402	0.604401
17	UP	0.5014	0.5168	0.4889	0.5182	0.413136	0.4674	0.543871	0.5397	0.5389	0.5157	0.504401
18	Uttarkhand	0.4443	0.4257	0.4352	0.3967	0.360227	0.3299	0.366536	0.3945	0.4298	0.4593	0.404216
19	Delhi	1.7599	1.626	1.2876	0.836	0.428984	0.6397	0.473321	0.5549	0.3681	0.2983	0.827281
20	Andhra	0.3397	0.2967	0.3599	0.3283	0.325641	0.3626	0.356503	0.4627	0.3854	0.4429	0.366034
21	Telangana	0	0	0	0	0.290117	0.2178	0.30068	0.3259	0.3112	0.3318	0.29625
22	Karnataka	0.4219	0.3321	0.3857	0.4159	0.402989	0.368	0.371822	0.428	0.3938	0.4168	0.393701
23	Kerala	0.3404	0.3244	0.3315	0.318	0.364463	0.3411	0.401807	0.3035	0.5059	0.4277	0.365877
24	Tamil Nadu	0.5071	0.5842	0.4704	0.6047	0.589103	0.5695	0.398333	0.6512	0.6113	0.6396	0.562544
25	Puducherry	0.1106	0.1226	0.173	0.1604	0.249213	0.2039	0.1809	0.1968	0.2956	0.2644	0.195741
26	A&N Islands	0.6359	0.6674	0.6008	0.4447	0.411129	0.765	0.351867	0.5904	0.0778	0.875	0.542
27	Gujarat	0.4428	0.459	0.3671	0.5655	0.434086	0.4101	0.440329	0.4703	0.3859	0.5035	0.447862
28	MP	0.503	0.5976	0.6663	0.5585	0.692001	0.6518	0.715829	0.7199	0.6748	0.6118	0.639153
29	Chhattisgarh	0.378	0.3476	0.3798	0.3814	0.38229	0.3323	0.45012	0.3443	0.4273	0.3623	0.378541
30	Maharashtra	0.3823	0.3378	0.3642	0.3889	0.307952	0.2683	0.404567	0.3821	0.3757	0.3867	0.359852
31	Rajasthan	0.5227	0.4996	0.5152	0.5004	0.520449	0.4773	0.530453	0.5834	0.5671	0.543	0.52596
32	Goa	0.6181	0.6494	0.6429	0.644	0.630965	0.5611	0.263135	0.612	0.6011	0.581	0.58037

Table S7: Sustainable N Management Index (SNMI) in different states during the last 10 years.

S. N O.	State	2010-11	2011-12	2012-13	2013-14	2014-15	2015-16	2016-17	2017-18	2018-19	2019-20	Mean
1	Aruna chal	0.658741	0.581698	0.592228	0.572926	0.529081	0.575716	0.564861	0.604958	0.578941	0.56162	0.582077
2	Assam	0.266308	0.297779	0.219276	0.231339	0.225315	0.231153	0.237814	0.177211	0.242218	0.210405	0.2338817
3	Bihar	0.755872	0.617425	0.586913	0.627634	0.657835	0.667237	0.563927	0.551451	0.585758	0.643896	0.6257949
4	Jhar khand	0.687876	0.51372	0.451779	0.409927	0.428502	0.668688	0.421186	0.347402	0.552	0.470829	0.495191
5	Mani pur	0.451417	0.348884	0.581398	0.559372	0.66843	0.683382	0.584782	0.420872	0.649374	0.606034	0.5553946
6	Megha laya	0.664844	0.619653	0.586022	0.437672	0.310449	0.310291	0.457904	0.297129	0.476305	0.295869	0.4456137
7	Mizo ram	0.818373	0.819832	0.881806	0.866443	0.851943	0.845608	0.874776	0.927566	0.910407	0.901947	0.8698699

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8	Naga land	0.360477	0.382381	0.36326	0.327571	0.317712	0.470678	0.446188	0.435209	0.43121	0.419965	0.3954652
9	Odis-ha	0.777016	0.840295	0.734863	0.722395	0.687944	0.843755	0.651795	0.773313	0.715838	0.677195	0.7424409
10	Sik-kim	0.653239	0.667005	0.667419	0.665253	0.603877	0.69767	0.643252	0.670571	0.677063	0.673811	0.6619161
11	Tripu-ra	0.258304	0.309169	0.341206	0.295163	0.236761	0.245728	0.285281	0.229416	0.223442	0.213996	0.2638465
12	West Ben-gal	0.436432	0.477676	0.443619	0.378677	0.412591	0.421363	0.403971	0.373853	0.349094	0.354435	0.405171
13	Har yana	0.458796	0.444934	0.48044	0.430109	0.516942	0.495352	0.454762	0.489275	0.451052	0.447881	0.4669544
14	HP	0.497159	0.494982	0.498838	0.427473	0.489648	0.403086	0.337206	0.450194	0.451749	0.406834	0.4457169
15	J&K	0.688239	0.700095	0.645322	0.599882	0.833698	0.642233	0.661098	0.691377	0.518369	0.597036	0.6577349
16	Pun-jab	0.424656	0.41302	0.436361	0.374374	0.434517	0.433608	0.408471	0.323991	0.34705	0.359796	0.3955842
17	UP	0.498588	0.483217	0.511066	0.481789	0.603455	0.541844	0.456129	0.460282	0.461071	0.48431	0.4981751
18	Uttar khand	0.639137	0.649141	0.635016	0.666142	0.732721	0.72982	0.677295	0.643742	0.606828	0.569596	0.6549437
19	Delhi	0.759957	0.626017	0.287667	0.164013	0.571016	0.360244	0.526679	0.445123	0.631931	0.701687	0.5074333
20	Andh ra	0.697609	0.756442	0.670126	0.703415	0.70232	0.646172	0.660741	0.537248	0.627215	0.55709	0.6558377
21	Telan gana	0	0	0	0	0.773408	0.924114	0.74359	0.709157	0.726727	0.681521	0.7597529
22	Karna taka	0.650311	0.752346	0.713778	0.659635	0.669162	0.714613	0.739468	0.648181	0.693755	0.637387	0.6878637
23	Kerala	0.755378	0.75789	0.762145	0.780282	0.709275	0.743209	0.697174	0.784227	0.510973	0.668501	0.7169054
24	Tamil Nadu	0.492871	0.415826	0.529582	0.395286	0.410897	0.430475	0.62803	0.348748	0.38874	0.36043	0.4400886
25	Pudu cherry	0.889369	0.903257	0.826986	0.839619	0.750787	0.796105	0.820014	0.8058	0.704389	0.735549	0.8071874
26	A&N Is-lands	0.565686	0.526308	0.591474	0.673813	0.387722	0.326145	0.725572	0.422111	0.993545	0.132514	0.5344891
27	Guja-rat	0.573851	0.56809	0.702667	0.434505	0.575018	0.627615	0.573735	0.529844	0.649923	0.496455	0.5731702
28	MP	0.635403	0.491513	0.394749	0.539117	0.359589	0.425891	0.31735	0.311145	0.348434	0.420134	0.4243324
29	Ch-hattis-garh	0.802454	0.837181	0.781034	0.784346	0.778776	0.857741	0.6646	0.856084	0.724856	0.791295	0.7878368
30	Maha-ra shtra	0.761052	0.824605	0.803838	0.751993	0.885674	0.96632	0.728257	0.761157	0.775398	0.759043	0.8017336
31	Rajas than	0.620053	0.635613	0.584281	0.625689	0.577786	0.651185	0.57267	0.51103	0.507189	0.543033	0.5828529
32	Goa	0.394157	0.396793	0.415978	0.356024	0.377226	0.927189	0.736865	0.411514	0.422851	0.455082	0.489368

