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NEW APPROACH TO FERTILIZER SECTOR

The Fertiliser Association of India
(Founded in 1955)

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Our Cover

Our cover depicts about the theme of the FAI Annual Seminar 2019

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New Approach to Fertilizer Sector

Satish Chander

Indian farmers have served the country well during the last forty-five years. They not only ensured the food security of this vast country but also generated large surplus for exports of food grains and other commodities earning valuable foreign exchange. Food grains production increased from less than 100 million tonnes in 1974-75 to 285 million tonnes in 2018-19. But these quantitative achievements have now been over shadowed by a number of adverse developments. Our crop yields per hectare of major crops are much lower than China and other neighboring countries. For example, average yields of paddy in India is 3695 kg/ha compared with 6937 kg/ha in China and in 4618 kg/ha Bangladesh. Poor use efficiency of plant nutrients particularly that of nitrogen in India is one of the reasons of low crop productivity. This has adversely affected economic viability of agriculture and farmers' income. The second important development is deteriorating soil health and over-exploitation of natural resources like water. Third, imprudent use of inputs has not only affected the crop yields but has raised environmental and sustainability issues. Fragmentation of land holdings has also prevented penetration of modern technology in farm practices.

Fertilizer remains the major input in realizing potential of high yielding variety seeds. Simple laws of mass and energy conservation dictate that one cannot realize high yields without input of sufficient plant nutrients to the soil. Sources other than chemical fertilizers can at best supplement the nutrient requirement of modern agriculture. However, it is equally true that there is need for very judicious use of chemical fertilizers. In fact, organic carbon content of soil is extremely important for physical, chemical and biological health of the soil. Application of organic fertilizers helps in better water use efficiency and in improving use efficiency of chemical fertilizers. Therefore, maximum benefit can be derived only when entire basket of plant nutrients from all sources - inorganic, organic and biological is utilized.

Policies related to fertilizer sector were formulated in 1970s with two objectives: first to encourage use of chemical fertilizers for realizing high crop yields with HYV seeds and the second to promote domestic fertilizer production to maintain supply of this vital input. Both these objectives were very well met which is reflected in spectacular growth both in consumption and production of fertilizers in the decades of 1980s and 90s. Fertilizer consumption increased from 2.6 million tonnes nutrients in 1974-75 to 27.2 million tonnes nutrients in 2018-19. Simultaneously production increased from 1.52 million tonnes to 17.9 million tonnes nutrients during the same period. Such a growth in consumption and production was achieved because the policy ensured affordable prices of fertilizers for the farmers and reasonable return on investment for fertilizer producers.

Subsequent distortions and lack of reforms in policies for the sector are hurting both agriculture and industry. These policies are partly responsible for imprudent use of inputs and creating sustainability issues. The present heavy subsidy on urea is acting as barrier for introduction of more efficient products which are being used world over.

Lack of reforms in policies for the sector are hurting both agriculture and industry. These policies are partly responsible for imprudent use of inputs and creating sustainability issues.

These products give much higher nitrogen use efficiency than urea. The present policies have also badly affected the viability of domestic production after 2000. Last but not the least, huge fertilizer subsidy which is basically public money can be utilized better to address the issues of soil health, crop yields and farmers' income. Therefore, in the interest of all stakeholders viz. farmers, industry and public there is need for fresh look on fertilizer policies and reboot the same at the earliest.

Any new policy for the sector has to be successful on three parameters. First or foremost, it should encourage balanced use of plant nutrients in integration with organic sources. The policy has also to take into account that India has committed at United Nations for Sustainable Management of Nitrogen. Resolution on Sustainable Management adopted by UN Environment Assembly recognizes the importance of nutrients including nitrogen 'in global crop production and food security'. But the resolution also states 'nitrogen use across global economy is extremely inefficient leading to water, air and soil pollution'. Efficient use of nitrogen in agriculture will have to be part of strategy for sustainable nitrogen management. One of the important considerations to promote efficient use of nitrogen is the pricing of nitrogen through different products. It should be same through different products and it should also be in correspondence with prices of the other two primary nutrients viz. phosphorus and potash. Therefore, new policy has to ensure that there is no distortion in prices of different nutrients as is the case today. It should also encourage introduction of new and more efficient fertilizer products to improve nutrient use efficiency.

Second, the policies should ensure viability of domestic production. India is the second largest consumer of fertilizers in the world. India is heavily dependent on imports of raw materials and finished products. The present level of self-sufficiency built over the years is absolutely essential to secure our suppliers and avoid exploitation in the international markets. The complete distortion of original policy has nullified one of the objectives of policy i.e. reasonable return on investment in urea production facilities. Many plants are logging negative return while others are operating on wafer thin margins. Present policies for the sector have put the domestic production of both urea and NP/NPK fertilizers at disadvantage vis-à-vis imports. Discrimination is there in terms of taxation regime, reimbursement of reasonable cost and timely settling of the bills of fertilizer subsidy. These issues need to be addressed in new policy to ensure continued viability of the sector.

Third and equally important consideration in formulation of policies is the fiscal sustainability. For last several years, government is finding it difficult to make adequate provision for fertilizer subsidy in Union Budget. Therefore, the level of subsidy should not only be calibrated to derive maximum benefit for soil and crop yields but should also be fiscally sustainable.

Keeping in view the above discussion, theme of the FAI Annual Seminar has been kept 'New Approach to Fertilizer Sector'. Eminent economists, scientists, technologists and policy makers will make presentations and participate in discussion. Recommendations emerging out of this important event should help the policy makers in overhauling the policy environment of this vital sector which is critical to viability of Indian agriculture and well-being of rural population. ■

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Major Modifications in Ammonia Converter for Performance Improvement and Upgradation in KRIBHCO

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Abstract

Krishak Bharati Co-operative (KRIBHCO) Ltd. is operating two ammonia plants. In ammonia plant, cartridge type ammonia converter (105-D) was originally designed by M/s Kellogg. The main construction features of converter include 3-beds & 2-quench, having axial gas flow inside bed. Convertor effluent exchanger 122-C is installed on top of 105-D at a height of about 20 metre.

Ammonia converter retrofit was carried out in 1993 in ammonia-2 plant and in 1995 in ammonia-1 plant through M/s Casale to change gas flow inside bed from axial to axial- radial flow. Construction features modified from 3-bed, 2-quench to 3-beds, 1-quench & additional inter-bed interchanger inside bed. This resulted in substantial reduction in pressure drop across converter, increase in volume of catalyst & higher ammonia production with lower specific energy consumption. Catalyst was also replaced with lower size than that of original size.

Converter refurbishment was again carried out through M/s Casale in the year 2013 in ammonia-1 plant and in the year 2019 in ammonia-2 plant to replace inter-bed interchanger, to provide elastic ring seal sliding joint between 122-C inlet and gas return pipe and for connection between bottom of interchanger and top of third bed inner collector. Also, opportunity was utilised to change inconel wire screen with the new slotted plates on inner and outer collector. Entire execution job was done in-house under guidance of M/s Ammonia Casale. This article highlights major modifications carried out in ammonia converter, constraints with corrective action taken and benefits achieved after modification.

Key words: Ammonia plants, ammonia converter retrofit, inter-bed interchanger

Introduction

KRIBHCO plant operates two streams of M W Kellogg design ammonia plants based on natural gas as feedstock and four streams of Snamprogetti design urea plants. The commercial production of urea commenced from 1986.

KRIBHCO Hazira plant has been making outstanding performance on continuous basis since its inception from 1985-86. Since commissioning of the plant, KRIBHCO has become trend setter in multiple front in operation and maintenance. Each ammonia plant was revamped in phased manner from 1350 MTPD to 1520 MTPD to 1890 MTPD.

Ammonia synthesis converter (105-D) is considered heart of the plant. Improved long term reliability and trouble-free operation of converter is of prime importance. Because of aggressive environment of high pressure, high temperature and flammable gas contained in its operation, risk involved in its failure is significant.

Need for Modification

Energy consumption of plant is one of the important parameters to compare both financial and operating performance of the plant. In view of these and to improve reliability, major modifications in ammonia converter was implemented for performance improvement, upgradation and long-term reliability. Comparison of construction features of original and modified converters is given in **Figure 1**.

Brief Process Description and Flow Path Inside Converter

The main stream of feed synthesis gas enters the converter then it flows upward flushing the vessel in the annular space between vessel and cartridge. At converter top, it enters the converter effluent exchanger 122-C shell side where it is preheated by cooling the product gas. At 122-C exit the fresh gas is mixed with the gas coming from interchanger. The temperature of mixture can be controlled by the by-pass gas. The gas then enters the first bed where its flow pattern is inward. After leaving the first bed, it is cooled down in the inner collector by the quench gas and then flows inwardly through second bed. Before entering 3rd bed, the gas is cooled down in the new interchanger flowing shell side. Gas then passes through 3rd bed where its flow pattern is inward. After leaving 3rd bed, the product gas is cooled in the 122-C tube side and exit the converter from top **(Figure 2)**.

Major Modifications in Ammonia Converter

Ammonia converter retrofit was carried out in the year 1993 in ammonia-2 plant and in the year 1995 in ammonia -1 plant through M/s Casale. Following modifications were carried out during retrofitting of the existing internals:

i. Change of gas flow inside bed from axial to axial-radial flow resulting in reduction in

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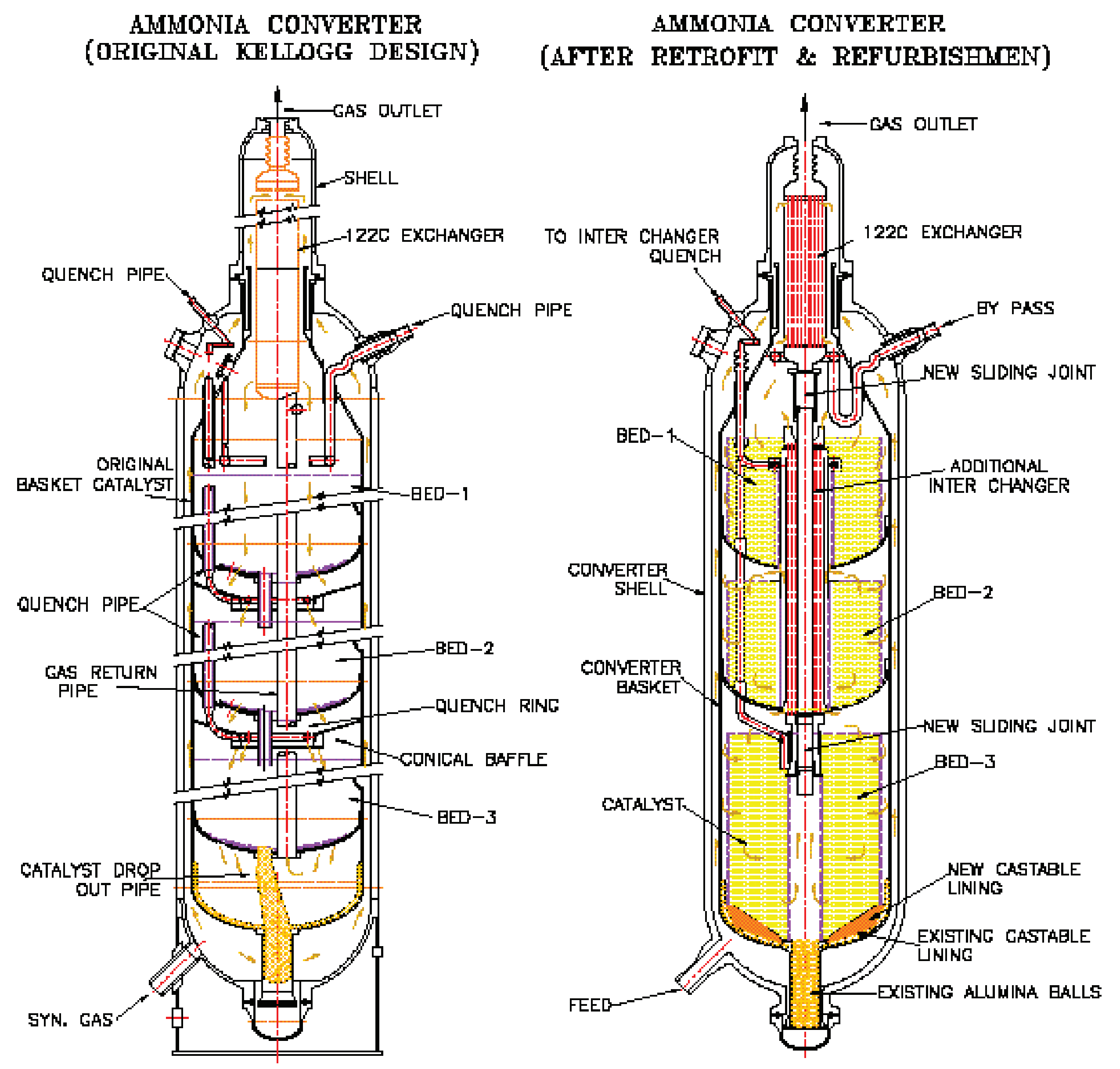

Figure 1. Comparison of construction features of original converter and modified converter

pressure drop across converter.

ii. Construction features modified from 3-bed, 2-quench to 3-bed, 1-quench & additional inter-bed interchanger inside bed.

iii. Catalyst volume increased for higher ammonia yield.

iv. Catalyst replacement with lower size than that of original size.

This modification resulted in increase in ammonia concentration of converter output from 14.5% to 19.5%. As a result, the average energy saving of about 0.258 GCal/ MT of ammonia had been obtained.

Ammonia converter refurbishment implemented through M/s Ammonia Casale in 2013 in ammonia-1 plant and in the year 2019 in ammonia-2 plant along with following major jobs:

i. Replacement of expansion joint between 122-C inlet and gas return pipe with elastic ring seal sliding joint **(Figure 3)**. Replacement of the connection between bottom of interchanger and top of third bed inner collector with elastic ring sliding joint.

ii. Catalyst replacement.

iii. Replacement of existing 122-C exchanger with the new one in ammonia-2 plant.

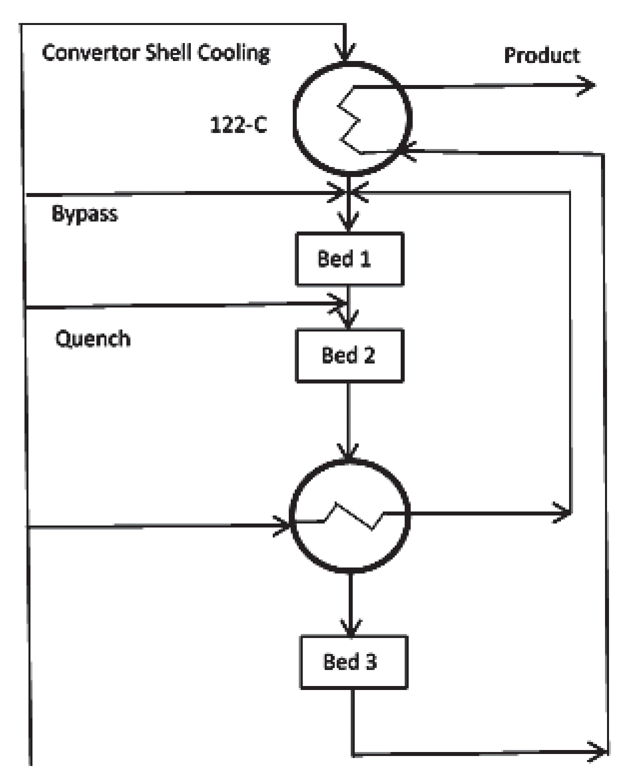

Figure 2. Flow path of synthesis gas inside converter

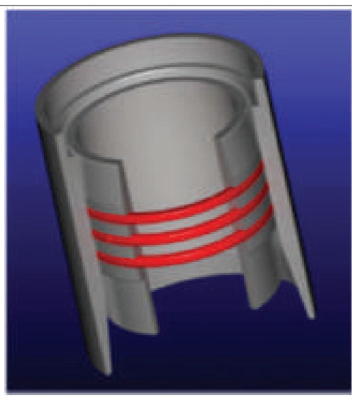

Figure 3. Elastic ring seal sliding joint

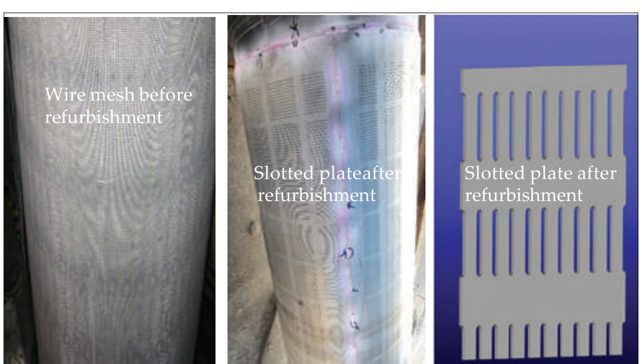

Figure 4. Wire mesh before and slotted plate after refurbishment

iv. Replacement of existing bed interchanger with new in ammonia-2 plant.

v. Replacement of the inconel wire screen with the new slotted plates **(Figure 4)**.