Table S8: Normalized score of Sustainable N Management Index (SNMI) in different states during the last 10 years.

S. No.	State	2010-11	2011-12	2012-13	2013-14	2014-15	2015-16	2016-17	2017-18	2018-19	2019-20	Mean
1	Aruna chal	25.9315	35.59997	32.83919	33.87615	37.79066	40.4218	36.5745	34.78003	41.7298	37.73247	35.72762
2	Assam	70.0565	67.03278	75.13324	73.3002	73.65465	76.07909	73.29706	80.89502	75.62082	76.67214	74.17415
3	Bihar	15.0102	31.6446	33.44191	27.56198	23.28286	30.95077	36.67938	40.54862	41.04362	28.61042	30.87744

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4	Jhar khand	22.6557	43.12583	48.76654	52.68856	48.75133	30.8006	52.70705	62.54691	44.44137	47.79857	45.42825
5	Mani pur	49.2429	61.37488	34.06726	35.44049	20.83024	29.27993	34.33769	54.62621	34.64071	32.8082	38.66486
6	Megha laya	25.2454	31.39797	33.54289	49.48635	63.67079	67.88946	48.58422	67.96678	52.06002	67.19664	50.70406
7	Mizo ram	7.98269	9.236105	0	0	1.265255	12.49199	1.775656	0	8.367874	0	4.111957
8	Naga land	59.4681	57.66642	58.80495	62.19358	73.54269	51.29169	49.89974	53.08057	56.59885	53.43796	57.59846
9	Odis-ha	12.6328	6.970601	16.66384	16.62527	18.15226	12.68376	26.81313	16.62982	27.95119	24.91846	18.00412
10	Sik-kim	26.5502	26.15557	24.31223	23.22031	30.37211	27.80138	27.77234	27.70634	31.85384	25.2937	27.1038
11	Tri pura	70.9565	65.77179	61.30597	65.93397	58.63885	74.57077	67.96715	75.26689	77.51068	76.27394	69.41966
12	West Ben-gal	50.9278	47.11631	49.69197	56.29528	49.98321	56.39509	54.64006	59.69524	64.86385	60.70338	55.03123
13	Har yana	48.4132	50.74117	45.51634	50.35923	39.47615	48.73828	48.93692	47.25172	54.60176	50.3429	48.43778
14	HP	44.0997	45.20034	43.42991	50.66349	42.70058	58.28651	62.13682	51.46505	54.53162	54.89375	50.74078
15	J&K	22.6148	22.49222	26.81805	30.76505	2.705528	33.53833	25.76846	25.46328	47.8263	33.8059	27.1798
16	Pun-jab	52.252	54.27443	50.51502	56.79192	49.60568	55.1279	54.13477	65.0708	65.06959	60.10899	56.29511
17	UP	43.9391	46.50286	42.04328	44.39463	29.12404	43.92711	48.78347	50.37738	53.59339	46.30391	44.89892
18	Uttar khand	28.1359	28.13328	27.9868	23.11771	14.16692	24.47432	23.94987	30.59882	38.923	36.84811	27.63347
19	Delhi	14.5509	30.69343	67.37752	81.07058	0	62.72007	40.86177	52.0117	36.39639	22.20305	40.78854
20	Andh ra	21.5613	16.25402	24.00527	18.81585	15.62429	33.13069	25.80858	42.07974	36.87102	38.23472	27.23855
21	Telan gana	0	0	0	0	12.72937	4.367772	16.50588	23.54641	26.85516	24.43889	18.07391
22	Karna taka	26.8795	16.70746	19.05489	23.86865	16.69411	26.04802	16.96873	30.12022	30.17376	29.33209	23.58474
23	Kerala	15.0657	16.09373	13.56997	9.944275	74.05855	23.08873	21.71769	15.45318	48.5708	25.88238	26.34451
24	Tamil Nadu	44.5818	53.96372	39.94341	54.37829	41.96401	55.45218	29.48155	62.40184	60.87343	60.03871	50.3079
25	Pudu cherry	0	0	6.216731	3.095985	11.06697	17.61477	7.924578	13.12744	29.10351	18.44878	10.65988
26	A&N Is-lands	36.3946	41.73226	32.92465	22.23226	0	66.24878	18.52907	54.49264	0	85.308	35.78623
27	Guja-rat	35.4765	37.10654	20.31502	49.85192	9.794867	35.05106	35.57811	42.87803	34.58547	44.95738	34.55949
28	MP	28.5557	45.58439	55.23406	37.77815	56.01068	55.9265	64.36634	66.45575	64.93027	53.41915	52.82611
29	Ch-hattis-garh	9.77262	7.315324	11.42781	9.475196	16.33324	11.23636	25.37532	7.706335	27.04352	12.26811	13.79538
30	Maha-ra shtra	14.4277	8.707676	8.841829	13.20925	0	0	18.22759	17.94033	21.9565	15.84396	11.91549
31	Rajas than	30.2816	29.63103	33.74036	27.78656	24.94718	32.61184	35.6977	44.90634	48.95161	39.79326	34.83475
32	Goa	55.6812	56.07085	52.82651	58.90977	47.55632	4.049504	0	55.63505	57.44015	49.5445	43.77139

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Table S9: Gross and net cultivated area (million ha) in India during the last 10 years.