Constraint Faced during Modification and Job Executed

With limited opening inside converter, there was restriction for movement of internals, manpower, tools and tackles which made implementation job almost sequential. Internal were designed in such a way that all internal can be installed inside through limited available opening.

With such constraint, it had always been challenging to execute the job and to meet time line. It was an inspiring job to install internals inside converter through limited available manway opening. Despite such limitation, job could be executed successfully 2 days in advance due to detailed advance planning and continuous supervision. Problem faced & major observation are enlisted below:

i. Bulging of 122-C Jacket Shell of Tube Bundle: 122C Jacket shell found bulged **(Figure 5)**. After lifting for about 200mm with Crane, 122C bundle was not getting lifted freely with crane. With innovative ideas and effective brain storming, it was made possible to lift 122-C bundle **(Figure 6)**.

ii. Interchanger shell support found bulged **(Figure 7)** and it was replaced by new one.

iii. Wire mesh was found damaged as shown in **Figure 8.**

iv. Trapping of Catalyst in the Annular Space: Catalyst was found trapped in annual space between outer collector of 2nd and 3rd bed and cartridge wall. Catalyst was removed by cutting small windows at the bottom of outer

Figure 5. Bulging of 122-C bundle jacket shell

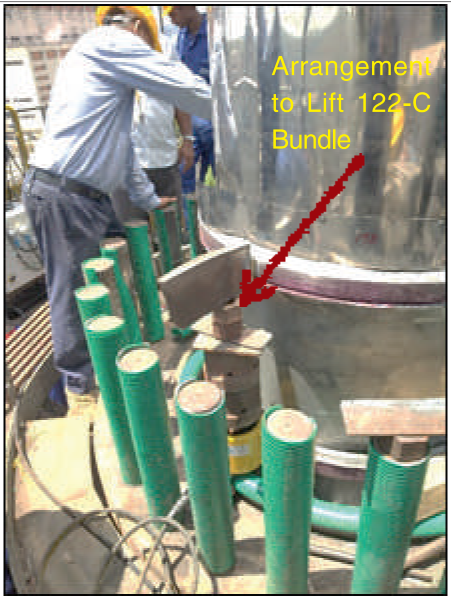

Figure 6. Arrangement to lift 122-C bundle

collector of 2nd bed. In 3rd bed, catalyst started coming out freely from annular space between outer collector of 3rd bed and cartridge wall. Windows were cut to remove catalysts and welded back after removal of trapped catalyst **(Figure 9)**.

v. ***Cracking during Welding due to Nitriding Layer:*** Cracking of weld joint of new internal with existing material. Nitriding layer was required to be removed by grinding which consumes lot of time (above a certain temperature, depending on the type of steel, ammonia reacts with iron to form a hard and brittle Fe- N inter-metallic compound. This phenomenon is called nitriding.)

Figure 7. Interchanger shell support bulging

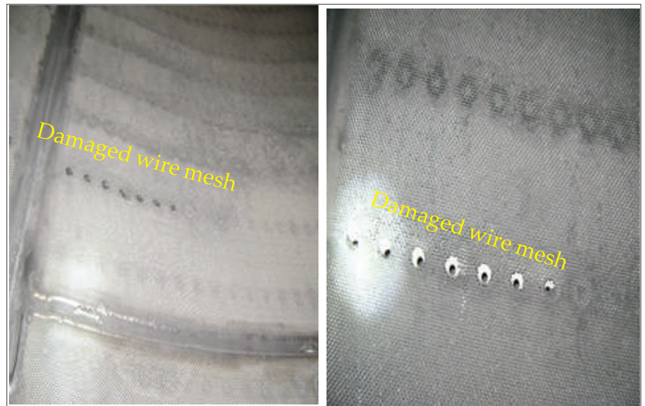

Figure 8. Damaged wire mesh

Figure 9. Arrangement for removal of catalyst

vi. ***Centering and Alignment of all Internals, Exchanger & Interchanger with Converter***: Perfect centering (with respect to 105-D shell) was needed for installing all internals, exchanger & interchanger so as to avoid mismatch/ misalignment of sliding joints. Centering and alignment was ensured by using specially fabricated cross and piano wire.

Benefits

Benefits achieved after installation of casale internals in both ammonia plants:

- Higher ammonia production
- Lower pressure drop across converter
- Lower synthesis loop pressure
- Increase of catalyst volume

Benefits achieved after ammonia converter refurbishment in both ammonia plants:

- Increase in reliability of the internals
- Replacement of 122C & inter-bed interchanger without hot work inside converter has been made possible due to sliding joint by using elastic ring seal system. ■

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Environment Management at CFCL, Gadepan

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Abstract

This article gives an insight to the environment management at Chambal Fertilisers and Chemicals Limited (CFCL). The complex is spread over 400 hectares of land. Environmental aspects are taken care in the design stage itself and all norms are strictly complied. Continual improvements are done with emphasis on maximizing recycle and reducing wastage, discharges and emissions. The company has won many Environment Awards. It has been our endeavour to ensure that environment and industry co-exist together.

Key words: Ammonia plant, urea plant, environment management, waste water treatment, zero liquid discharge, reverse osmosis, solid waste management

Introduction

Chambal Fertilisers and Chemicals Limited is located at Gadepan is about 35 km from Kota city in Rajashtan. The total land acquired for factory and residential facilities is about 1060 acres. This complex has three hi-tech nitrogenous fertilizer (ammonia - urea) plants and associated utilities and 3.4 million MT of urea contributing to major chunk of urea consumed in leading agricultural states of the country. Plant-I, plant-II and plant-III were commissioned in 1994, 1999 and 2019, respectively. These plants use the state-of-the-art technology from Denmark, Italy, United States and Japan.

Phase-III plants comprise of ammonia-III plant, urea-III plant, water treatment plant-III, steam & power generation plant-III, bagging plant-III, effluent treatment plant, sewage treatment plant, reverse osmosis plant, zero liquid discharge plant and other utility facilities.

Ammonia - III plant is based on M/s KBR's Technology and it was constructed by TEC (Japan). It is based on natural gas as feedstock. The main sections of ammonia plant are: process air compressor, mild reformer, secondary reformer, HT shift conversion, LT shift conversion, CO_2 recovery through aMDEA (OASE) process, purifier and synthesis section.

Urea-III plant is based on Toyo Engineering Corporation's advance cost and energy saving (ACES-21) process. This process has the advantage of high conversion and better heat utilization which results in lower overall energy consumption, high reliability and lower emission of liquid and gaseous pollutants. Urea III plant consists of two streams each of 2000 MTPD capacity with common prilling and condensate treatment sections.

Elaborate environment protection facilities are installed. The facilities also comply with the stipulations made by the Ministry of Environment and Forest, Government of lndia, Central Pollution Control Board and Rajasthan State Pollution Control Board. A snapshot of CFCL plant is shown in **Figure 1**.

Figure 1. Photograph of CFCL plant

Salient Features of Gadepan Complex at a Glance

Salient features of Gadepan fertilizer complex are the following:

- Presently available clean technology adopted in all the plants.

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- Use of arsenic and chromate is completely eliminated.
- Complete recycle of ammonical effluent with recovery and reuse of ammonia and water.
- Large holding ponds to hold treated effluent for sufficient duration.
- 65 km long extensive irrigation network to utilize the treated effluent within the industry's campus.
- Natural draft type prill towers (104 m high for phase-I, 118 m high for phase-II & 141 m high for phase-III) have been constructed in order to achieve better dispersion of particulate matter as well as ammonia gas into the environment.
- Atmospheric pressure double wall ammonia storage tanks with integrated refrigeration system.
- De-dusting system in bagging plant to recover urea dust and provide clean working environment.
- Height of all the stacks is more than 30 meters.
- A wide green belt plantation developed all around the complex.
- Well planned landscape for township, plant and non-plant area for maintaining eco-balance. More than 33% area is covered under green belt. Use of only treated effluent in green belt
- Phase-III plant is zero liquid discharge (ZLD) plant.
- Effluent of phase-III plant along with part effluent of phase-I & II is treated in RO & ZLD plants. Permeate is used as cooling water make up.
- Three stage storm water management system, which provides the leak-proof devices and ensures that no water will go outside the boundary wall except during monsoon. There is zero discharge from surface drains.
- Installation of hydrolyser and stripping unit for treating the effluent containing urea from the urea plant's floor washing.
- Pressure linked emission control in urea plants to stop the plants in case of threat of emission.
- Use of harvested rain water (in two low height dams) for all plant operations.
- Installation of bio-gas plant for processing and treatment of kitchen waste.

Environmental Aspects at CFCL

To ensure that CFCL succeeds in maintaining the integrity of the environment on a long-term basis, the under mentioned aspects of environment management are focused and given the utmost importance in all the operations of CFCL.

- Energy conservation
- Water conservation
- Emissions
- Liquid effluent & solid waste
- Biodiversity

Energy Conservation

Conservation of energy and natural resources is given the prime importance in the operations of CFCL. With this objective, CFCL has implemented various energy saving schemes since commissioning of Gadepan-I and Gadepan-II plants which have resulted in substantial reduction in energy consumption of plants which is summarized below:

Gadepan -I

- 1999 – 2000 : 6.082 Gcal/ MT urea
- 2018 – 2019 : 5.415 Gcal/ MT urea

Gadepan -II

- 1999 – 2000 : 6.127 Gcal/ MT urea
- 2018 – 2019 : 5.403 Gcal/ MT urea

Water Conservation

Considering the scarcity of water in future, CFCL has taken specific water conservation measures since beginning of its operations at Gadepan. CFCL has few unique features, viz.:

- CFCL is utilizing only harvested rain water for its operations.
- To ensure availability of water, CFCL has constructed a low height dam of 6 meter height on non-perennial river Kalisindh.
- Backwash water from raw water filters is recycled back to raw water reservoir and re-used in plant operation.
- Higher cycles of concentration (CoC) is maintained in cooling water system to reduce the water consumption. Special cooling water treatment program has been adopted to achieve this.
- Cathodic protection system for underground cooling water, firewater and raw water lines has been provided to control the corrosion in pipelines and leakage of water.
- Schemes for maximum recycling of service water, compressor inter-stage condensate, etc., which was earlier being drained in surface drain, have

been implemented. Service water mainly used for sample coolers in ammonia, SPG and urea plant has been recycled to cooling tower.

- Green belt development and coverage of gardens, lawns and landscapes associated with a unique irrigation network having fountains and pop-up systems to use the treated effluent water all over the premises.
- Liquid effluent management system is unique which provides free hand to manage the effluent and have the adequate storage capacity of 180000 M^3 for the lean period too.
- Reverse osmosis (RO) plant has been installed alongwith Gadepan-III, to treat 200 m^3/hr of effluent and re-use the permeate (treated water) as cooling tower make-up.
- ZLD plant also has been installed with Gadepan-III to treat the reject from RO plant. The concentrated waste from RO and ZLD is sent to Pollution Control Board approved treatment facility at Udaipur.

As a result of various initiatives the water consumption has reduced from 6.20 M^3/MT urea in 2009-10 to 4.85 M^3/MT urea in 2018-19.

Emissions Control

In all the plant's operations, natural gas is used both as feedstock and fuel. The Sulphur content of natural gas is very low (<1 ppm) which results in insignificant Sulphur dioxide emission from stacks.

The main source of emissions *i.e.* point stacks in all the plants are indicated below:

a) Ammonia Plant

- Primary reformer stacks
- Flare stacks

b) Urea Plant

- Prilling towers based on natural draft.

c) Captive Power and Steam Generation Plant

- Boiler stacks
- Heat recovery steam generation (HRSG) stack

d) *Bagging Plant*

- De-dusting system stacks.

All these stacks are installed as per the guidelines of regulatory authorities. The stack emissions analysis meet the standards prescribed by Rajasthan State Pollution Control Board, EP Acts / Rule and Central Pollution Control Board.

Pressure Linked Emission Control System of Blow Down Stacks in Urea-I & II Plants: Urea plant can become an environment hazard if a potential situation like safety valve release is not handled timely. Detection and control of emissions from release of safety valves is an essential requirement to ensure protection of environment and sustainability. As a consequence, concept of providing pressure based automatic detection and control of emission from PSVs discharge through PLC trip logics was conceived and implemented in the blow down stacks of urea-I & II plants and their trip logics were defined for tripping of the urea plant in case of SV passing unknowingly to the blow down stacks.

This is first of its kind, innovative & cost effective scheme of detecting emissions and automatic control mechanism through PLC system has emerged as an effective approach towards commitment of maintaining a safe environment.

Continuous Ambient Air Quality Monitoring Station (CAAQMS): In addition to the routine monitoring of emissions all around the plant boundary, CFCL has installed five continuous ambient air quality monitoring stations at different locations around CFCL complex boundary wall (**Figure 2**). Their results are displayed at factory gate.

Figure 2. Ambient air quality monitoring stations

Table 1. Performance of process condensate stripping unit

Parameter	Unit	Design		Actual Performance	
		Inlet	Outlet	Inlet	Outlet
Ammonia	mg/L	500	10	450-500	2.5
Carbon di oxide	mg/L	600	10	500-600	6
Methanol	mg/L	1000	20	600-700	12

Noise Monitoring and Control: Noise levels from Noice ***Noise Monitoring and Control:*** Noise level from compressors/ blowers have been restricted below 90 dBA by adopting suitable features since design stage itself. Further wherever necessary, the machines have been provided with acoustic insulation to minimize the noise. In addition, all the process and steam vents have been provided with silencers to curb the noise pollution during start up/shut down of the plant. In the new Gadepan-II plant, a specific attention has been given on noise control and hence the discharges of all the pressure safety valves (PSVs) have been provided with silencers. The monitoring of noise levels at work place, ambient air station and other vulnerable points is done regularly.

Effluent and Waste Management

Liquid Pollution Control System: A systematic approach has been followed at CFCL to segregate the waste waters based on their characteristics so as to achieve the effective treatment and disposal meeting the statutory norms.

a) Ammonia Process Condensate Treatment : In ammonia plant, process condensate is mainly of two types. Overhead condensate is available after condensation of moisture from the carbon dioxide in the overhead coolers. This condensate carries dissolved carbon dioxide. Other condensate generated from process gas contains ammonia and methanol. These condensates are treated in process condensate stripping unit where stripping is carried out with steam. The bottom purified product is sent to water demineralization plant for further polishing. The polished water is recycled as boiler feed water which reduces consumption of water. The design flow of this waste water is 2208 M^3/day. During any upset in stripping section, condensate is stored in a guard pond having 3 days holding capacity for reuse. The stripper has extra capacity to take additional load of recycled condensate from guard pond. The performance data are presented in **Table 1**.

b) Urea Process Condensate: The process condensate of urea plant contains ammonia, urea and carbon dioxide. The condensate treatment system is integrated in the process and is provided with a hydrolyser (**Figure 3**) to hydrolyze urea and recover ammonia by distillation. Deep hydrolysis of urea and proper stripping of ammonia and carbon dioxide

Figure 3. Deep hydrolyzer in urea plant

Table 2. Performance of urea process waste water treatment

Parameter	Unit	Design		Actual Performance	
		Inlet	Outlet	Inlet	Outlet
Urea	mg/L	500	10	450-500	2.5
Ammonia	mg/L	600	10	500-600	5
Carbon di oxide	mg/L	1000	20	600-700	5

gives purified water suitable for recycling as boiler feed water. This not only helps in pollution control but also reduces consumption of water. Design flow of this water is 1368 m^3/ day.

Similar to ammonia plant, in case of any disturbance in treatment section, condensate is collected in urea guard pond having three days holding capacity for reuse. The urea is subjected to thermal hydrolysis into ammonia and carbon dioxide under pressure. The ammonia and carbon dioxide are recycled to the process after stripping. The bottom purified water is sent to the water demineralization plant for further polishing to use as boiler feed water.

The average performance data are presented in **Table 2**.

c) Turbine Condensate : Turbine condensate generated at different surface condensers of steam turbines is pure and free of contamination. This is sent directly to water demineralization plant for use as boiler feed water after polishing.

d) Steam Condensate : Steam condensate from heat exchangers of urea plant is used as boiler feed water after polishing in the water demineralization plant.

e) Waste Water from Water Pre-treatment Plant :

Following two types of liquid effluent are generated in water pre-treatment plant (WPT).

i. Clarifier sludge.

ii. Sand filter back-wash.