Year	Gross Cropped Area (m ha)	Net Sown Area (m ha)
2010-11	187.04	141.34
2011-12	186.18	140.6
2012-13	182.57	139.9
2013-14	188.79	141.34
2014-15	185.54	139.93
2015-16	186.11	141.34
2016-17	189.53	139.93
2017-18	188.2	139.22
2018-19	186.12	140.64
2019-20	191.32	140.64

Table 3: 10-year (2010-11 to 2019-20) mean values of Total N input, Total N removal (N yield), and Total N surplus in different states of India.

S. No.	State	Total N input		Total N Removal (N yield)		N Surplus		NUE	SNMI	Normalized SNMI Score	
		Tg yr^{-1}	kg ha-1yr^{-1}	Tg yr^{-1}	kg ha-1yr^{-1}	Tg yr^{-1}	kg ha^{-1} yr^{-1}			Value	Rank
1	Arunachal Pradesh	0.0197	61.99	0.0141	44.38	0.0056	17.77	0.715	0.582	33.08	18
2	Assam	0.3928	102.75	0.3103	81.17	0.0826	21.59	0.79	0.234	73.11	1
3	Bihar	1.5622	191.89	0.6227	76.45	0.9396	115.56	0.398	0.626	28.06	20
4	Jharkhand	0.2886	88.58	0.1904	58.17	0.0982	31.12	0.655	0.495	43.07	12
5	Manipur	0.035	88.22	0.0214	54.14	0.0136	34.68	0.616	0.555	36.15	16
6	Meghalaya	0.0238	100.17	0.0134	56.31	0.0039	43.86	0.783	0.445	48.77	8
7	Mizoram	0.0116	82.82	0.0046	33.09	0.007	49.82	0.403	0.869	0	32
8	Nagaland	0.0297	63.99	0.026	56.26	0.0036	7.77	0.878	0.395	54.53	3
9	Odisha	0.6976	111.33	0.2976	47.55	0.3999	63.91	0.427	0.742	14.65	27
10	Sikkim	0.0069	59.58	0.0045	39.13	0.0024	20.54	0.655	0.662	23.9	24
11	Tripura	0.0344	84.27	0.0572	71.12	0.0053	13.34	0.846	0.263	69.66	2
12	West Bengal	1.3153	141.67	0.7885	84.85	0.5268	56.92	0.599	0.406	53.42	5
13	Haryana	1.3878	221.58	0.7396	118.05	0.6482	103.52	0.533	0.467	46.32	10
14	Himachal Pradesh	0.0975	89.6	0.067	61.54	0.0306	28.14	0.686	0.445	48.76	9
15	Jammu & Kashmir	0.1534	111.35	0.0738	53.76	0.0796	57.87	0.481	0.658	24.38	23
16	Punjab	1.8251	246.47	1.1019	148.79	0.7232	97.72	0.604	0.395	54.52	4
17	Uttar Pradesh	4.665	187.56	2.3544	94.67	2.3107	92.92	0.504	0.498	42.73	13
18	Uttarakhand	0.2121	163.62	0.0851	65.86	0.127	98.33	0.404	0.655	24.71	21
19	Delhi	0.0079	186.96	0.0051	120.69	0.0028	66.26	0.827	0.507	41.66	14
20	Andhra Pradesh	1.9579	211.56	0.6956	77.43	1.2622	134.61	0.366	0.656	24.61	22
21	Telangana	1.2566	220.29	0.374	65.43	0.8826	154.72	0.296	0.76	12.66	28
22	Karnataka	1.6691	154.95	0.656	60.84	1.0132	94.14	0.394	0.688	20.92	25
23	Kerala	0.1982	166.98	0.071	60.21	0.1272	106.31	0.366	0.717	17.58	26
24	Tamil Nadu	0.8988	189.74	0.5068	106.73	0.3919	83.89	0.562	0.44	49.41	7
25	Puducherry	0.0114	541.64	0.002	95.03	0.0094	446.61	0.196	0.807	7.21	31
26	A & N Islands	0.0015	139.06	0.0006	55.62	0.0009	83.43	0.542	0.534	38.55	15
27	Gujarat	1.8484	177.06	0.8317	79.42	1.0167	97.94	0.447	0.573	34.11	17

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28	Madhya Pradesh	2.6548	110.08	1.7043	70.27	0.9505	39.76	0.639	0.424	51.22	6
29	Chhattisgarh	0.7239	122.79	0.2739	46.46	0.4499	76.31	0.378	0.788	9.43	29
30	Maharashtra	1.884	129.43	1.0387	46.61	1.845	82.82	0.359	0.802	7.83	30
31	Rajasthan	2.2273	113.17	1.1721	59.55	1.0551	53.68	0.525	0.583	32.99	19
32	Goa	0.007	127.25	0.0044	79.98	0.0026	47.26	0.58	0.489	43.74	11

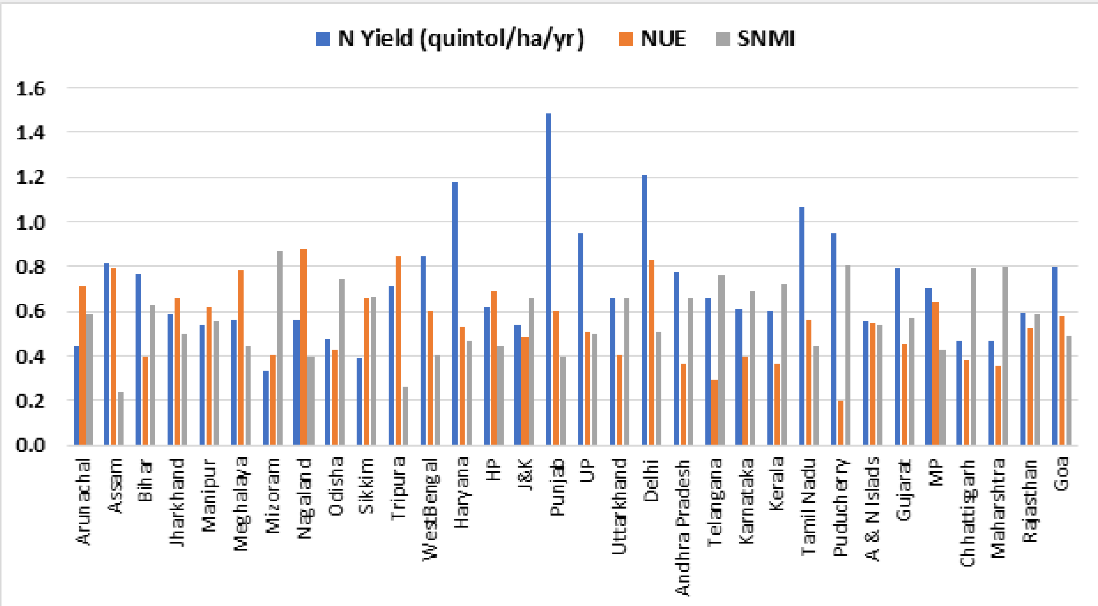

Figure 1: N Yield, NUE and SNMI in different states during the last 10 years.

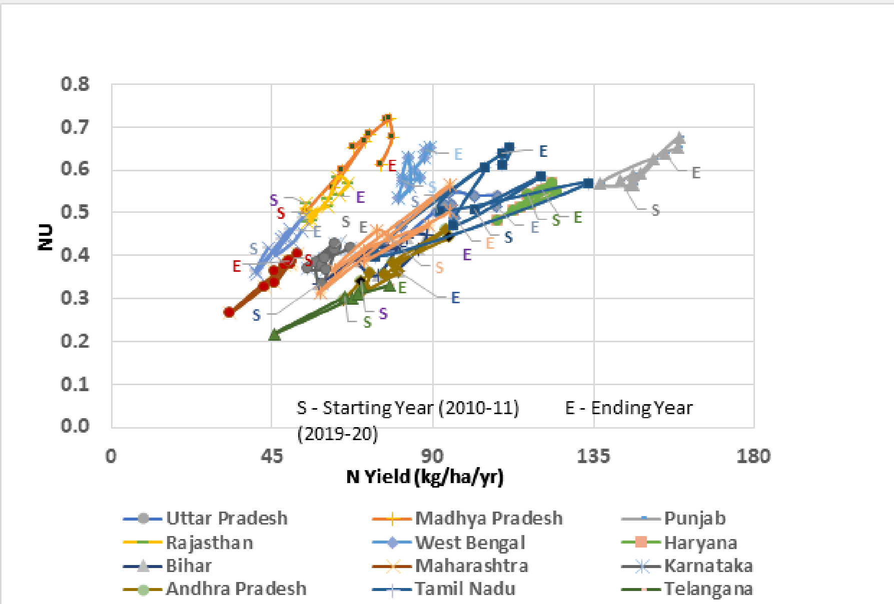

Figure 2: Trends (2010-11 to 2019-20) in Harvested N Yield and NUE for Important States of India

The evidence for environmental Kuznets curve (EKC) pattern of declining N pollution with improving NUE in agriculture was observed [1]. Indian agriculture should meet the NUE goal of 0.7 by 2050 to restrict the N pollution within the set target [1]. The environmental performance of Indian agriculture and NUE increases at international level only when the environmental performance of agriculture and NUE of different states and UTs would improve. Thirty-two states and UTs under assessment were divided into 5 groups based on the NUE (Table 4). First group of six states namely Arunachal Pradesh, Assam, Meghalaya, Nagaland, Tripura (North-

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East states) and Delhi have NUE more than 0.70. Except Delhi, in the remaining 5 states, NUE was very high as both N inputs and crop yields were low which is not compatible with achieving the first part of SDG2 of reducing hunger. There is a need to improve the NUE by 0.1 in these six states by improving the crop and N yields. The second group of Jharkhand, Manipur, Sikkim, Himachal Pradesh, Punjab, and Madhya Pradesh have NUE of 0.6 - 0.7 which should be improved by 0.15 during next 3 decades. Third group of 7 states had NUE of 0.5 - 0.6 (West Bengal, Haryana, Uttar Pradesh, Tamil Nadu, Rajasthan, A&N Islands, Goa). The NUE of this group of states should be improved to 0.70 - 0.80 by 2050. The fourth group of 5 states (Mizoram, Odisha, Jammu & Kashmir, Uttarakhand, Gujarat) had NUE of 0.4 - 0.5 which would be improved by 0.25 by 2050. The last and the 5th group of 8 states (Bihar, Andhra Pradesh, Telangana, Karnataka, Kerala, Puducherry, Chhattisgarh, Maharashtra) had NUE below the world average NUE (0.46) [2]. These states are very important to achieve the SDG2 goal of food production as well as the NUE as they contribute to food grain production of India significantly. There are plenty of chances to improve the NUE by 0.30 and food grain production in 5th group of states as these states have lot of potential.

Table 4: Grouping of states based on the NUE.