Sludge generated from clarifier is in slurry-form and is taken to a centrifuge. Clear waste water is then taken to effluent treatment plant or raw water reservoir as per the quality of the water. Solid cake from centrifuge consisting of mainly silt is sent to demonstration farm. Sand filter back wash water does not contain high quantity of suspended solids. This water is again recycled to water pretreatment plant. Thus entire quantity of waste water (1092 M^3/day) is recycled and solid cakes are reused in the demonstration farm.

f) Waste Water from Demineralization (DM) Plant: In DM plant, waste water is generated due to regeneration of ion exchange resin columns. The waste water is highly acidic or highly alkaline depending upon the regeneration cycle. This is taken to a neutralization pit for pH correction by mutual mixing. The neutralized waste water is routed to the effluent treatment plant.

g) Waste water from Laboratory : The small quantity of waste water that generates during the laboratory analysis is transported to the neutralization pit of DM plant.

h) Waste Water from Cooling Towers**:** Two types of liquid wastes are generated in cooling tower

i. Cooling tower blow down

ii. Cooling tower side stream filter back-wash water

Figure 4. Treatment of oily waste water

Non-chromate cooling water conditioning system is practiced in all the cooling towers. The blowdown water contains 1200-1500 mg/L total dissolved solid and 4-8 mg/L phosphate. The blowdown water is routed to effluent treatment plant where it is mixed with other waste water. Filters back wash water and cell basin blow down are also transported to the effluent treatment plant.

i) Oily Waste Water: Oily waste water from different sections in all ammonia and urea plants is collected in a pit and then pumped to the oil separator unit in effluent treatment plant facility. Flocculation of emulsified oil takes place by treatment with alum and polyelectrolyte. Oil layer on the top is skimmed out and collected in drums. Clear waste water is taken to effluent treatment plant. Oily sludge generation is very small. It is collected in drums and composted in demonstration farm. Photograph of oily waste water treatment plant is given in **Figure 4**.

Final Effluent Management

a. Effluent Treatment Plant : The waste water from various sources as indicated earlier is transferred to effluent treatment plant. Here, pH control and stabilization of waste water take place. Different effluent streams as described above get thoroughly mixed in six compartment of mixing chamber. From mixing chamber, effluents flow into a stabilization section followed by settling tank. Sedimentation of the suspended particles takes place in the settling tank. The treated waste water of the effluent treatment plant is pumped to the two large holding ponds.

b. Holding Ponds: The total capacity of two holding ponds is 180000 cubic meter. These ponds are suitable for retaining treated waste water for more than three months. Most of the treated effluent water from holding pond is sent to the reverse osmosis plant and irrigation network except during monsoon when it is discharged to Kalisindh river. This is discharged through two nos. six km long underground HDPE pipe line having diffusers anchored on the river bed. Treated waste water of the holding pond always complies with the standards of the Rajasthan State Pollution Control Board & Environment Protection Act / Rules. The migratory birds at holding pond are shown in **Figure 5**.

c. Sewage Treatment and Disposal Scheme: Total sewage generation from all the plants and colony is about 1000 M^3/day which is treated in three STP plants. For phase-I & II plants, the adopted sewage treatment scheme is based on extended aeration process and clarification in clarifier and tube settler respectively.

In phase-III plant, in addition to the extended aeration process, the equalized sewage is pumped into the anoxic tank forwarded by MBBR tank where biological treatment on the sewage takes place. It is also provided with diffuser system at the bottom of the tank for aeration and with MBBR media for enhanced surface area for microbial development. Aeration helps in maintaining the dissolved oxygen levels in the reactor. The mixed liquor suspended solids (MLSS) scarry out the biological degradation of the effluent. The overflow is taken in the secondary clarifier where clarification of the liquid takes place. The overflow from the secondary clarifier is sent to the clarified water tank where sodium hypochlorite is dozed for disinfection purposes. This disinfected water is then pumped through a pressure sand filter and subsequently through an activated carbon filter where the colour and odour from the sewage is removed. The treated water from ACF passes through the UV system to remove the traces of organic. This treated water is used for horticulture purposes.

d. Reverse Osmosis (RO) Plant *:* 4800 KLD RO plant is installed to treat all the effluent from phase-III plants along with some quantity of phase-I & phase-II plants effluent. RO plant permeate is used as cooling tower make up.

The schematic of RO plant is shown in **Figure 6.** The HP effluent is pumped to the stilling chamber equipped with oil & grease trap. A slotted pipe skimmer has been provided to remove the floated oil layer. Sodium hypochlorite dosing is done at the inlet of oil and grease trap. Effluent from stilling chamber outlet enters the flash mixing chamber; here lime/dolomite solution, soda ash and coagulant are dosed for silica & hardness reduction. The solids formed during the chemical reaction are separated in the clarification zone of downstream high rate solids contact clarifier (HRSCC). Poly electrolyte (PE) solution is dosed at the inlet chamber of HRSCC. The clarified water from the outlet of HRSCC is collected in the clarified water tank and pumped to the dual media filters & activated carbon filter followed by UF for further treatment.

Separate backwash pumps are provided for backwash of the dual media filter (DMF). Activated carbon filter (ACF) is backwashed with feed water. Ultra-filtration (UF) permeate water is used for DMF backwash

Figure 5. Migratory birds at holding pond

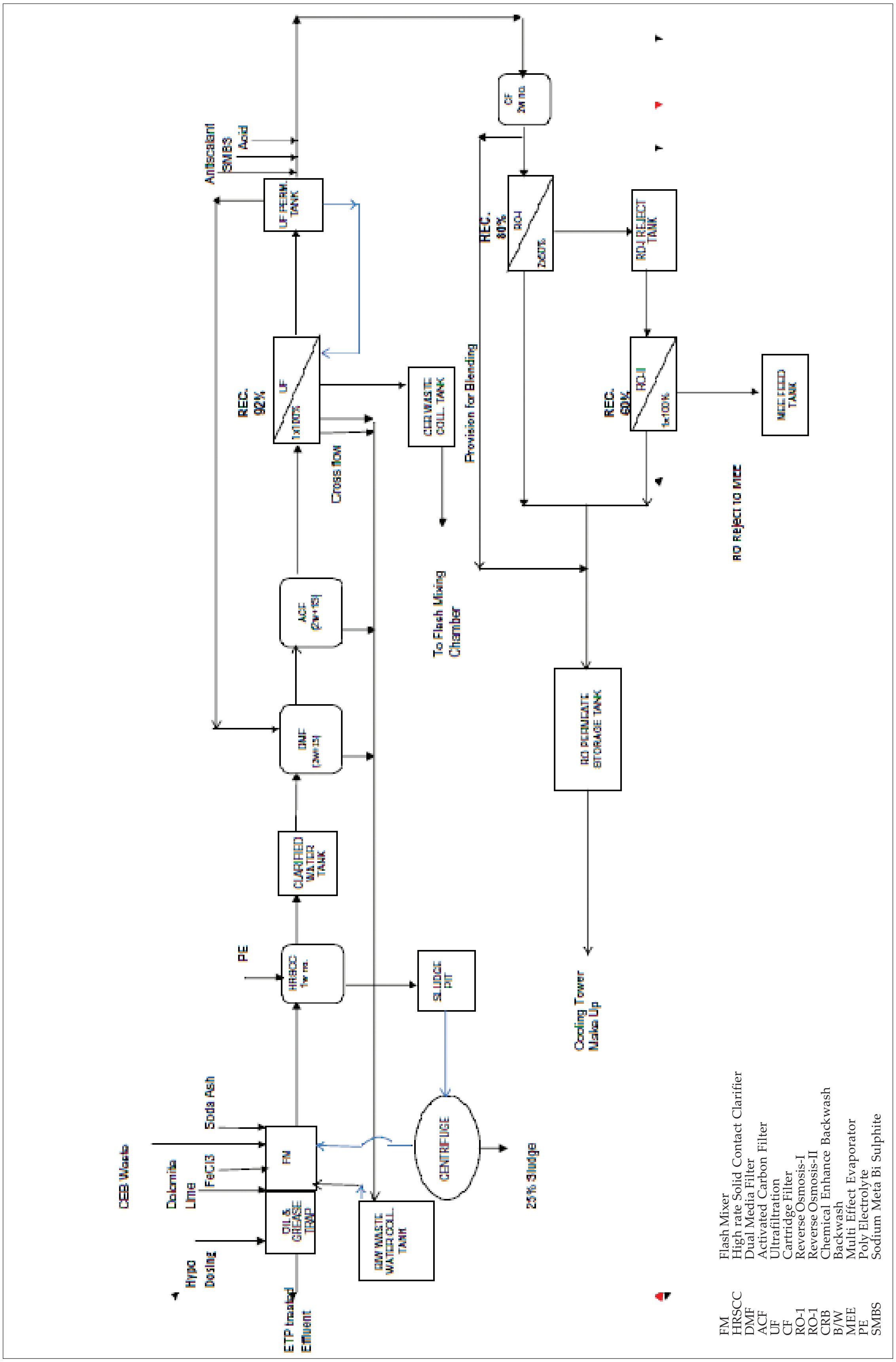


Figure 6. Reverse osmosis plant at CFCL

purpose. The DMF & ACF backwash waste is routed to waste recycle tank. Common air scour blower is provided to air-scour the filter media before the backwash and sludge pit. The settled sludge from HRSCC is periodically drained to the sludge pit. Sludge from sludge pit is pumped to a centrifuge for further sludge dewatering. Centrate from centrifuge is led to flash mixing chamber. The dewatered sludge from centrifuge outlet is disposed to RPCB approved Treatment, Storage and Disposal Facility at Udaipur.

Filtered water from the ACF is fed to UF unit to reduce the fine suspended/colloidal impurities. Provision of $FeCl_3$ dosing prior to basket strainer inlet has been made. UF unit is back flushed automatically based on pre-set frequency. The UF membranes are back-flushed by UF permeate water. Permeate from the UF system is collected in UF permeate tank. During the backwash of the UF stream, the feed water to DMF is re-circulated to clarified water tank through DMF feed pump. The UF normal backwash waste along with continuous reject is routed to the waste recycle tank. UF CEB waste water is routed to UF CEB waste collection tank. The waste from UF CEB waste collection tank is pumped to flash mixing chamber after neutralization as required. UF permeate from UF permeate tank is passed through the micron cartridge filter of 5 micron nominal rating for further fine (micron) filtration prior to RO inlet.

Provision of sodium meta bi-sulphite dosing prior to cartridge filter has been made for dechlorination. Also provision for dosing of antiscalent and HCl has been made prior to cartridge filter. The cartridge filtered water is pumped to the RO-I block using HP pumps. Permeate from RO-I is collected to common RO permeate tank. RO-I reject is led to RO-I reject tank and passed through RO-II skid by reject RO-II feed pump.RO-I reject is passed through the micron cartridge filter of 5 micron nominal rating for further fine (micron) filtration prior to RO-2 inlet. Provision of antiscalent & acid dosing prior to cartridge filter has been made. The reject from RO-I reject tank is pumped to the RO-II block using HP pumps. Permeate from RO-II is collected to RO permeate tank. This permeate is used as cooling tower make up. RO-II reject is led to MEE (multi effect evaporator) feed tank.

e. Zero Liquid Discharge Plant

456 KLD zero liquid discharge plant is installed to treat the RO reject. Schematic of ZLD is shown in **Figure 7** and photograph in **Figure 8**. RO reject is concentrated in five effect evaporator followed by pusher centrifuge. Feed flows in forward feed manner in evaporators. All effects are forced circulation type. RO reject from MEE feed tank is transferred by MEE feed pumps. The feed is preheated by series of pre-heaters. First the feed enters the preheater–1 where the feed is heated by process condensate. From preheater-I, feed enters to next preheater-2 where the feed is heated by the partial vapours from calendria -5 and so on.

After preheater-6, the feed enters into the first effect in duct of vapour liquid separator for effect-1. When the desired level in VLS-1 is reached, then RO reject is kept in recirculation by starting pump to maintain tube side velocity and to achieve desired heat transfer coefficient. The same pump is used for recirculation and to transfer RO reject to next effect. Similarly, when the desired level in VLS-2 is reached the RO reject shall be transferred to next stage up to 5th stage. Finally, RO reject is collected in thickener tank, where pusher centrifuge separate out salts and mother liquor. Mother liquor is recycling back to 5th stage VLS.

Dry saturated steam of 3.0 kg/cm^2 (g) is fed to the inlet of TVR (X-7501) as a motive fluid. Partial vapours from effect I (V-7501) is sucked by TVR to mix up with live steam which is given to shell side of 1st effect calendria. The effluent mass which is in recirculation through calendria –1 is flashed in vapour liquid separator-1. The vapours generated in vapour liquid separator-1 go for next calendria-2 and so on. Finally, vapour from VLS-5 is entering in surface condenser where vapour is condensed by cooling water and is mixed up with process condensate of Calendria-5. This is final product of ZLD plant. Whole plant is running under vacuum.

Solid Waste Management

a. Bio-Gas Plant: A bio-gas plant (capacity 500 kg) is operational at township of the company. The bio-box, a decentralized, organic waste treatment plant is containerized as a plug and play model. The waste is manually segregated into biodegradable and non-bio-degradable fractions. The bio-degradable fraction is fed into the box, which has a sufficient retention capacity to digest the degradable matter into biogas and liquid manure. The generated biogas is used for cooking in CFCL guest house and the liquid manure is used for horticulture. The filtered liquid is recycled back into the digester. This is truly a scientific and environmentally friendly way of disposal of organic waste and harnessing of renewable energy therefrom.

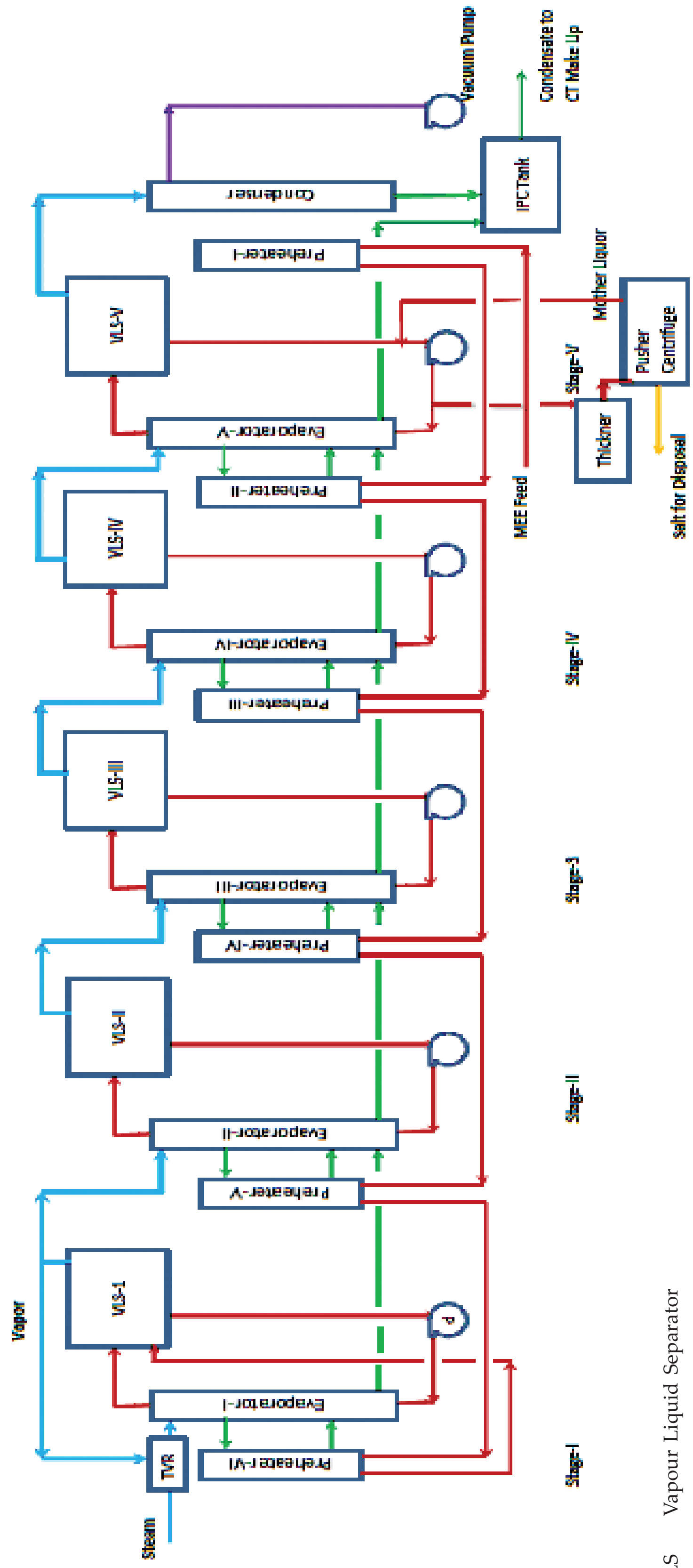
b. RO/ZLD Sludge and Salt : All the generated sludge and salt from RO and ZLD plants is being disposed to Rajasthan State Pollution Control Board (RSPCB) approved TSDF site at Udaipur with the help of RSPCB approved dumpers.

c. STP Sludge: STP sludge generated from all the three STP plants is used as manure in horticulture.

d. Hazardous Waste Disposal : CFCL is disposing its hazardous waste as per the conditions of authorization issued by RSPCB. Main hazardous waste is used oil, spent catalyst, RO-ZLD sludge, discarded containers used for hazardous chemicals and contaminated cotton rags.

Green Belt Development and Horticultural Activities

CFCL started its operations on uncultivated and rocky



VLS Vapour Liquid Separator
TVR Temperature Vapour Compression or Ejector
IPC Intermediate Process Condensate
Stage circulation by axial flow pumps
MEE Multi Effect Evaporator
CW Cooling Water

Figure 7. Zero liquid discharge plant

Figure 8. Photograph of ZLD plant

land. Plantation or greenery was hardly seen in this barren land. CFCL took up project "Operation Green" to convert this rocky land into a wide spread green fields with massive tree plantation. A positive change in the ecology of the surrounding area is experienced due to development of a dense green belt, forest development, development of gardens, lawns, ground covers and various landscaping in the area of about 340 acre (more than 33% of total area). In the green belt, different species of plants have been selected based on climatic conditions and soil quality. Especially broad leafed trees and fruit trees are added to attract birds. For utilizing the waste water from holding pond (HP) and STP, a massive modern irrigation network spreading over more than 65 km has been developed. This irrigation system covers the total green belt, plant areas and township. Only the treated effluent is used for irrigation purposes. In the township, each bungalow, flat and quarter have been provided the treated waste water connection to develop the kitchen garden. Free saplings, manure, etc., are distributed for motivating residents for developing greenery and better surrounding. The development of green belt, afforestation, garden lawns, landscaping etc. which are dense enough everywhere in the complex not only attracts event body but also helps to maintain temperature and humidity in the hot summer at a tolerable level to make life comfortable. Garden and plants create a soothing effect. The CFCL complex has become home of many birds like peacocks and various migratory birds. CFCL has proved that industrial development is possible without disturbing the eco-system.

Meteorological Studies

Micrometeorological data namely wind velocity and direction, temperature, relative humidity, rain fall and barometric pressure are recorded in a central computer situated in the environment cell of CFCL. This data is mended for predicting the possible impact and development of dispersion models. Wind roses and other patterns are developed with the help of computer. This data is regularly sent to the Pollution Control Boards.

Quality Control and Environment Cell

CFCL has developed a modern laboratory housed by automated microprocessor based instruments and qualified experienced staff for environment management. Regular analyses are carried out for air stack emission, water and noise. The results are appraised to management as well as regular reports are sent to Rajasthan Pollution Control Board and other statutory bodies.

Conclusion

CFCL has proved that industrial development need not disturb the eco-system and CFCL contributed to this by adopting innovative ideas and designs. Total dedication and commitment of CFCL has brought about the excellent results *vis-à-vis* environmental management. Due to proper site selection and use of natural gas as raw material, the plant has negligible impact on natural environment in the form of air pollution. Installation of RO-ZLD plant is an important milestone to maintain zero liquid discharge status of our phase-III plants. CFCL's operations are completely dependent on harvested rain water in the two low height dams built by the company, on the Kalisindh and Parwan river. Due to stored water in dams, the water table in the surrounding area has improved, which is beneficial to the local residents and livestock, for their farming and drinking water purpose. ■

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Experience with Hemihydrate Process to Produce Premium Quality Phosphoric Acid

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Abstract

Indo Jordan Chemicals Company (IJC), located at Eshidiya; South Jordan neighbouring with Jordan Mines and Mineral Company (JPMC) LLC, was established in the year 1997 and has been performing at its best to date. The Company is producing premium quality phosphoric acid using hemi hydrate (HH) process and exporting to its esteemed customers.

Using low quality rock phosphate, achieving 118 % plant capacity utilization with 98 % on-stream factor to produce and meet the customers' premium quality export is the main focused discussion in this paper. Over a period of time, IJC faced a tough challenge on rock phosphates quality as JPMC has downgraded its rock phosphate supply to its internal customer without compromising quality of commercial grade rock phosphate to international customers even in variations of phosphorites purity in operating mines in Eshidiya.

This paper is intended to share the IJC's experiences on HH phosphoric acid plant operation to handle low grade rock phosphates and achieving best quality of phosphoric acid. Its journey towards continuous improvement on plant's reliability, productivity and efficiency may be useful for other producers worldwide. Other than fertilizer grade acid, IJC has started its journey to attract its Asian and European customers for animal food grade phosphoric acid. With continuous endeavour and bench scale study, quality of food grade acid has been brought well within the norms set by international bodies.

Methodology of handling of sub-commercial rock, up-gradation of MOC of equipment to the latest trend, maintenance practices & performance monitoring of equipment in predictive and proactive manner, revision of standard operating procedures, industrial best practices and training of employees with latest technological advancement are few success stories of the company and have been discussed in the paper.

Key words : Phosphoric acid, hemi hydrate process, rock phosphate, reliability, quality

1. Introduction

The project in Eshidiya complex consists of 224,000 MTPA (as 100 % P_2O_5) phosphoric acid plant, 660,000 MTPA dedicated sulphuric acid plant and associated utilities & offsite facilities and an acid storage facility at Aqaba sea port.

IJC plant is designed by M/s Yara to handle predominantly A & B grade rock phosphate supplied by nearest JPMC mines with plant efficiency of 94%. After commissioning, IJC started production from 1997, but plant was started operating with different grade (schedule D) rock since November 1998 as a blend with other two types.

IJC faced a tough challenge on rock phosphate quality since JPMC diversified rock phosphate quality due to increased demand of commercial grade rock phosphate in international market and degradation of phosphates purity in operating mines.

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IJC's commitment to supply the high-quality merchant-grade phosphoric acid to the international buyers and strongly withstand its vision & mission of not to deviate processed rock phosphate grade affect the final product acid quality of various satisfied customers.

IJC's policies and concepts evolved and adopted based on the experience and expertise of the multidimensional teams' involvement from the project implementation to operate the plant from complicated conditions to user-friendly directions.

This paper covers various difficulties experienced by IJC to operate the plant more than the name plant capacity and troubleshooting carried out to maintain the premium quality acid.

2. Overview of IJC Phosphoric Acid Plant's Equipment Capacity, Capability and Reliability

IJC HH process designed by Yara is considered to be 1st project of its kind and success story of its performance, capacity utilization and quality of acid had change the mind set of many producers on HH process which considered to be tougher than Dihydrate (DH) process. Basic disadvantage of the process is comparative lower efficiency than DH or hemi dihydrate (HDH) process but it has many other advantages.

We would like to highlight eight pillars of silver lined landmarks.

- Overall capacity utilization.: 118% and marching forward
- Continuous reduction in the specific consumption of raw materials and consumable chemicals in phos acid : (e.g. rock phosphate, sulphuric acid, defoamer, anti scaling agent, raw water and power)
- Fulfillment of quality fronts.: 0% customer complain from fertilizer sectors and marching forward to animal food grade acid
- On stream factors:98%
- On stream efficiency:114%
- Safety compliances: Zero loss time accident, awarded and honoured by BSC.
- Environmental aspect and waste management: awarded non-compliance from Government of Jordan
- Wellbeing to stakeholders: Awarded and honoured by BSC (British Safety Council)

3. Operation with Different Grade Rock Phosphate

IJC, as a merchant grade phosphoric acid producer, is increasingly encountering regularly fall in P_2O_5 grade of rock phosphates and simultaneously increase of impurity content from its parent supplier Jordan Phosphates and Mines Company (JPMC).

Being faced these unavoidable circumstances, shifting from existing operational methodology and adopt the new standard operating procedures (SOP) is a challenge due to the increasing global demand across the globe and to make the business economically viable.

In addition to that there are many changes on quality of acid, set by international fertilizer fraternity, by lowering the limit of minor elements present in acid making stiffer competitions among merchant grade acid producers.

However, IJC has taken adequate and timely measure to meet the changing standards.

3.1 Comparative Evaluation of Jordanian Phosphorites: a Basic Raw material for Phosphoric Acid Production

With changing quality of rock phosphates' over the period of time and the requirements of various corrective measures for processing the rock phosphate without affecting the volume & quality of production with optimum efficiency in IJC HH process of phosphoric acid unit are considered.

In year 1997, IJC was getting basically three grades of rock phosphate from JPMC Eshidya mine as given below :

- **Schedule-A**: Commercial grade rock, 73-75 TCP, dry rock carrying only 2.5-3% moisture.
- **Schedule-B**: Commercial rock for selected customers, 70-72 TCP, wet phosphate having 14-18% moisture.
- **Schedule-D**: Sub-commercial, 60-65 TCP, dry rock having 5-10% moistures.

IJC is obliged to receive and process more non-commercial rock phosphate from the year of 1998.

Following are the present status of rock quality received:

- *Schedule A has been shifted to A2 (which is next down grade level of the export quality A1) :*TCP 68-70, 3-4% moisture and sometime A2 is mixed with S_2 grade rock phosphate from different mining source to standardize A2 quality with respect to TCP but doing so it contributes higher degree of R_2O_3 (Al_2O_3 & Fe_2O_3).
- *Grade B has been modified as A1A3:* It's a mixture of beneficiation plant's filter output of A1 grade rock with A3 grade: TCP-63-65, moisture 15-18 %. Commercial is available only on demand with high moisture for selective customers.
- *Grade D: Sub commercial in nature:* Un- beneficiated, 58-61 TCP, dry but rich in unwanted elements of silica, chloride, Al, and Fe.

Individual rock quality and blended feed rock quality is shown in the **Table 1.**

IJC identified ratio 60:20:20 and or 60:30:10 performs better than other mixing composition.

3.2 IJC Methodology for JPMC Supplied Rock Phosphate Quality Control:

- As a daily routine job, a team from IJC comprising of highly experienced supervisor and quality control team work together with JPMC mines area supervisor to segregate out the different strata of phosphates situated at various screen in mines area.
- Composite samples are brought to lab for analysis and on basis of lab report, either samples are qualified or reported back to JPMC for further improvement with the intended mission of not to suffer the plant with respect of volume of

Table 1. Individual rock *vs.* blended feed quality

Eshidiya, Jo- Mines Phosphates					Ratio of RP, (in PCT) A1A3 : D : A2			
Parameters	UOM	A1 A3	D	A2	1:01:01	50-25-25	60-20-20	60-30-10
Moisture	%, w/w	16.49	2.2	5.25	7.98	10.11	11.38	11.08
TCP / Grade	%	66.99	61.94	67.41	65.44	65.83	66.06	65.52
P_2O_5	%, w/w	30.66	28.35	30.85	29.95	30.13	30.24	29.99
CaO	%, w/w	45.05	45.44	49.51	46.66	46.26	46.02	45.61
Silica	%, w/w	10.68	14.07	12.30	12.35	11.93	11.68	11.86
SO_3	%, w/w	0.54	1.10	0.68	0.77	0.72	0.68	0.72
F	%, w/w	2.74	2.46	2.75	2.65	2.67	2.69	2.66
CO_2	%, w/w	3.40	4.86	2.84	3.70	3.63	3.58	3.78
Chloride as Cl	%, w/w	0.02	0.10	0.02	0.05	0.04	0.04	0.04
Al_2O_3	%, w/w	0.63	0.90	1.35	0.96	0.88	0.83	0.78
Fe_2O_3	%, w/w	0.38	0.78	0.95	0.70	0.62	0.57	0.56
MgO	%, w/w	0.21	0.23	0.17	0.20	0.21	0.21	0.21
Na_2O	%, w/w	0.29	0.37	0.28	0.31	0.31	0.30	0.31
K_2O	%, w/w	0.08	0.10	0.12	0.10	0.10	0.09	0.09
Org. Matter,C	%, w/w	0.1150	0.1050	0.0830	0.10	0.10	0.11	0.11
FCR		0.81	0.51	0.69	0.651	0.685	0.707	0.685
MER		0.04	0.07	0.08	0.062	0.057	0.053	0.052
P_2O_5/CaO		0.68	0.62	0.62	0.64	0.65	0.66	0.66
Reactive silica	%, w/w		60.00					

Sieve size	**UOM**	**A1 A3**	**D**	**A2**
+ 6.3 mm	%	Nil	Nil	Nil
- 6.3 + 4 mm	%	Nil	Nil	Nil
- 4 + 2 mm	%	2.72	7.73	7.10
- 2 + 1 mm	%	6.64	12.27	11.90
- 1+ 0.5 mm	%	23.09	15.88	22.30
- 0.5 + 0.212 mm	%	32.58	31.04	32.80
- 0.212 mm	%	34.97	33.08	25.90

Other Minor elements in Eshidiya RP		
Cd	ppm	4-5
As	ppm	14
Pb	ppm	1-2
Cu	ppm	15-19
Zn	ppm	190-200
Ni	ppm	27
CO	ppm	9
Mn	ppm	330
Cr	ppm	50-66
Ti	ppm	60-70
V	ppm	40-70
Hg	ppm	nil

Table 2. Comparision of an ideal rock with IJC processed rock

Rock phosphate index	Effects on process	Ideal values*	IJC blend values
High P_2O_5/CaO	Gives better yield of process	0.71	0.66
Low carbonate	Less foaming and SA consumption	1.7	3.58
Low organic matter	High organic matter in combination with CO_2 increases foam stability index.	0.04	0.11
Right FCR values of rock phosphate	It affects crystal habit, shapes and size.	0.8	0.707
Low non- reactive silica	Silica required as reactive to minimize ill effect for HF but non-reactive silica effects total reaction process by additional unwanted solid generation and highly erosive to rotary equipment.		65% of total silica in rock phosphate
Low alkali metal impurity	Helps less scaling in equipment especially colder zones of vacuum circuits.	-	0.39
Low cationic impurity	It helps to minimize orthodox scaling in combination with other impurity and less influence on downstream derivatives of phosphoric acid.	-	
Sufficient selective cationic impurity	Some cations have a positive effect of crystal habit modification and helps for better filtrations.	-	
Superior reactivity of rock phosphate	Less needs higher reacting volume and time to complete the reaction.		Jordanian rock phosphates are reactive as mentioned by researchers
Softness of rock phosphate respect to grinding requirement	Low power consumption		No grinding requirement for HH process
Low chloride	Invites corrosion	<0.03%	0.04%
Low MER	Helps low viscosity, low scaling, no side effects in fertilizer	Not to exceed 0.1	0.053

*TOGO high grade rock is taken as reference

production and quality of final acid.

Comparision of an ideal rock with blended rock processed by IJC is given in **Table 2.**

4. Short Description of Reaction, Scrubbing, Filter Operation and Concentration Section

There are some special features of HH reaction and filtration circuits which demands special attention for process control, selection of MOC of equipment, fabric for filter cloth and addition of specialty chemicals to prevent foaming in reactor, chocking of lines and vessels from scaling and reductions of heat transfer coefficients in manufacturing the products.

Due to high temperature reaction, reaction vessels and roof are required for better protection than DH plants.

- IJC faced serious deterioration of reactor roof concrete due to torturing effects of evolving fluorinated gases and hot vapour/fumes generated due to acidulation of reactor slurry from acid mixture situated in 3rd reactor (R2). With continuous benchmarking with other industries, a special quality high temperature bearing resin is started applying in dry surface of reactor roof for last couple of years which had given comparative relief from deterioration.
- Regarding MOC selection of reactor agitators, latest developed austenitic stainless steel are used as per recommendations of OEM suppliers. It is found to be performing better than earlier.
- Regarding pumps, those are connected to reactor; to handle slurry were initially found to be suffering higher rate of erosions and damage of internal lining. IJC has developed a well-recognized design house that has tailor made the pumps spare parts which have improved life to more than double.
- Liberation of obnoxious gases through reaction is more in comparison of other process. Without compromising environment and employed health, MOC selection has been done meticulously with

right specification.

- Gas scrubbing sections are made more efficient by ventury scrubbing system and circulating scrubbing water in 3 stage yields a 50-100 mbar negative draft over the reactor. The gases liberated through final stage to atmosphere are well below the environmental norms as specified by pollution board of Jordan.
- As IJC uses sub commercial rock phosphate as a blending with other veriety e.g. A2 & A1A3 – as per sieve analysis shown before, it contains 6-7% +2 mm particles . These particles, if reside in reactor for prolonged time, damages the rotary parts of agitators and pumps. Therefore daily discard of higher size particle through reactor draining nozzles to sump is an invariable practice.
- In IJC, HH filters are running 15 days nonstop. Scheduled online checking procedures are carried out on daily basis by operation and mechanical PM team and cross checked and verified by inspection team.
- Monthly two times washing of filters are taken for 8 hours stoppage. During this time no circuits, vessels and associated rotary equipments are kept untouched or unattended from cleaning and inspections. Major to minor maintenance requirements are fulfilled with proper planning.
- Reaction shut down is planned every 30 days interval for preventive cleaning of gas circuits in scrubbers section and cleaning of high flow rate slurry circulation pumps' suction nozzles to maintain its performance unchanged.
- Selections of materials and its durability for various other equipment's and lines are noted satisfactory as compared with bench mark study.

4.1 Reaction System Details

The reactor is the heart of the process, so the most emphasis is placed on improving reactor performance. **Figure 1** shows the process flow diagram of PA. Our hemi hydrate reaction system consists of three cylindrical tanks of equal volume and dimensions. The first two reactors are named R1A and R1B.The third one is R2. Reactor R1A and R1B are deficit in sulphate and have been designed as two separate tanks to enhance the release of gas produced by the reaction of rock and acid thereby improving process control.