Group	NUE	States (Numbers)	Target increase in NUE by 2050
1	>0.70	Arunachal Pradesh, Assam, Meghalaya, Nagaland, Tripura, Delhi (6)	0.1
2	0.60 – 0.70	Jharkhand, Manipur, Sikkim, Himachal Pradesh, Punjab, Madhya Pradesh (6)	0.15
3	0.50 – 0.60	West Bengal, Haryana, Uttar Pradesh, Tamil Nadu, Rajasthan, A&N Islands, Goa (7)	0.2
4	0.40 – 0.50	Mizoram, Odisha, Jammu & Kashmir, Uttarakhand, Gujarat (5)	0.25
5	<0.40	Bihar, Andhra Pradesh, Telangana, Karnataka, Kerala, Puducherry, Chhattisgarh, Maharashtra (8)	0.3

Discussion

NUE and SNMI at country level during the last 10 years

There was a steep increase in the N input by 3.5% in 2018-19 and 8.8% in 2019-20 over that of 2010-11. Higher N input including fertilizer N during the recent 2 years resulted in record food grain production in India. During 2019, the South-West monsoons were favorable and reported at 110% of its long period average rainfall. In the year 2020, the reservoir levels in certain key areas were higher than levels in 2019 and vis-à-vis the 10-year average levels. Moreover, the rainfall in the monsoon season of 2020 was predicted to be normal. As a result, 2020 monsoon sowing was early and higher than previous years which resulted in steep increase in fertilizer N consumption and food grain production [20]. The food grain production was 285.3Tg in 2018-19 and 296.5Tg in 2019-20 [14]. Higher food grain production also resulted in higher N yield (79.8-82.8kg N /ha^{-1} yr^{-1}) during the last two years. Similarly, the variation in atmospheric N deposition was observed due to the variation in the net sown area from 139.9 m ha in 2010-11 to 141m ha in 2019-20. Country level NUE was low i.e., below 0.5 during the period from 2010-11 to 2015-16 (Table 2). But it was increased to above 0.5 during the last 4 years with the highest NUE in 2017-18 (0.527) which may be due to introduction of neem coated urea in place of normal urea. There was a major policy change in India with respect to urea. In order to increase the NUE of urea the Indian Government has made it mandatory for urea manufacturers to produce entire urea as neem coated urea including imported urea from June 2015 onwards. As a result entire urea utilized in India was replaced by neem coated urea from monsoon season of 2016. Application of neem coated urea (NCU) at recommended rates improved the yield of paddy, sugarcane, maize, soybean and pigeon pea to an extent of 5.8, 17.5, 7.1, 7.4, and 16.9%, respectively and also improved the NUE by 5-10% over the normal urea (NU) [21]. Lower NUE in crop production leads to higher N_{sur}, higher SNMI and higher environmental pollution. The NUE of India is very low as compared to USA and Canada (0.68). The last 10-year average NUE of India was 0.487 and the latest 4-year average NUE was 0.502. Zhang et al. [2] quantified global and national N budgets for crop production of 115 countries over 1961-2015. With respect to India, they considered N input of 25Tg N yr^{-1} whereas in the present study it is 28.03Tg N yr^{-1} for the year 2010-11. The N yield was 8Tg yr^{-1} in Zhang et al. [1,2] whereas N yield here is 13.03Tg yr^{-1} so NUE is 0.465 against 0.30, respectively. It seems the N yield was underestimated in their computations. Globally about 161Tg of N were applied to crop lands but only 73Tg of N made it to the harvested crops which means a total of 86Tg of N was ending up in the air, water and soil [2]. The average global NUE in agriculture needs to improve from 0.46 to 0.7 to meet dual goals of food security and environmental stewardship in 2050 [1]. Keeping in view global concerns, The EU nitrogen expert panel recommended a NUE of about 0.900 as an upper limit for crop production. To achieve global targets of NUE, India would be the most urgent place to im-

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prove the NUE as it is one of top fertilizers users in the world after USA, China. Enhancing crop production and NUE depends upon several factors including climate, soil type, irrigation potential, crop varieties, socio-economic condition of farmers, Government policies etc. About 52% of net sown area in India is under rainfed condition with 84% of marginal and small farmers having <2 ha land holding. Even then India can't be left out to fix NUE targets with the available resources. Since India has already achieved the NUE of above 0.50 in the recent past, it can easily target the NUE to improve to 0.7 by 2050. There is a need to assess the status of crop productivity and NUE at state level as India is a sub-continent with wide variation in climate, rainfall, soil type, crop type, irrigation, food habits, crop management practices etc. to develop regional and crop specific action plans for achieving the set NUE target of 0.70. Therefore, in this study an assessment of NUE has also been made at state level using the state-wise crop production data and fertilizer N input during the last 10 years.

NUE and SNMI in different states of India during the last 10 years

The NUE of different states determines the crop productivity, profitability and environmental performance of agriculture. The critical analysis of current status of NUE and constraints in various states is essential to develop a strategy for enhancing NUE in different states by fixing targets. The 10-year average total N input into agriculture may not give correct trend as the total N input depends on the gross cropped area. The gross cropped area was highest in Uttar Pradesh and so the N input was also highest in this state (Table 3). The N input per unit area was highest in Puducherry state (541.6kg N ha^{-1} yr^{-1}). A study needs to be undertaken in Puducherry to understand whether the fertilizer N purchased by it is consumed in Puducherry itself or transported to neighboring states. After Puducherry, the N input was higher in Punjab followed by Haryana but the N yield was also higher in Punjab and Haryana due to higher crop productivity (3981 - 4658 kg food grains ha^{-1}) with highest percent irrigated area (92-98% of net sown area) [14]. Therefore, reasonably less N_{sur} in these states. The results clearly showed that the crop productivity determines the N_{yield}, N_{sur}, and NUE. The SNMI, an indicator of environmental pollution is inversely related to NUE. The status of NUE vis-a-vis the environmental performance of all major states needs to be improved to enhance average NUE of India to 0.70 during next three decades by 2050 to achieve the global targeted N surplus (50Tg N yr^{-1}) [5].

North-east Indian states (Arunachal Pradesh, Assam, Meghalaya, Nagaland, Tripura) and Delhi recorded higher NUE of more than 0.700. The SNMI which was in inverse proportion to the trend of NUE, varied from 0.234 in Assam to 0.869 in Mizoram. The contribution of north-east states to Indian agriculture production was very less. Out of 32 states and UTs, 14 states contributed almost 91% of the Indian food grain production (Figure 2). Among these 14 major agriculture states, the SNMI was the lowest in Punjab and highest in Maharashtra state. In Punjab, the highest N yield (148.8kg N ha^{-1} yr^{-1}) and moderate NUE (0.604) resulted in the lowest SNMI (0.395) with normalized SNMI score of 54.52 with the 3rd rank among the 32 states and UTs studied. The normalized SNMI score varied from 73.11 in Assam with 1st Rank to 7.21 in Puducherry with 31st rank indicating the poorest environmental performance of Puducherry agriculture due to the highest N input and lowest NUE.