Phosphate rock is discharged into reactor R1A, while 98.5% sulphuric acid is fed to reactor R2 through the concentric static acid mixer where it is mixed with the return acid flows (approximately 19- 21% P_2O_5 phosphoric acid from filters). Reaction slurry overflows from reactor R1A to reactor R1B then to reactor R2 through launders.

From reactor R2, part of the slurry is recycled to reactor R1A by a recirculation pump with the pump capacity of 1800 m^3/hr, so that only 40% of the total CaO (w/w %) fed to reactor R1A is precipitated. Further from R2, part of the slurry is cooled in a flash cooler by evaporation of water from the slurry under vacuum to 94 °C.

This flows back through a down leg sealed in R2 and helps in maintaining the temperature of slurry 98-100 °C. The free sulphate level in reactor R2 in its liquid phase is controlled at around 2.0 w/w %. Slurry from reactor R2 is fed to hemihydrate vacuum filters.

4.2 Reactor Volume Adequacy Study

Hydro over-sized the reactors to provide extra surface area to handle foam. These specified 2 m^3 reactor volumes per t/d P_2O_5 capacity x 700 t/d —> 1400 m^3. The original equipment list shows all three reactor have ID of 10,730 mm; WH (working height): 5,500 mm; TH (total height): 6,500 mm; working volume: 465 m^3 (which agrees with calculation of ID & WH).

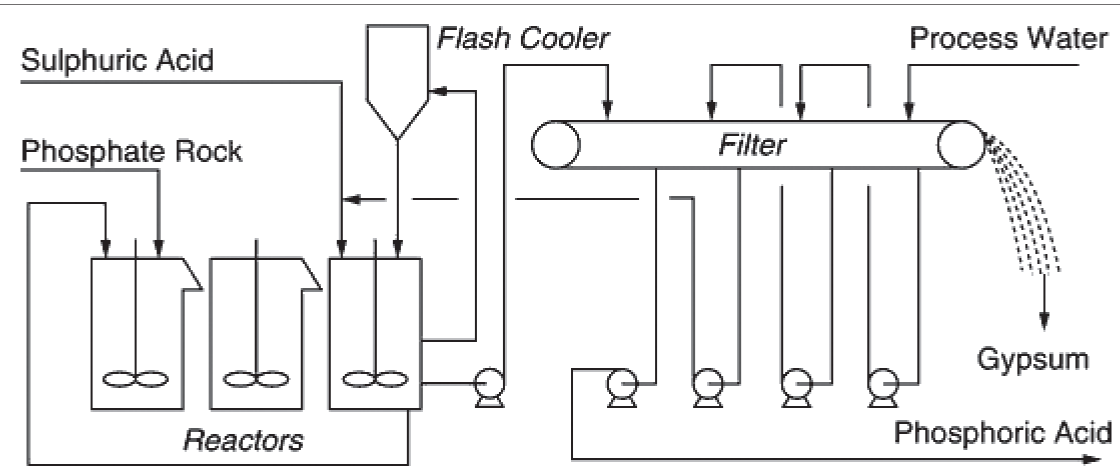

Figure 1. Process flow diagram of HH phosphoric acid

Table 3. Reactor dimension Comparison benchmark

Description	Comparative data			
	IJC	Plant 1*	Plant 2*	Plant 3*
Plant load (t. P_2O_5)	700	750	1460	600
Reactor (M^3)	400*3	218*5	735*4	400*3
Reaction volume (Design) - M^3/MT of PA	**1.72**	**1.45**	**2.01**	**2**
Reaction volume(Working) - M^3/MT of PA	**1.42**			

** Plant 1, 2 & 3 are the reputed phosphoric acid producers:*

Table 4. Main technological and economical process parameter of IJC – phosphoric acid plant

Index	Unit	Values	Remarks
Rock Blending ratio	-	60:20:20	Additive rock, blended
Specific volume of reactor used on 900 MT production/day	M^3/TP_2O_5	1.3	More than 1 is acceptable
Degree of decomposition – rock phosphates	%	95.5 max	Due to +2 mm~6-7%
Gypsum washing efficiency	%	98.5	IJC needs to improve further on crystal size
Specific capacity of filter	T/M^2/day	5-5.2	Based on max production achieved (900 MT/day)
Specific consumption - RP	T/T	3.8-3.9	Due to +2 mm~6-7%
Sulphuric acid	T/T	2.75-2.86	Target3.1
Defoamer	Kg/T	9-10	Target<10
Anti-scale agent	Kg/T	2.5-2.5	Target <3.5
Raw water	M^3/T	3.5-4	Target<4.5
Power	KWH/T	180-190	Target 220

Three reactors at 465 m^3 equal 1395 m^3. 1395 m^3 / 700 tpd = 1.99. During normal operation there will be about 100 m^3 of free space in reactor 2, leaving an effective volume close to 1300 m^3.

Based on the comparison of other plant reactor volume data **(Table 3)**, IJC's calculated specific volume to run the plant at 110% load is 1.4 m^3 /tpd P_2O_5. Normally Hydro would provide about 1.4 -1.5 m^3/ tpd. On other projects, we have found that specific volume as low as 1 m^3/tpd is acceptable with Prayon multi-tank reaction systems (*i.e* more than 3 tanks).

However those Prayon multi-tank reactors have 8 or 9 compartments. The larger number of compartments provides more effective use of the total volume, compared to a 3-reactor system.

A specific volume of 1 m^3/tpd has not been demonstrated for a 3-reactor system like at IJC.

Main technological and economical process parameters of IJC-phosphoric acid are given in **Table 4**.

4.3 Protection from Large Size Particles Entry into the Reactor

Rock phosphate, received from JPMC mining area, sometimes is contaminated with big size bolder (size.>1").

That on passage to reactor creates huge nuisance to equipment and deposits at the bottom to reactor.

It not only reduces the effective reaction volume but also affects the agitator performance.

IJC took required steps to reduce big size stones from mines area by earmarking area for IJC and additionally installing 2- stages vibrating screen at assigned position on rock feed system to eliminate higher size particles. As the blended rock phosphate contacting average 9-10% moisture, installation of vibration screen mesh <10 mm was found to be not suitable as screen getting chocked. However, dry rock having 2-3% moisture once pass through the screen can eliminate desired limit of +4 mm oversize particles.

The small amount of oversize (+2 mm dry rock and +10 to 20 mm damp rock) from both the dry screen and the piano wire screen could be discarded.

However , in our cases particle size more than +4 mm was found to be 6-7 % in series of samples taken daily. The management wanted to eliminate such particles

Figure 1. An image of vibrating screen on-line in rock feeding system

by installation of an on-line crusher after vibrating screens **(Figure 1)** but not found to be economical.

4.4 Reactor Agitator

The blended rock used (additive rock) has about 80% of the feed less than 1mm size while the plant is designed for 80% less than 0.5 mm size. The coarse material above 2 mm size does not react well and some of the coarse unreacted/partly reacted particles get accumulated at the bottom of the first reactor. This necessitates reactor draining once in a day for about 10-20 minutes otherwise the carbon brick lining inside the reactor and propeller of agitator gets eroded fast.

The drained liquid is strained through coarse strainers to a sump from which the filtrate is recovered back to the reactors **(Figure 2)**. Installation of suction strainer to high flow slurry pump associated with 3rd reactor is given in **Figure 3.**

4.5 Scaling Issues

The solid content in the reactor slurry is increased by 1% to handle the additional quantity of solids generated on account of processing lower grade rock. Increase in scaling inside the flash cooler and slurry inlet and outlet ducts was noticed. There is a slight increase in the whitish silica deposits in the scrubbers and vapour ducts. The quantity of gypsum handled also increases from 5 tonnes to 6 tonnes per tonne of P_2O_5 due to increase of impurity percentage in gypsum from 8% to 10% due additional silica loading from input rock quality.

4.6 Filtration Efficiency

Normally in HH process gypsum loss is higher than the other processes because of its single filtration method. In IJC design, gypsum loss is 1.15 % P_2O_5 as insoluble and 0.50 % as water soluble P_2O_5 at 700 T P_2O_5/day load. We operate the plant more than 15 % higher than the design load and maintain the gypsum loss slightly higher than the design norms. Though, we are consuming the blended rock as feed, plant is operating now with overall efficiency of 88-89% and maintain the filtration efficiency as 90-91%. Gypsum crystals in majority are as agglomerated rhombohedral and approximately 20-25% finer size crystal and 2-5% are needle shape.

4.7 Zero Break-down Maintenance

IJC customized its maintenance practices based on its equipment failure rate and nature of failure. It has developed predictive and proactive maintenance practices for all its critical equipments. Routine maintenance practices are in line and routine cleaning maintenance schedule is strictly followed.

Upgradation of equipment and selection improved MOC for various parts of the equipment based on their failure rate are a cultural part of IJC's maintenance practices.

Figure 2. Reactor draining facility to remove settled heavier particles from vessels bottom

Figure 3. Installation of suction strainer to high flow slurry pump associated with 3rd reactor

IJC uses all spare parts and consumable items from most recognized and well versed manufacturing houses without compromising on the quality. Results are being recorded by operation and noted to be satisfactory. Last 3 years, no un-expected break-down or shutdown was experienced and 100% uptime was recorded. Complete survey of storage tanks in every three years and study of its health conditions is one of its best maintenance practices.

4.8 Gypsum Management

IJC follows dry disposal of gypsum and stacking methods. It consists of series of belt conveyors and projectile thrower system at the end point situated around 1.8 km away from plant site.

The filter cake at the exit of belt filters contains 18-22% w/w free moisture. Though filtration is normal but variation of moisture in the cake is noticed which is obviously due to the type of rock processed and the plant parameters.

Advantages

- Transportation of gypsum in dry mode is experienced simpler when compared to handling of gypsum slurry, which poses problems of pumping and plugging of pipelines.
- The initial cost for dry stacking is less compared to wet stacking, as the lining of the ponds and the complex under drain systems are not required.
- The problems of percolation and flooding of acidic water from the dry gypsum stacks are less in most of the cases, and virtually absent if the stacks are located in dry climate.
- The down-time of phosphoric acid plant is lower in this dry stacking.
- A separate maintenance team along with operational supervisor is continuously monitoring the gypsum and rock conveyors and necessary maintenance is done in time.

5.0 Concentrators and Cooling Towers Performances

IJC phosphoric acid cooling tower is forced draft type having six cells in line all time with one cell as spare. As per HH process designed goodness, the size of tower and capacity of pumps are considerably less than DH process.

Mass and heat load features in brief are as follows:

- Total 3000-3500 m^3/hour cooling water flow is sufficient to handle the heat load released from reaction section flash cooler, reactor gas scrubber, filter condensers & 3 numbers of concentrator for producing 850-900 MT/day production.
- Total hot water circulation flow to tower is equivalent to cooling water flow to process circuit for plant running.
- Differential temperature across the tower is 12-12.5 ^oC which is noted to be satisfactory.
- Phosphoric acid cooling tower performances are rated higher than as signed in 1990s. IJC has taken series of steps to control, monitor and correct its performances in day in and day out.

Following are the notable points of IJC maintenance practices

- Changing of cooling tower cell headers and drift eliminator twice in a week.
- Changing of pump seal from gland packing type to mechanical seal has given a good boost to be maintenance practices. The maintenance frequency has been reduced drastically owing to renewal of pump for gland leakage.
- Preventive maintenance of phosphoric acid cooling tower fans are taken every week interval as it encounters highly corrosive mist.
- In year 2014, phosphoric acid cooling tower inlet hot water trench route is channelized through settling pit, which settles the silica carried by water coming out from gas scrubbing section. This process improved phosphoric acid cooling tower performance to a large extent by reducing solid levels of cooling tower water.

5.1 Concentrator's Performance

IJC has three numbers of concentrator with capability to produce 1000 MTPD strong phosphoric acid of 54-56% concentration. IJC shares the customer satisfaction as its pride for producing premium quality acid.

- Life cycle for each evaporator at present stage is 10-12 days. Improvisation action plan is initiated for minimization of calendriya scale forming by introducing specialty chemicals prohibitive to avoid scale formation.
- IJC concentrators are well capable to produce 54-55 % acid in sustainable basis.
- IJC evaporators are capable to handle the designed performances :

o Specific LP steam consumption is 0.70-0.85 Mt/Mt P_2O_5 for 14-15% enrichment of concentration.

o Specific cooling water requirement concentrator is 3.5-3.7 m^3/Mt/hour P_2O_5 for getting heat load of 10 ^oC/Mt/hour.

o Capacity of each evaporator is 15 Mt/hr but capable to produce 18.5 Mt/hr. without affecting its quality.

A study was made on concentrators to reduce chlorides and fluorides and to increase efficiency in vacuum evaporative circuits operating under 100-110 mm bar vacuum. A series of study reveals that 80-85% fluorides and 55-60 % chlorides are eliminated from feed acid solution which are sufficient for SPA to meet the acid quality norms specified by international agencies for shipment.

6. Quality of IJC Merchant Grade Acid

Table 5 gives the quality of merchant grade acid produced by IJC.

Notable Features

♦ Fertilizer grades friendly, least effect on off grade generation on DAP.

♦ Enriched in P_2O_5 values un-parallel with many international suppliers.

♦ Lowest in Cl, F values & solid content.

6.1 Impurities and its Effect on Fertilizer Production and IJC's Efforts to Control the Minor Elements in its Production Unit

Fertilizer grade phosphoric acids produced by exporters are obliged to maintain the various minor elements presence to its below specified limit.

The boundary levels are further being narrowing down with a stipulated time limit for acid used for animal food grade customers.

Customization and tailor making product quality needs extra cost for processing. It is a challenge to the major phosphoric acid producers and IJC obliged the challenge and customized its product quality further as per requirement for food processing customers and opened up its market to European countries.

Customer feedback report reveals that IJC supplied phosphoric acid quality is superior to any other major producers and especially fertilizer grade acid has received very delightful customer survey report which enable IJC –delighted.

IJC has taken several trial runs in fertilizer unit within its group of companies to customize its quality standards and successfully eliminated the undesirable factor by a team of researchers. Following notable points are mentioned below:

• Magnesium (MgO) forms ammonium magnesium phosphates, Mg (NH_4) PO_4, as insoluble precipitate in DAP derivatives.

• RP MER is indicative of its suitability for its use in wet process acid production. Acid producers has to take sufficient precautionary measure on parameter controls and thus eliminate those elements to be best possible extent in reaction, filtration and storage acid

Table 5. Quality of IJC merchant grade phosphoric acid

Parameters	Unit	Values	Sample-I	Sample-II	Sample-III	Sample-IV
Specific gravity at 30^{o}c		**1.63 - 1.70**	1.674	1.678	1.677	1.669
P_2O_5	%	**52-56**	55.08	55.28	55.05	54.82
CaO	%	**0.05-0.5**	0.27	0.26	0.26	0.27
Chloride	%	**0.015-0.03**	0.011	0.012	0.017	0.018
Fe_2O_3	%	**0.6-1.14**	1.13	1.17	1.08	1.09
Al_2O_3	%	**0.5-1.2**	1.00	0.98	0.90	0.82
MgO	%	**0.2-0.6**	0.41	0.38	0.42	0.40
Fluoride	%	**0.3-0.4**	0.33	0.31	0.25	0.24
SO_4	%	**3 maximum**	1.89	1.90	1.93	2.24
O.M.	%	**0.03-0.1**	0.04	0.04	0.05	0.04
Solids	%	**0.2-1.0**	0.10	0.11	0.17	0.11

clarification stages.

The MER values formulated by notable scientist as:

MER = (Fe_2O_3%+Al_2O_3%+MgO%+MnO_4%)/ P_2O_5%.

MER <0.10, suspended of available solid in acid <2.0%.

- Manufacturing DAP and various derivatives of NPK will be hassle free as far as acid quality is concerned.

MER values marginally higher

- Affecting DAP processing can be adjusted by external addition of N by means of urea.
- It was experienced by our team that little adjustment of free sulphate level in feed acid and/ or controlling the conversions of MAP/DAP ratio in slurry feed to granulator.

MER values above the range 0.132

- DAP grades are failed and it goes as low as 16:48:0
- It needs to have a tough control N/P ratio in slurry fed to pipe reactor or pre neutralizer for further ammonization of slurry in granulator.
- N/P adjustment can be used to vary the Nitrogen and Phosphate level in the derivative 18:46:0 by adjusting the ratio of MAP (NH_4 H_2 PO_4) -lower N and higher P, and DAP [($NH_4)_2$H PO_4]- for high nitrogen and lower P.

7.0 Sulphuric Acid Plant

7.1 Breakthrough Achievements in IJC- Sulphuric Acid Plant to Sustain the Highest Production

After achieving sustainable plant capacity utilization of phosphoric acid plant up to 120%, a parallel focus got shifted to sulphuric acid plant's improvement in overall capacity utilization that was 110 %. Total day production was marginally lagging to meet the sulphuric acid requirement in phosphoric acid plant.

Though sulphuric acid plant has crossed over its total production target with sustainable 110% capacity utilization but potentially it can be pushed to 120% production.