Zhang & Davidson [1] has suggested the reference yield level which is defined to measure a country's progress in achieving a certain yield target which addresses land use efficiency and food security. In this study the reference N yield would be targeted at 90kg N ha^{-1} yr^{-1} which is approximately the desired global average N yield to meet food production targets of 2050 without expanding the current agriculture area [5]. The N yield at country level varied from 69.64kg ha^{-1} yr^{-1} in 2010-11 to 82.84kg N ha^{-1} yr^{-1} in 2019-20 which was below the FAO targeted N yield of 90kg N ha^{-1} yr^{-1}. Among the 32 states and UTs, only 6 states (Haryana, Punjab, Uttar Pradesh, Delhi, Tamil Nadu and Puducherry) had the N yield more than the reference N yield (Figure 2). Punjab, Haryana, Uttar Pradesh and Tamil Nadu contribute significantly to the food grain production. Therefore, there is a plenty of scope to improve the N yield thereby NUE and crop production. Historical trends of N_{yield}, NUE and N_{sur} for India was presented earlier for the period of 5 decades (1961-2011) using the projected data [1]. This data showed a smoothen trend line for India for the said period, but when actual crop production data was used for computing N_{yield}, there were ups and downs in the N_{yield} due to variation in the crop production mainly depending upon the rainfall and other weather aberrations during the last 10 years (Figure 2). During the last 10 years, one or other parts of India suffered from weather aberrations such as prolonged dry spells/droughts/floods/excessive rainfall etc. [22].

A strategy has been suggested to enhance NUE of India to 0.700 by 2050 from the existing mean NUE of 0.510 by fixing the NUE targets to different states based on the present status of NUE. The 32 states and UTs under assessment were divided into 5 groups based on the NUE (Table 4). Six states namely Arunachal Pradesh, Assam, Meghalaya, Nagaland, Tripura (North-East states) and Delhi had NUE more than 0.700. The NUE was very high in north east states as both N input (82.6kg N ha^{-1} yr^{-1}) and crop productivity were low which is not compatible with achieving the first goal of SDG2 of reducing hunger. There is a potential to improve the NUE by 0.1 in these states by improving the crop productivity and N yield. In north-east India, land is almost virgin and the crops were grown virtually organic with low inputs under subsistence farming. Major niche crops grown in north-east states are lemon, medicinal rice, passion fruit, pineapple, orange, cardamom, and ginger. Therefore, Indian Government is developing organic farming hub in north-east India to meet the demand for organic products. This region has a potential of about 47Tg of organic manures including 37Tg from animal excreta and 9Tg from crop residues. Crop productivity and NUE can be improved through integrated farming system models which comprise *ex-si-*

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tu/in-situ rainwater harvesting, livestock particularly piggery and poultry, legume crops along with niche crops, composting, cover crops, biofertilizers etc. [23]. These studies also suggested to occupy at least 30% of cropped area under legumes for higher productivity and N use efficiency. In Delhi, the crop productivity was better than north east states but needs improvement in NUE.

The second group of Jharkhand, Manipur, Sikkim, Himachal Pradesh, Punjab, and Madhya Pradesh have NUE of 0.6 - 0.7 which should be improved to 0.75-0.85 during next 3 decades. In India, the highest crop productivity (4.7t ha^{-1}) was attained in Punjab with 84% irrigated area. The popular perception is that the crop yield plateau was attained in Punjab and may not possible to further improve the crop productivity. But contrary to this perception, the average wheat yield of Punjab increased by 2.4 times from 2.73t ha^{-1} in 1980-81 to 6.5t ha^{-1} in 2017-18 due to two factors i.e., (i) improved variety of wheat (HD 2967) and (ii) incorporating the uncut paddy straw back into soil instead of burning in rice - wheat cropping system. It shows an opportunity to further improve the NUE in Punjab with integration of crop variety with best agronomic practices. Another important state in this group is Madhya Pradesh (MP) which contributed about 11.3% (32.3Tg) to total India's food grain production (285.3Tg) in the year 2018-19. The average productivity of food grains in Madhya Pradesh (MP) was very low (2t ha^{-1}) as compared to that of national average (2.3t ha^{-1}). Soybean (5.4m ha) and rice (2.4m ha) in monsoon season and wheat (5.5m ha) and gram (3.1m ha) in winter season were major crops in MP. There is a lot of potential to improve NUE in MP with crop specific strategies as it is bestowed with black soils (80%) and higher average annual rainfall (>1000mm). Addressing water logging, nodulation, micro-nutrients (Zn, Mo) and sulphur management with pest tolerant variety in soybean improved the average productivity (1.2 to 2.5t ha^{-1}) [24]. Similarly, improved variety, irrigation, S and Zn management in wheat improved the grain yield and NUE. Seed treatment with bio-fertilizers, 1 or 2 supplemental irrigations, Zn, Mo and P management, new variety in gram improved the yield from 1.3t ha^{-1} to 2.0t ha^{-1}. Major crop production constraints in Jharkhand, Manipur, Sikkim and Himachal Pradesh was the soil acidity and emerging micro and secondary nutrient deficiencies [25]. About 28m ha land in north east India (Manipur, Sikkim, Assam, Arunachal Pradesh, Meghalaya, Nagaland, Tripura, and Mizoram), 4m ha in Jharkhand and 0.75m ha in Himachal Pradesh are having soil acidity (pH <5.5). In India, farmers are reluctant to apply large quantities of liming materials for reclamation due to economic reasons. Hence, it was suggested ameliorating the acid soil with minimum quantities of lime with application of all deficient macro- and micronutrients at recommended rates in a balanced way so that farmers can achieve reasonably good yields of soybean on acid soils [26]. In studies conducted in seven states of India, the application of lime at 200-300kg ha^{-1} with balanced fertilization improved crop yields by 16-48%. Application of half of the recommended rate of N, P and K with lime produced crop yields at par with or superior to the full dose of NPK without lime [25]. Other strategies discussed above for 6 north east states are also applicable to Manipur and Sikkim.