But it faced some insurmountable obstacle, as it seems, for further moving forward.

Sulphuric acid on-stream factor was achieved 98% but IJC targeted it to be 100 %.

Outsourcing of sulphuric acid from market was primary action plan and IJC started doing so for couple of months but it was not easy to match the economics of the business due to volatile S price in international market that makes the sulphuric acid procurement costlier and that to IJC could not catch the competitive market because of its location.

Basically sulphuric acid plant was facing frequently (at least once in a quarter) hot shut down due to:

- Tower acid circulation Pumps' discharge strainer blocking by black sticky mass **(Figure 4)** which started hindering flow to acid coolers after certain interval of plant operation.
- It makes an impact in pump tank acid temperature to be maintained high and high temperature of circulation acid will reduce the performance of absorption tower that leads to more SO_3 through stack.
- Due to which load cannot be increased more than 110 % and frequent hot shutdown was necessary to clean the strainers.

It was a great challenge to the IJC team to resolve the issue. The new journey started thereafter.

- Team visited different sulphuric acid producers in and around the country and shared their knowledge mutually.
- Invited designers and tried to understand the root cause.
- Frequently meet in SGD (small group discussion) and analyzed the probable reasons and step by step attempted to eliminate irrelevant causes.

Team concluded the following major contributors for black mass in sulphuric acid circulation line strainers.

- Lime used in sulphur- melting section for free acid neutralization.
- Erosion of ceramic in acid distribution bed in absorption tower.
- High silica content in process water for pump tank

Figure 4. Black sticky material was observed in the circulation acid system. Strainers were accumulated with this black material.

dilution

- Phosphate content in combustion air
- Oil content in dilution air for furnace view glasses

Based on many technical discussions and using statistical tools on PARETO analysis, it was finalized that high silica content in pump tank dilution water was the reason for this black material.

Then we installed the RO unit to reduce the process water silica content, and the RO water with less silica content has been lined up to DM as feed water.

We have installed the RO unit near to the WTP plant. RO water outlet was lined up to WTP as feed water, and then we improve the ion exchangers yield.

Result Obtained

- After lined up the DM water to pump tank, we observed that frequency of strainer chock has been drastically reduced to zero.
- Pump tank temperature was maintained at less 82 ^{o}C as per design.
- Plant running with 110% load consistently and possibility to move forward.

8.0. Way Forward

IJC is planning to run existing plant at 1000 P_2O_5 MTPD by utilizing the existing capacity in near future by adopting the following measures.

8.1 Installation of Additional Filter

As per operating procedure of HH process, the filter should be washed every 4 hours with hot water for every 7 days to avoid scale formation and 4 hours stopped for maintenance intention. Since we are operating two HH filters, we have to take filter wash two times in a week. During filter wash period, upstream of filter has been operating with 50% load and this leads to reduce the on-stream efficiency. By installation of third filter, we can operate the plant 100% continuously for the duration of filter wash time also.

We are making the modification in reaction system to increase the residence time. The IJC has decided to run the three filters continuously.

8.2 Agitator Design Modification

To avoid the solid settling in reactors and high feed rate, we are conducting the technical discussion with reputed agitator designers to change the agitator design in reactors. Presently agitator running with 110 KW hydraulic power, IJC is ready to increase the hydraulic power.

8.3 New Filter Feed Tank

The new seal compartment will be installed between reactor R2 and the filter feed tank. It would be approximately 2.5 m x 2.5 m x nearly 6 m deep, with its bottom sloping into the filter feed tank. A new opening would be cut into the upper side of reactor R2 to receive slurry from the new seal compartment. Ideally, the seal compartment would be close coupled to the filter feed tank on one side and to reactor R2 on the opposite side (like in Prayon mark 3 reactors).

The tops of the filter feed tank and seal compartment would be at the same elevation as the top of reactor R2. Consider either cylindrical or square shape of the new filter feed tank. A square tank requires no baffles.

Size of the slurry piping in and out of the flash cooler needs to be carefully evaluated.

8.4 Increase the Recirculation Flow

Recirculation from reactor 2 to 1A has to be proportional to production rate. This requires a bigger pump. The big change in rock quality might cause a need for a different ratio of slurry recirculation rate to production ratio to get optimum performance. This may require in-plant testing at different ratios. We are conducting the various studies to finalize the RC flow rate.

Conclusion

IJC got experience in sustaining the highest production in phosphoric acid plant and achieving the same by operating the plant higher than the name plate capacity. This has been done by utilizing inhouse expertise and with major capital investment.

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Advanced Technological cum Efficient Options in Manufacture of Sulphuric Acid

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Abstract

The sulphuric acid industry faces challenges such as energy efficiency, cost constraints and environmental concerns. Proven to withstand the harsh conditions of acid plants, broad portfolio of corrosion-resistant heat exchangers provides outstanding heat transfer required for process efficiency. These are from weak acid coolers, drying tower coolers and intermediate absorption tower coolers to final absorption tower coolers, product acid coolers, oleum coolers and oleum interchangers. The technology provides formidable thermal efficiency for heat transfer, heat recovery and other duties associated like pollution control with sulphuric acid production. Sulphuric acid involves highly aggressive operating environments. The process technology has a wide selection of corrosion-resistant plate materials and durable, highly resilient gaskets tailored to fit the most demanding sulphuric acid duties. With vast industry expertise, we have to select the right material to match the sulphuric acid process thereby ensuring reliable operation, heat recovery and uptime.

The substantial quantities of heat released by the large-scale production of sulphuric acid represent revenues to be harnessed. Many technology suppliers of the world have varied heat recovery technology options to maximise gain. Over the past few decades, energy recovery in sulphuric acid plants, like the contact process itself, has stabilized around a few key design features. Most companies require the recovery of as much process heat as possible to produce high pressure steam, which can be used to produce power or run other turbines in the plant. The development of low temperature economizers in the 1980s caused sulphuric acid plant energy efficiency to peak. With approximately 70% of available heat converted into high pressure steam, and with the remaining 30% lost to the atmosphere or to cooling water in the strong acid system, the industry seemed to have reached maximum energy efficiency. The different commonly available sulphuric acid plant designs have their own relative merits and drawbacks and the same are discussed in the paper.

Key Words: Sulphuric acid, process technology, sulphur combustion system, heat recovery systems

1. Preamble

Starting point for the production of sulphuric acid at the reference installation utilizing a double contact double absorption process is purified liquid sulphur. The liquid sulphur is delivered at 140 – 150 °C. The double contact process can be utilized when an autothermic operation is possible. Therefore, the SO_2 concentration has to be at least 4% in the reaction gases.

$S + O_2 = SO_2$ -296.9 kJ/mol (i)
$SO_2 + ½O_2 = SO_3$ -99.0 kJ/mol (ii)
$SO_3 + H_2O = H_2SO_4$ -132.5 kJ/mol (iii)

In the first step the sulphur is combusted in rotary burners with an excess of dry air (dried with sulphuric acid). The oxygen level is adjusted to the subsequent step to ensure a complete oxidation to SO_3. A waste heat boiler is used to reduce the gas temperature to 450 °C and to produce steam with 400 °C and 40 bars. The gas stream containing SO_2 from reaction (i) is subsequently fed into the catalytic converter without further purification.

In the second step, the gas containing sulphur dioxide reacts in the contact tower with excess oxygen to sulphur trioxide (ii). The contact tower consists of four catalyst layers; each with a size of approximately 20 m³ of V_2O_5 based catalyst. Since the conversion is an exothermic process, the gas temperature rises from approximately 400 – 450 °C to 600 – 650 °C. Heat exchangers between the catalyst layers reduce the gas temperature to approximately 400 – 450 °C.

With double contact processes, SO_3 is absorbed in an intermediate absorber installed after the second catalyst layer. Gases supplied to the intermediate absorber are cooled in counter current to the gases leaving the intermediate absorber, thereby SO_2 gases leaving the intermediate absorber being heated. The gases are conducted to the final catalyst layer for the conversion of the residual SO_2 to SO_3. The reaction product is absorbed in a final absorber resulting in sulphuric acid (iii) with a concentration of 96 – 98%.

With the intermediate absorber after the third catalyst layer, the reaction equilibrium can be shifted towards SO_3 by removing the product. Thus, higher rates can be achieved resulting in lower SO_2 emissions. The interpass absorber can be placed after the second or third catalyst bed **(Figure 1)**.

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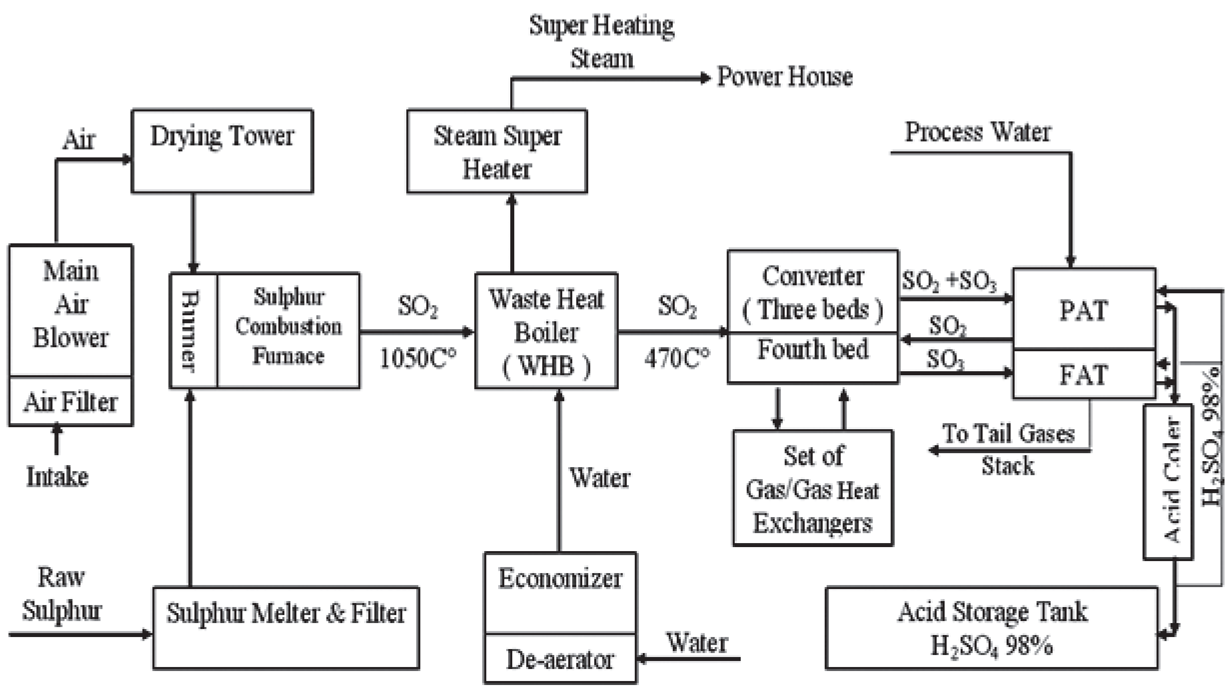

Figure 1. General sulphuric acid manufacturing diagram

2. Heat Generation

The most interesting use of the said energy is for generation of steam, either for process purposes or for electricity generation. Energy input into the system comes from the chemical energy of the sulphur and the electrical energy from the ID fans.

Superheated steam is produced to recover process heat:

- from the combustion gases after the incinerator
- in the boiler
- in the steam superheater
- after catalyst layers in a heat exchanger and
- an economizer

Some heat recovered in the third catalyst layer is used to reheat the reaction gas after the intermediate absorber in the intermediate heat exchanger.

The typical distribution of energy in a sulphuric acid plant as Sankey diagram is shown in **Figure 2** (*Sankey diagram* is a specific type of flow diagram in which the width of the arrows is shown proportionally to the flow quantity).

Heat generation in a 1000 MTPD DCDA plant is given in **Table 1**. Traditionally, about 60% of the initial energy is potentially recovered in form of HP-steam, while a large amount of the energy, - the remainder of almost 40%, is related to acid cooling and eventually dissipated to the environment, typically via evaporative cooling. In order to transfer a significant part of the said 40% portion to useful energy, the production of low pressure steam (LP-steam) is an attractive option. LP-steam can be used for numerous process applications in the chemical industry. e.g. concentration of weak phosphoric acid, crystallization of fertilizer or electricity generation. The latter is obviously most attractive, as electricity can be used as "by-product" of sulphuric acid manufacture at virtually every location.

Table 1. Heat generation in a 1,000 t/d 3+1 double absorption sulphur burning plant

Source	Equipment	Generated heat(MW)	Temperature level(°C)
1	Sulphur furnace	33.8	1125
2	Catalytic bed 1	6.9	625
3	Catalytic bed 2	2.9	530
4	Catalytic bed 3	1.1	460
5	Catalytic bed 4	0.6	433
6	Drying tower	1.7	85
7	Interpass absorption tower	14.8	110
8	Final absorption tower	4.3	90
Total heat generation		66.1	

Source: Clark Solutions

2.1 *Increase in Plant Efficiency with Low Level Heat Recovery*

Typical starting point for sulphuric acid plant absorber operation:

- Heat available ~1,900 MJ/tonne acid (~500,000 kcal/t)

- All transferred to cooling water (using additional energy)
- Typical acid temperature level range from 70 to 120 °C

Potential plant efficiency improvement through use of:

- Hot water preparation, e.g. P_2O_5-concentration
- Boiler feed water pre-heating
- Potable water production (multiple stage distillation of sea water)
- LP steam generation, requiring 160 ~220°C acid temperature at intermediate absorber
- HP steam production rate boosting – proprietary process

2.2 *Designing a Heat Recovery System to Observe Certain Criteria and Priorities, which cannot be Compromised*

1st Priority is safety: The sulphuric acid plant has to be designed so that operational issues are early detected and the plant can easily be brought into safe conditions; contributing factors are instrumentation, materials of construction, etc.

2nd Priority is sustainable acid production: It is mandatory, as this is basically the rational for the sulphuric acid plant. Ensure that acid production is operative, irrespective of the heat recovery system being in operation or not. Impact on the acid production capability of the plant through failure or shut-down of the heat recovery system cannot be tolerated!

3rd Priority is generation of low pressure steam: It significantly improves the economics of the acid plant operation (essentially replacing fuel), but must not introduce obstacles and risks which may be in the way to ensure the commitment to priority 1.

4th Priority is to maximize high pressure steam: The production enables the acid making process at all, but also provides the basic economics for the plant through generation of electricity.

One major issue of any heat recovery process for LP steam production is the need to operate part of the absorption section with concentrated sulphuric acid of very high temperatures, typically 200 to 220 °C. This is thermodynamically required when producing saturated LP steam of e.g. 10 bar. Concentrated acid at approximately 200 °C can be extremely corrosive unless a very strictly defined window of operation is adhered to with respect to acid concentration and temperature. A few suitable materials of construction have been identified (stainless steel materials), but all are characterized by said window of operation, different in size for different materials.

Up to approximately 67% of process waste heat can be converted to superheated steam. Approximately 30 – 40% of waste heat, which is released in the intermediate absorber (n), the final absorber (o) and

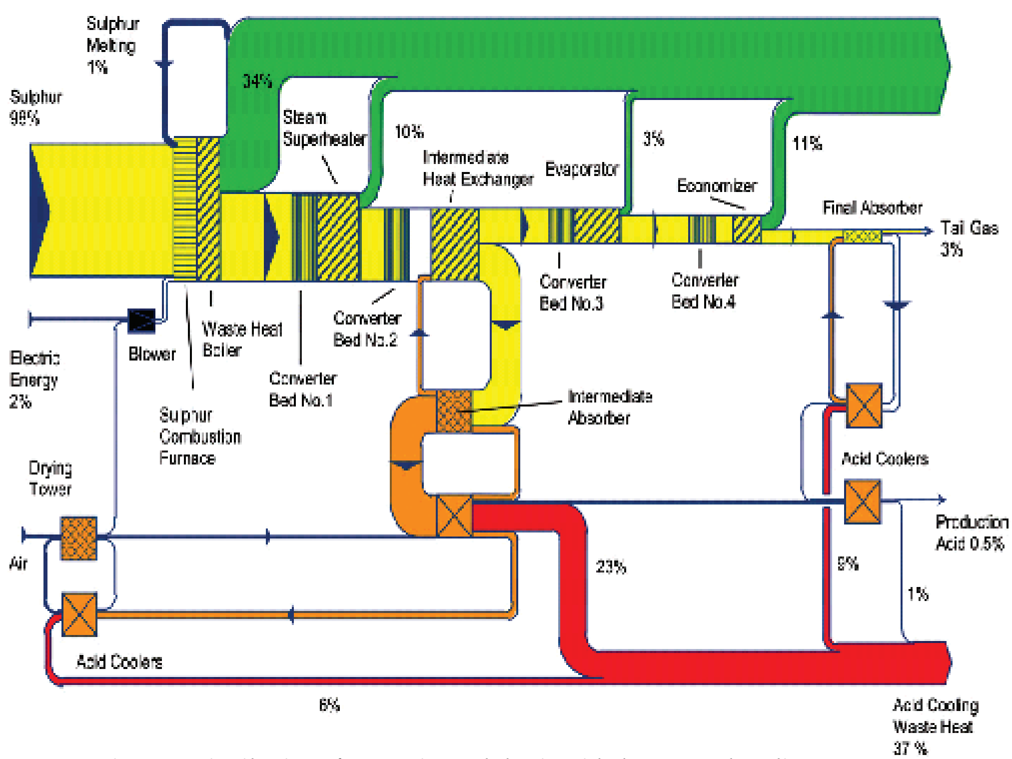

Figure 2. Distribution of energy in a sulphuric acid plant as Sankey diagram

the gas drying (m), is available at a temperature level between 85 and 120 °C. It is possible to use this energy; the rest is lost as thermal loss, in the waste gas and the product. By using the waste heat, a thermal efficiency of 85 – 90% is possible. In addition to the thermal need, energy is required for the gas transport and added by the electric ID fans. The energy needed for the ID fans, which is the greatest part of the plants electricity demand, ranges from 35 to 50 kWh/t H_2SO_4 – depending on the SO_2 concentration in the raw gas and increases with decreasing SO_2 concentrations. Distribution of energy in a sulphuric acid plant as per Sankey diagram is illustrated in **Figure 2**.

3. Advances in Sulphuric Acid Technology

♦ Improvements in the reaction heat recovery have been made possible through big advances in equipment configuration as well as materials technology.

♦ With the development of stainless steel spiral and plate heat exchangers, with lesser 'temperature approach', the old cast iron cascade coolers were replaced by stainless steel spiral and plate heat exchangers. This made it possible to raise the maximum temperatures in the acid circuits from 65 °C to 70 °C to 90 °C to 95 °C and recover the waste heat for low level heating duties, such as boiler feed water preheating within the plant.

♦ Later, the anodically protected shell-and-tube heat exchanger was able to withstand still higher temperatures (125 °C to 160 °C) and so the waste heat could now be used for raising low pressure steam.

♦ As a result of this progress, the energy efficiency of sulphuric acid plants has improved dramatically over recent years, from 1.1-1.2 kg high pressure steam per kg acid typical in the plants prior to 1970s to 1.3-1.4 kg per kg acid in 1980s.

♦ The development of MECS's Heat Recovery System (HRS) in the 1980s shifted the energy recovery paradigm of the sulphuric acid industry. HRS increased the thermal efficiency of an acid plant to greater than 90%, and the steam recovered in an HRS could be: (i) used to produce power; (ii) used as process heat within the site; or (iii) sold to an external customer. MECS commercialized nineteen HRS during the 1990.

♦ Outotec HEROS heat recovery system generates steam using waste heat from the acid cooling process. It is designed as a peripheral system that can be taken in and out of service without impacting plant operation. Acid-resistant brick lining and stainless steel ensure the maximum possible reliability and widest possible operational window. The system reduces cooling water consumption, and the steam can be used for heating purposes or for electricity production on site.

♦ Clark Solutions SAFEHR® is a patented sulfuric acid heat recovery technology that addresses issues such as safety and corrosion in an absolutely innovative way. SAFEHR® technology can increase high pressure steam generation in an acid plant by almost 20% and total energy recovery by as much as 35%. SAFEHR® is a registered trade mark of clark solutions.

♦ ChemeticsR offers the Chemetics Energy Solutions (CES) suite of process add-ons that allow for full utilization of all the energy released during sulphuric acid production. The Acid Low Pressure Heat Absorption (ALPHA™) system is used to produce valuable steam from the energy released during the absorption of SO_3 into the strong acid in the ALPHA™ tower. Steam is produced at pressures up to 10 bar allowing for a wide range of uses. The ALPHA™ System has been developed with two main focus areas: (i) Safety – Due to the high operating temperatures the operation of the ALPHA™ System must be tightly controlled to prevent excessive corrosion and possible operator exposure. (ii) Availability – The ALPHA™ system must not reduce the availability of the sulphuric acid production of the plant as the cost of lost production very quickly exceeds the value of the additional low pressure steam produced.

4. Monsanto Enviro-Chem's (MECS) Heat Recovery System (HRS), 1985

♦ MECS commercialized nineteen HRS during the 1990s, all but one of which is operating today. Low fertilizer, metal, and energy prices reduced demand for HRS in the early 2000s, but the technology has seen revitalization in the past few years due to high steam values and a long track record of HRS reliability around the world.

♦ *Heat Recovery System Design:* The HRS functions simultaneously as an interpass absorbing system and as a generator of intermediate pressure steam. The HRS, consisting of a high temperature absorbing tower, boiler, heater, and diluter, recovers heat evolved in the interpass tower circulating system in the form of intermediate pressure (typically 3 to 10 barg) steam. A steam injection vessel and preheater are provided as options for additional heat recovery.

Energy recovery in a sulphuric acid plant is shown in **Table 2**.

DuPont™ MECS® HRS™ system (Figure 3) uses the following principles to design for long equipment life and high on-stream time.

– Increase the acid temperature in the interpass circuit above the boiling point of 3-10 brag steam.

Table 2. Heat recovery comparisons for conventional *vs* with HRS system with/without steam injection

Steam generation as energy recovery	Conventional	Conventional plant with HRS	HRS w/o steam injection
HP Steam tonne/tonne	1.27	1.20	1.19
IP Steam tonne/tonne	0	0.40	0.48
Heat Recovered	70%	93%	94%
Net power kW/MTPD	10.6	14.6	14.8

– Control the acid concentration within an optimum window (for a comparison of the HRS operating window to the interpass system operating window).

– Match system components with materials of construction that exhibit low levels of corrosion in the operating window and during upset conditions.

5. Outotec Heat Recovery System (HEROS)

This is to improve energy efficiency with Outotec HEROS **(Figure 4).** This heat recovery system generates steam using waste heat from the acid cooling process. As a peripheral system, it can be taken in and out of service without impacting plant operation. Acid-resistant brick lining and stainless steel ensure reliability and the widest possible operational window. Cooling water consumption is also reduced and the steam can be used for heating purposes or for electricity production on site.

- Improves energy efficiency with steam production from waste heat
- Operates independently from acid plant, so shutdown does not affect plant availability
- Improves plant availability through digital monitoring system (Outotec PORS)
- Offers safe and reliable heat recovery
- Gives a wide operational window thanks to acid-resistant materials

5.1 *HRS and HEROS Basis*

- The basis of the HRS and HEROS technology was the high absorption efficiency at higher

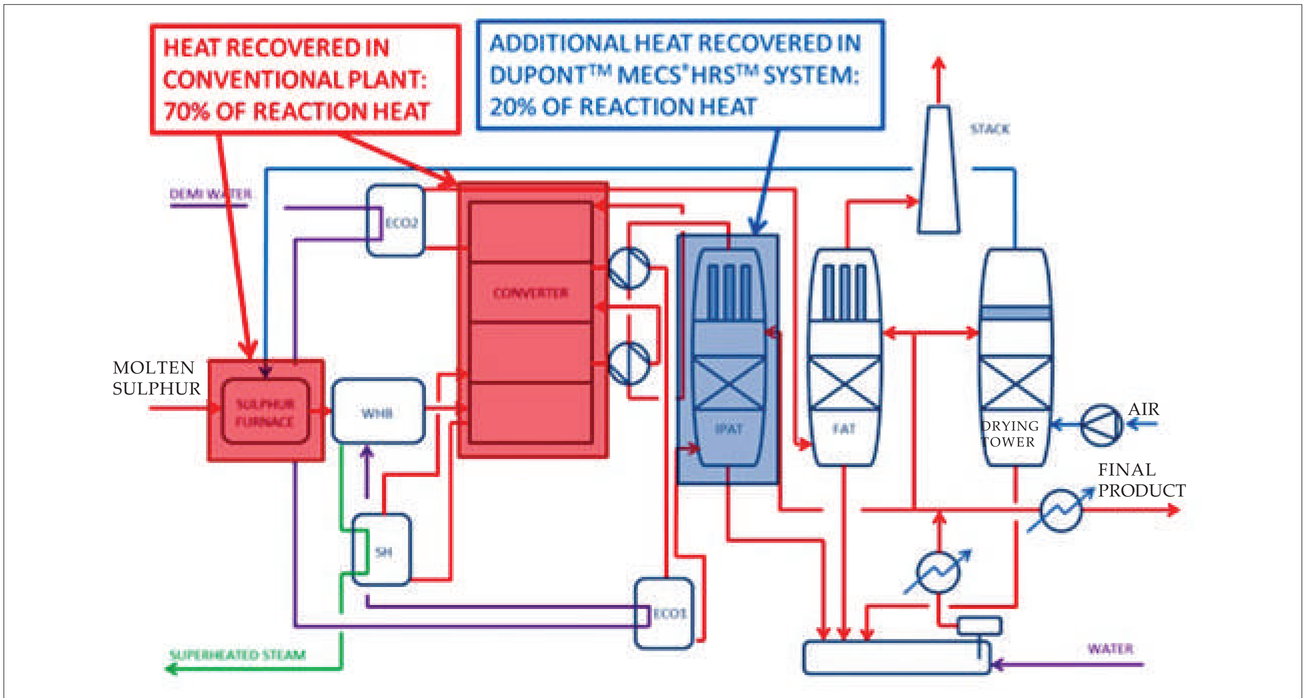

Figure 3. DuPont^{TM} MECS® HRS^{TM} system

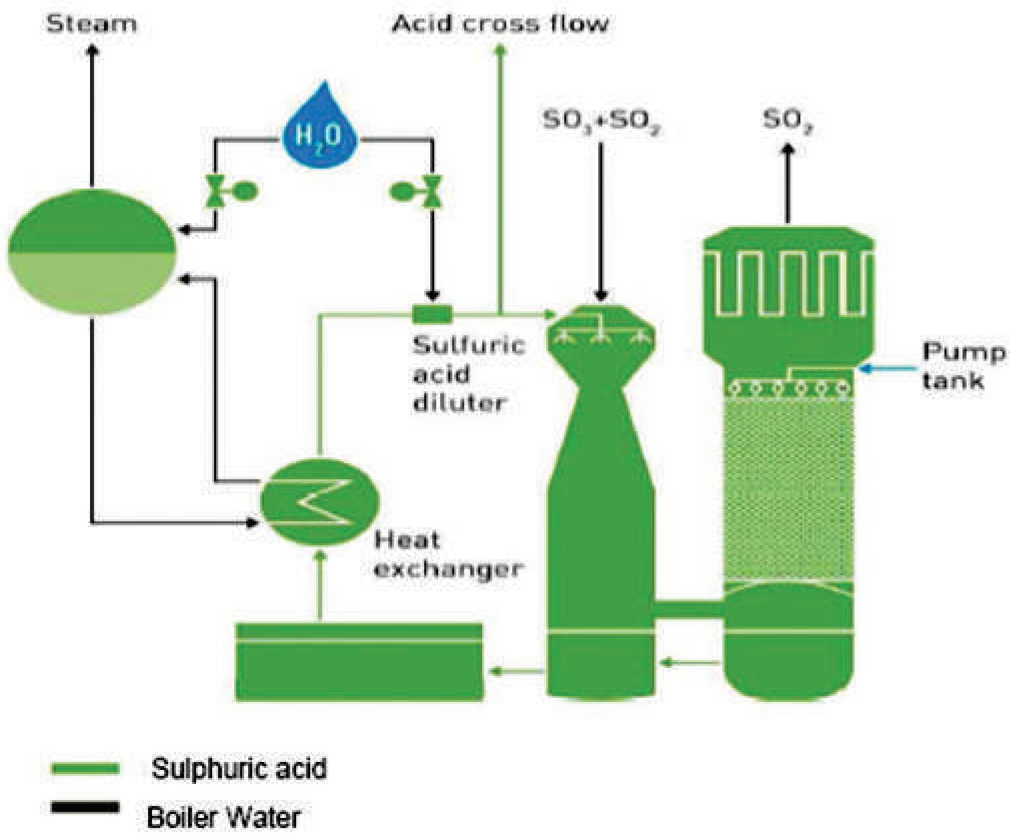

Figure 4. Outotec HEROS system

temperature and surprisingly low corrosion rates of improved commercial stainless steels at sulphuric acid concentrations above the normal operating concentration of 98 per cent H_2SO_4.

- Both systems generate saturated steam and additional low pressure steam of 0.5-0.6 tonne per tonne of H_2SO_4. The heat recovery system is basically an absorber that operates at 204 °C and uses a boiler to remove the absorption heat as steam (at up to 10 bar g), instead of acid coolers.
- In the HRS process, the concentration of acid leaving the absorption tower is rigorously maintained at 99-100 per cent. At this concentration, stainless steel equipment corrodes at an acceptably low rate, at operating temperatures of over 120 °C, which are high enough to generate medium pressure (10-bar) steam.

6. ClausMaster™ Regenerative Scrubbing Technology by MECS

- MECS has licensed its ClausMaster™ regenerative scrubbing technology **(Figure 5)** for many years, with over 10 references in a wide variety of applications. While the ClausMaster™ technology had successfully demonstrated its ability to remove SO_2 from gaseous waste streams, it did so with a few relatively critical drawbacks. In the late 2000s, MECS reviewed ClausMaster™'s most glaring limitations and set out to develop an improved solvent that would be readily available worldwide, would use lower cost materials of construction, and would be designed to operate in the "sweet spot" of tail gas emissions from a single absorption sulphuric acid plant. This effort began with an extensive search of physical property databases to identify families of solvents meeting MECS' rigid performance criteria. Next, a worldwide intellectual property review led to a determination that preliminary work would result in the development of a technology that was both free from infringement risk and also could be patented. Pilot plant tests verified the performance of the solvent, in both SO_2 removal efficiency and resistance to corrosion. MECS's upgraded regenerative technology was named MECS's SolvR® technology, first used at a sulphur burning plant in the United States in 2014, follows the same principles of unit operations as the ClausMaster™ process.

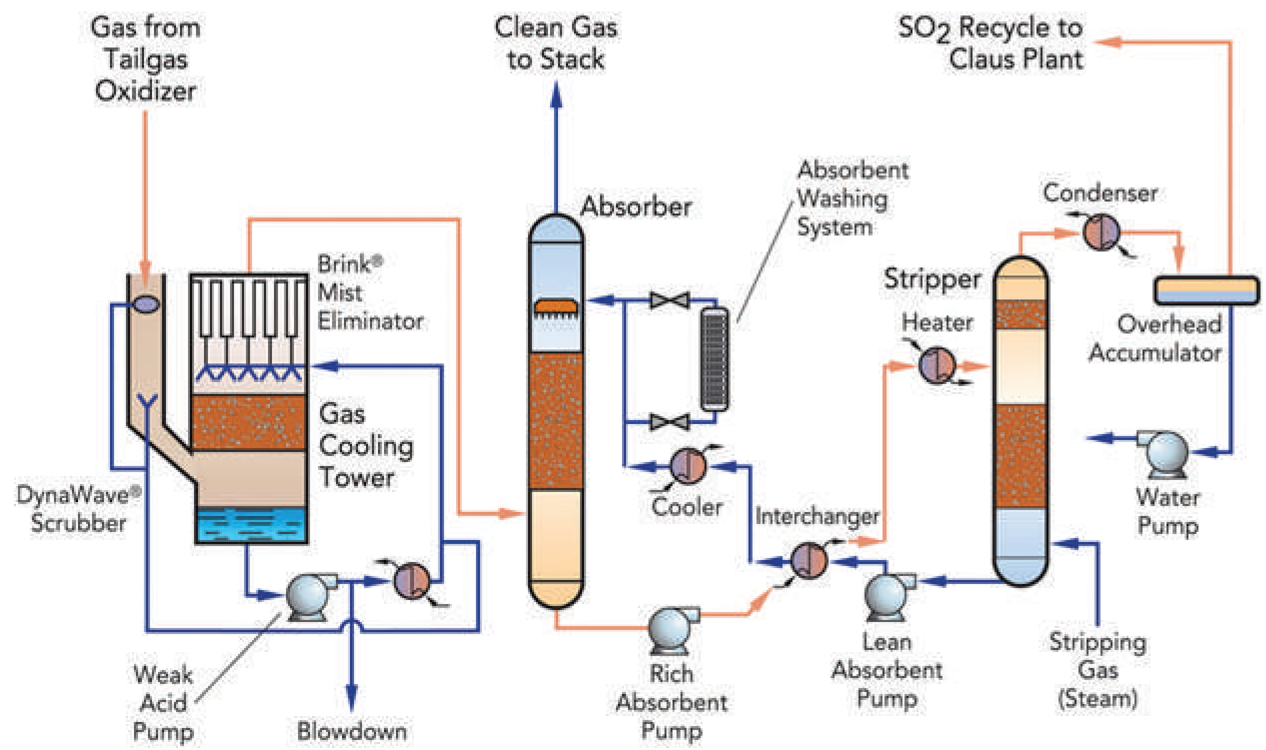

Figure 5. ClausMaster™ regenerative scrubbing technology

7. MECS® SteaMax HRS™ System

- MECS pioneered heat recovery systems in sulphuric acid plants and has accumulated over 25 years experience with their proprietary HRS™ technology. The newest breakthrough is the SteaMax HRS™ System. It provides for a significant increase in medium pressure steam, adding to the flexibility of the steam's use and customization for site specific energy requirements and other local conditions. When the unit cost for energy is high, and if the local requirements for steam are met, commercial opportunities for production of electricity can provide a revenue stream from the sale of the electrical energy. Sulphuric acid plants throughout the world can utilize and profit from the recovered heat and enhanced steam generation provided by the MECS SteaMax HRS™ System.