The current NUE (0.5 - 0.6) should be targeted to increase to 0.70 - 0.80% by 2050 in third group of states (West Bengal, Haryana, Uttar Pradesh, Tamil Nadu, Rajasthan, A&N Islands, Goa). Rice is the major crop in West Bengal and Tamil Nadu states. The average NUE was very poor in rice and rice based cropping systems which varied from 0.3-0.4 due to denitrification losses. Efficient N use rice varieties viz., Nagina-22, Himdhan, Taipe and MTU 1010 need to be promoted on farmers' fields by making availability of sufficient seed [27]. Matching N fertilizer application and rates to the actual requirements of rice crop using leaf colour charts (LCC), PAU-Urea Guide, soil test based N doses etc would reduce N losses and thereby enhance NUE. Demonstrations on LCC on farmers' fields produced higher yields of transplanted rice, maize, wheat, basmati rice, direct seeded rice, and cotton in Bassian village, Punjab [28]. NUE in rice can also be improved by inoculation of seeds with endophytes and rhizobia at sowing and subsequent assimilation of fixed N by rice plants [27]. Rice and wheat occupied major areas to the extent of 1.5m ha and 2.6m ha in Haryana and 5.8m ha and 9.5m ha in Uttar Pradesh, respectively. The strategies discussed above for enhancing NUE in rice are also suitable for Haryana and Uttar Pradesh. Precision N management tools such as green seeker optical sensor recorded 26% higher NUE in wheat as compared to soil test-based fertilizer application [29]. Integrated use of farmyard manure (FYM) at 10-15t ha^{-1} with recommended dose of NPK produced NUE of 0.72, 0.75, and 0.78 in Maize-wheat in Punjab, Delhi, and Himachal Pradesh states, respectively and NUE of 0.82 in rice-wheat system in Chhattisgarh states [7]. Both central and state governments are promoting integrated farming system (IFS) models involving livestock, field crops, vegetables etc. in Goa which would help in generation of sufficient quantity of dung manure for recycling to enhance crop productivity and NUE. Rice based IFS model (rice-brinjal-mushroom-poultry) produced higher rice equivalent yield, input use efficiency and net income to farmers as compared to only rice crop [30].

The NUE of fourth group of states (Mizoram, Odisha, Jammu & Kashmir, Uttarakhand, Gujarat) should be targeted to increase to 0.65-0.75 from existing NUE of 0.4 - 0.5 by 2050. Cotton and groundnut are the major crops in Gujarat grown in an area of 2.7 and 1.6m ha, respectively. In Gujarat, farmers grow *desi* cotton in areas where salinity is high and canal irrigation is not available. Improved varieties of *desi* cotton with short duration need to be made available to the farmers for better yields and higher NUE [31]. Other constraints in cotton production in Gujarat were continuous cropping with only cotton and wider spacing. These could be overcome by promoting crop rotation and encouraging farmers to grow intercrop in wider spaced cotton [32]. Inadequate availability of quality seeds of high-yielding varieties, terminal drought due to early cessation of monsoon and susceptibility to stem and collar rot are the major constraints limiting the productivity gains of groundnut in Gujarat. Sowing of early maturing varieties like GG2, GG5, GG7 etc., protective irrigation, in-situ soil moisture conservation and seed treatment with *rhizobium* sp can

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help in increasing groundnut yields thereby NUE. In Odisha, rice is the major crop occupied about 3.9m ha out of 5.8m ha gross cultivable area and grown in both irrigated and rainfed conditions. The productivity of rice in Odisha was very low (2t ha^{-1}) which needs to be improved to enhance NUE by alleviating major constraints such as drought and floods, moderate Fe toxicity in low lands, Zn deficiency and coastal salinity. The strategies discussed for Uttar Pradesh for enhancing NUE in rice and wheat are also applicable to Uttarakhand and Jammu & Kashmir due to same climate and soil type.

The NUE was less than 0.40 in 5th group of states (Bihar, Andhra Pradesh, Telangana, Karnataka, Kerala, Puducherry, Chhattisgarh, Maharashtra). This group is the most important group from agriculture point of view which contributed 23 % of food grain production. The NUE was very less as about 63.6% of net sown area is under rainfed conditions. The net rainfed area is about 81.3% in Maharashtra, 80.8% in Kerala, 68.1% in Karnataka, 67.6% in Chhattisgarh, 54.3% in Madhya Pradesh, 52.1% in Telangana and 40.8% in Bihar. Therefore, increasing the NUE to 0.70 in this group is a major challenge. But there were several success stories in which crop productivity enhanced with integration of rainwater harvesting for supplemental irrigation during prolonged dry spells/droughts with growing diverse crops and best management practices. Pigeon pea, chickpea, soybean, etc. are the major rainfed crops. Farm pond based integrated farming system approach with 2 supplemental irrigations from harvested rainwater during prolonged dry spells increased the pigeon pea seed yield to 20q ha^{-1} from 10q ha^{-1} in Farmers' practice. The preparedness with implementation of *ex-situ* rainwater harvesting in different rainwater harvesting structures and/or in-situ rainwater conservation to overcome weather aberrations would help in enhancing productivity of rainfed crops and NUE. Micro-dosing of fertilizer N application in synchronization with soil moisture under rainfed conditions saved 15-20% of fertilizer N without affecting the crop yields [33]. In maize-horse gram sequence grown on semi-arid Alfisol soil, NUE increased from 0.51 to 0.68 with zero tillage and balanced fertilizer application [33].

Andhra Pradesh and Maharashtra are also major fruit producing states and contribute about 30% of total fruit production in India. The global average NUE in horticultural crops was very low (0.15) [1]. This may also be the reason for low NUE in these states. India has fixed its goal to produce about 500Tg of fruits and vegetables by 2050 to meet its rising domestic and export demands. This may lead to enhanced fertilizer N requirements for horticulture crops in future. Therefore, special attention should be given to enhance NUE in horticulture crops particularly vegetable and fruit crops which constitute about 90% of horticulture crops. Studies with ^{15}N showed that the NUE in banana was only 22.3% when applied through split application [34]. But placement of N fertilizer at 30cm below the soil surface increased NUE to 60% in banana from 6.8% with broadcasted fertilizer N [35]. Excess irrigation was one of the root causes of N loss in horticulture systems. Fertigation through drip irrigation saved 30-70% of irrigation water and increased the yields by 25-80%. Government of India set a target to bring about 0.5m ha under micro-irrigation every year particularly in horticulture crops. The crop combination of capsicum-onion-watermelon-okra increased the NUE to 10.85 to 37.2% compared to solo crops (6.44-19.2%) [34]. Microbial interventions such as Arbuscular Mycorrhizal Fungi (AMF) and Azotobacter were found to increase the NUE through both N fixation and enhancing the N retention time [34].

In India, BNF by pigeon pea was low, 69kg ha^{-1} and amounted to only 50% of plant N uptake (Rao and Dart 1987). Since most of the pigeon pea grown under rainfed and drought prone stress conditions in India, improvement of N fixation depends upon host crop, rhizobial inoculation selection, improving soil organic matter and repeated seed treatment with biofertilizers. The most probable number (MPN) of rhizobia in pigeon pea were found to range from very low to low (10^2 cells/g). Pigeon pea has a large potential to enhance NUE. It is suggested to double or even triple current mean yield (850kg ha^{-1}) of pigeon pea by 2030 [27]. There is a need to select rhizobia that are superior symbiotically under moisture stress conditions and seed treatment with such rhizobia in all legumes before sowing should be made compulsory for enhancing NUE [36].

Conclusion

The environmental performance of Indian agriculture in terms of NUE and SNMI at country level and in different states/union territories was assessed using the crop production data of the last 10 years (2010-11 to 2019-20). The NUE of Indian agriculture varied from 0.465 in the year 2010-11 to 0.527 in 2017-18 with a mean of 0.487. There was a corresponding decrease in the SNMI from 0. 0.593 in 2015-16 to 0.501 in 2019-20 with a mean of 0.542. The normalized SNMI value varied from 56.55 in 2015-16 to 64.28 in 2017-18 with a mean of 60.29. There was a wide variation in the mean NUE of different states and union territories. The NUE at state level varied from 0.196 in Puducherry to 0.870 in Nagaland. States/union territories were divided into 5 groups based on the current status of NUE and the target NUE to be achieved by the year 2050 for each group has been suggested. Crop production constraints responsible for low NUE in different states and measures for enhancing NUE in different crops/cropping systems were identified. If all available crop-specific and state-specific technologies or measures are implemented on farmers' fields, the crop productivity and NUE targets to the global level could be achieved by 2050. Major recommendations which need immediate focus for enhancing NUE in different crops/cropping systems are;

a) Biological N fixation lead to lower levels of N surplus in soil as it provides a gradual input of fixed N to the soils. Therefore, the fraction of N inputs that are lost to air and water pollution will be less than in fertilizer input system. The goal set for 2030 is to increase biological NUE by at least 20-30% [27]. This target could be achieved by supplying good quality biofetilizers in sufficient quantity to the farmers for seed

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treatment at the time of sowing of legume crops particularly in pigeon pea, groundnut, chickpea and soybean.

b) Millets need relatively low levels of N input to fix carbon due to their physiological characteristics [37] compared to cereals and are also healthier due to increasing cases of diabetics. Government of India has already initiated several schemes to establish supply chains to promote value added processed foods of millets to increase the area under millets particularly in rainfed areas. There is a need to increase the area under millets in rainfed areas.

c) To achieve the target of NUE of 0.70 by 2050, the neem coated urea should be combined with natural urease inhibitors such as neem plus, vanillin and protocatechuic aldehyde derivatives etc. which are cost effective, socially acceptable and suitable for both tropical and temperate production systems. This option is expected to offer a 5% N saving over neem coated urea which has already achieved 5-10% savings above uncoated plain urea [27]. The immediate goal should be the mass production of plant-based urease inhibitors and supply to farmers.

d) There is a need to reduce losses of N through organic wastes to improve the agronomic NUE across the whole farm. Composting of organic wastes using a closed method instead of traditional unlined pit or open manure heap increased the dry matter recovery to 70% of organic materials from 50-55% with traditional method in Mumtajpur village, Haryana. Such improved composting methods should be promoted among the farmers throughout the country. Adoption of soil test based Integrated Nutrient Management (INM) with adequate use of organic manures and bio-fertilizers would substitute 25-50% of inorganic N fertilizers depending upon crops/cropping systems and also produce higher NUE.

e) More significant gains in NUE could be achieved from the adoption of 5R approach strictly (i.e., right source, right rate, right time, right place and right method of application) customized to local conditions rather than only from the genetic enhancement of NUE. A technique developed by the International Fertilizer Development Centre (IFDC) achieved an NUE as high as 80% in field studies around the world using urea deep placement [38]. Such methods should be promoted among the Indian farmers as a part of package of best practices.

f) Soil test based site specific balanced fertilization of all deficient nutrients to different crops instead of blanket fertilizer recommendations should be promoted among the farmers to achieve target yield potential for higher NUE. The NUE across studies in China, India and North America was increased to 54% for balanced fertilization from 21% for conventional treatment [39].

g) The NUE in fruits and vegetables is very low (0.15 – 0.22). India has fixed its goal to produce about 500Tg of fruits and vegetables by 2050 to meet its rising domestic and export demands. Implementation of improved technologies such as efficient horticulture crop combinations, micro-irrigation, inter crops in orchards, integrated nutrient management, placement of N fertilizer etc. should help in enhancing NUE.

h) Nano-N fertilizers are gaining importance in agriculture for increasing crop yields, enhancing NUE and reducing excessive use of N fertilizers. Results of 730 field demonstrations conducted in different districts of Uttar Pradesh on farmers' fields with 12 crops proved that with the 2 sprays of nano-N, the quantity of urea being applied by the farmers to supply nitrogen to their crops can be successfully reduced to 50-75% of recommended dose [40]. Already the nano-N or nano-urea fertilizer was approved by the Government of India and thereby included in the Fertilizer Control Order and consequently respective fertilizer company has already started mass production of nano-N. Once nano-N readily available to farmers in the market for application in major crops such as rice, wheat, maize etc. all over country, the NUE is believed to increase further.

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