Features and Benefits

- Recover more heat, resulting in up to 30% more steam
- Green technology – when HRS™ steam is converted to electricity, it's "CO_2 free" power
- Upgrading low pressure steam to medium pressure steam provides more utility and flexibility
- Maintains the same high reliability that is associated with MECS HRS™
- Easier to control the SteaMax HRS™ System within optimum operating parameters
- Less water usage for lower plant operating costs.

8. MECS's SolvR®

MECS's SolvR® technology, first used at a sulphur burning plant in the United States in 2014, follows the same principles of unit operations as the ClausMaster™ process. As shown in **Figure 6**, tail gas from a sulphuric acid plant is adiabatically hydrated in a DynaWave® scrubber and flows into a counter current absorbing column, where SO_2 is absorbed into a circulating flow of solvent.

Clean gas exits the absorber at the top, and the rich solvent is pumped to a stripping tower which removes SO_2 by steam stripping. SO_2 is recycled to the front end of the sulphuric acid process, and lean solvent is pumped to the top of the absorbing tower. MECS also provides a solvent regeneration system to remove sulphates that will accumulate over time. Effluent from the SolvR® system is an aqueous sodium sulphate solution that can either be sent to battery limits or concentrated to produce higher grades of sodium salt. It should be noted that SolvR® is an upgrade over ClausMaster™ for several reasons. First, the SolvR®

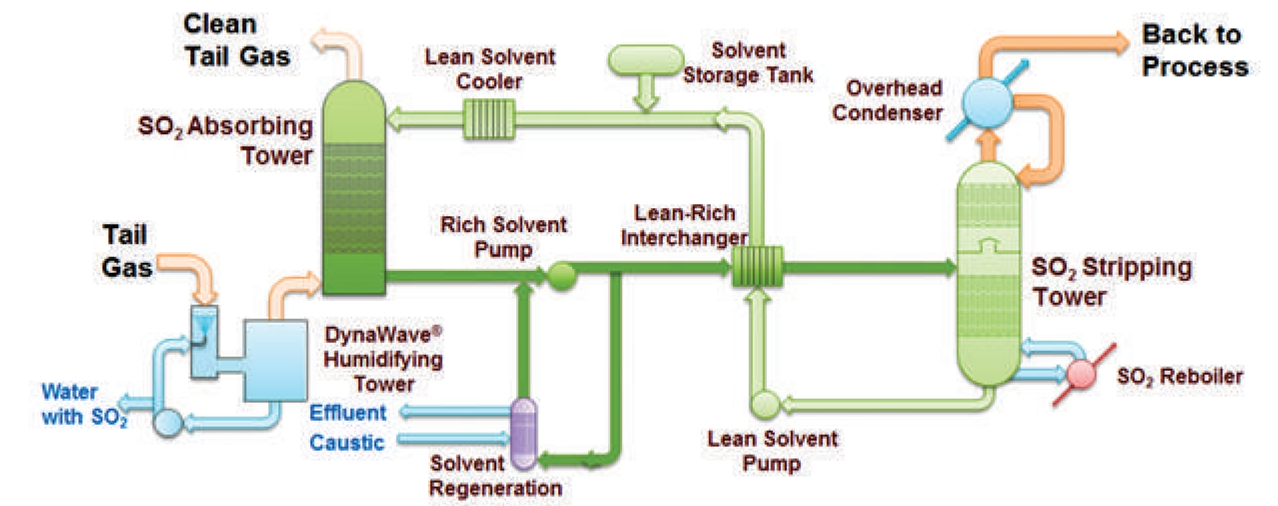

Figure 6. MECS's SolvR® technology

solvent does not require unique stainless steel materials, leading to a significant reduction in the cost of the system. Further, the SolvR® solvent is readily available and is much lower cost than other regenerative solvents used to remove SO_2. Finally, steam consumption is less than in the ClausMaster™ process. And while the SolvR®system is a net consumer of energy, steam injection – another MECS technology – can be used to closely integrate heat recovery between the SolvR® and the acid plant in a breakthrough way.

8.1 Steam Injection

Steam injection, a technology first commercialized by MECS more than fifteen years ago, offers an economically advantageous method for maintaining concentration control in the heat recovery acid system. A portion of the water required for concentration control is provided through the steam injection vessel, and the remainder is provided in the HRS diluter. Low pressure steam is injected into the process gas in a steam injection chamber upstream of the heat recovery tower. Since the overall enthalpy of the water fed to the HRS is higher when steam is used, the latent heat from condensation boosts generation of HRS steam compared to design without steam injection. Effectively, steam injection upgrades low pressure steam that would otherwise be vented to atmosphere.

About eight years ago, MECS introduced a step change improvement to steam injection called MECS's SolvR®

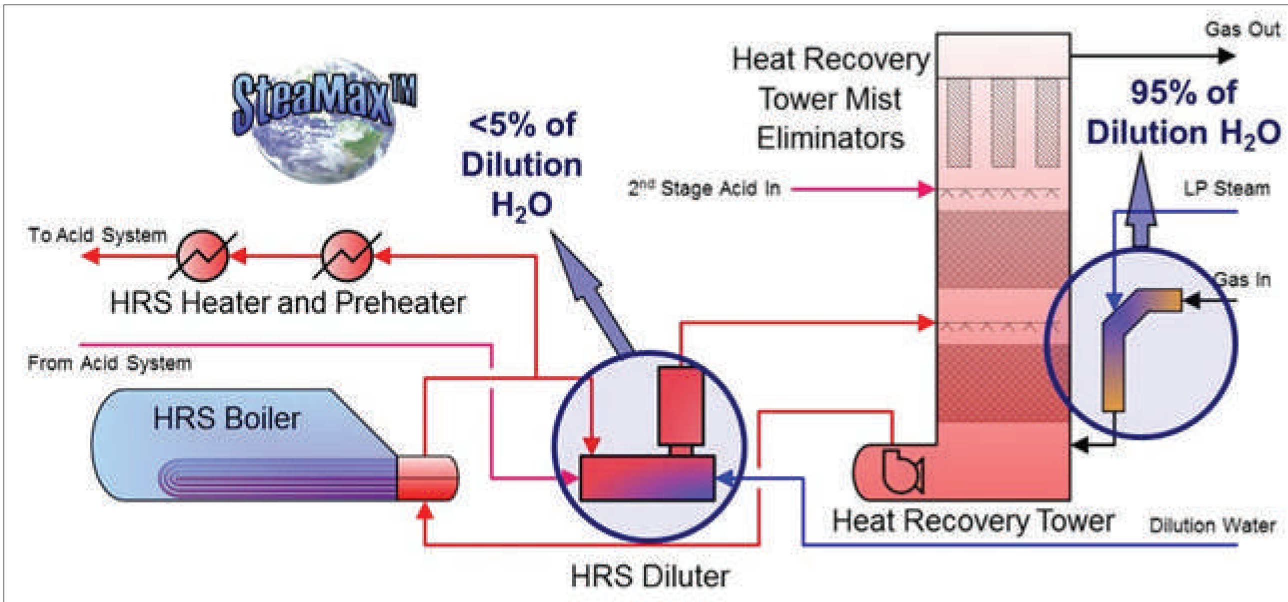

Figure 7. MECS improved steam injection - SteaMax™ HRS

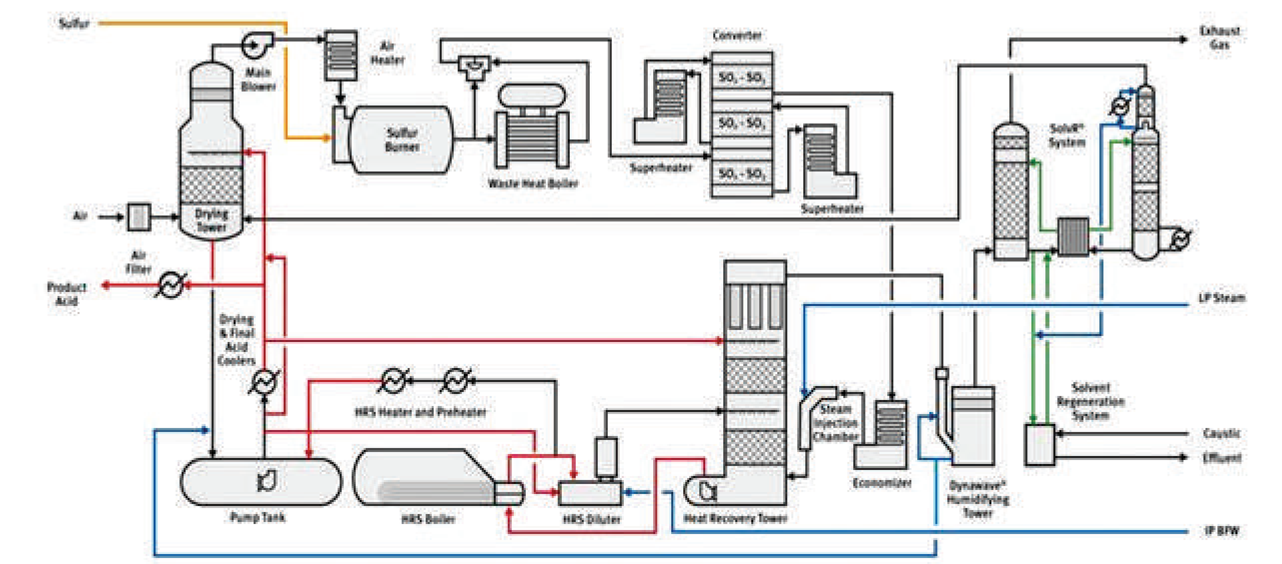

Figure 8. MECS® MAX3™ system

technology.

In SteaMax™ HRS design **(Figure 7),** MECS uses an even higher steam to liquid water ratio for dilution, approaching operation with little or no liquid water for dilution. This configuration multiplies the enthalpy effect of conventional steam injection, allowing most plants to realize gains in absorption heat recovery of 20-30% over a conventional HRS with steam injection. But the most important benefit of SteaMax™ was not realizable until the development of SolvR®. MAX 3™ was developed by combining these two technologies.

9. MAX3™ - Sulphuric Acid Technology

The proprietary **MECS® Max3™** sulphuric acid plant technology **(Figure 8)** simplifies the conventional sulphuric acid plant flow scheme by combining a single absorption HRS™) plant with MECS® SolvR® regenerative SO_2 scrubbing technology, thereby eliminating equipment, cutting costs and increasing efficiency. SolvR® regenerative SO_2 scrubbing technology utilizes the same principles as MECS®' proven ClausMaster™ technology , but with an improved solvent that reduces cost and increases efficiency. In this way, sulphuric acid plants not only save on water consumption, time and money, but can also recover more energy while achieving best-in-class emission levels.

MAX3™ Key Advantages

- High pressure steam ≥1.5 tonne steam / tonne of acid at 45 barg, 400 °C.
- Intermediate pressure steam ≈0.3 tonne steam / tonne acid at 10 barg saturated.
- Reduced SO_2 emissions to <20 ppmv.
- Reduced or maintained cooling water use equivalent to a double absorption HRS™ design.
- Reduced power use ~10% compared to a double absorption plant.
- Reduced caustic / chemical use by ~50% compared to a double absorption plant with a tail gas scrubber (or by 95% compared to a single absorption plant with a tail gas scrubber).
- Reduced or maintained overall capital cost compared to a double absorption HRS™ design with a tail gas scrubber to meet low SO_2 emissions.
- Reduced field construction time due to modular supply of the SolvR® system.

Why called MECS® MAX3™

- With decades of experience in designing sulphuric acid plants, MECS® has used its expertise to develop an integrated system for a single absorption plant with HRS™ and SolvR® that optimizes the three critical aspects of a sulphuric acid plant: (a) energy recovery, (b) emissions reduction, and (c) cost.

10. SAFEHR® Technology

- The concept behind SAFEHR® technology is the use of a family of proprietary inert fluids, CS fluids, to work as intermediate media between the hot acid and boiler feed water. The CS fluid products present a series of properties that make

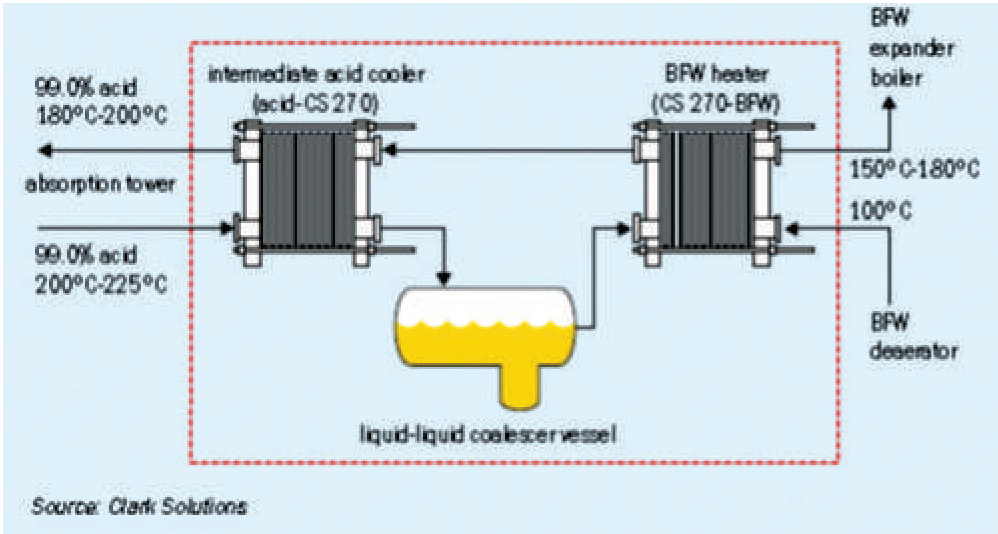

Figure 9. SAFEHR® closed loop for high temperatures

them unique for working as intermediate media in such systems.

- *Inert to Acid and Water:* The fluid is totally inert to acid (in any concentrations) and water.
- *Non-corrosive:* These can be used with virtually any materials without any corrosion risk, being compatible with strong acids, water, organics fluids among others.
- *Non-toxic:* The fluid is FDA approved and its handling and storage requires no special measures.
- *Non-flammable:* It will not catch fire, even if an ignition source is put in contact with hot fluid.
- *Non-oxidant:* Oxygen or atmospheric air will not oxidise the fluids, so they can be used and store in non-blanketed environments.
- *High boiling points:* boiling points will vary between 200 °C and 300 °C, depending on the fluid and application selected.
- *Density in-between Water and Acid:* Fluid densities at operating temperatures will be between 1.3 g/cm^3 and 1.5 g/cm^3, in between that of liquid water 0.88- 0.98 g/cm^3, and strong acid, 1.6 -1.8 g/cm^3, keeping the phases separated even in leakage situations.
- *Low Vapour Pressures:* Usually less than 20 mm WC which minimise losses by evaporation.
- *Odour:* Fluid is odourless and requires no mask or other respiratory devices while being handled.
- Basically the SAFEHR® system is a closed loop, where hot acid is cooled by the CS fluid, which in turn heats the boiler feed water.
- **Figure 9** shows the SAFEHR® closed loop for high temperature conditions. The CS fluid is a polymeric fluid, inert and immiscible to both water and sulphuric acid. The CS fluid system is maintained at a pressure below the acid and water systems so in the event of a leak, the leaking fluid follows into the CS fluid circuit, which will allow the leak to be identified. The interfacial tension and density differences between the fluids make a liquid coalescer an excellent storage tank. Acid will settle at the bottom of the coalescer and water will stay at its top, so, even in the improbable case that both fluids would leak, there would still be no contact between them. The coalescer/settling tank is designed to easily segregate the fluids. Conductivity and level control guarantee that a leak is quickly identified. **Figure 10** shows corrosion promoted by sulphuric acid with water contact (left) and CS 270 fluid contact (right).

11. Chemetics CORE-SO_2™ Process

Chemetics carried out a study of mega sulphuric acid plant (single train in excess of 10,000 MTPD).

Sulphur burning sulphuric acid plant has always used air as source of oxygen required for process. The conventional plant operates at approximately 12 % SO_2 into convertor balancing O_2:SO_2 ratio required for higher conversion and maximum allowable temperature in the first catalyst bed. The obvious disadvantage of using air is that each required oxygen molecule comes with approximately four molecules of inert gas (nitrogen/carbon dioxide and argon) which

(L) (R)

Figure 10. Corrosion promoted by water (L) *vs.* CS270 fluid(R) contact

come along through the whole plant till exhaust stack. However, use of pure oxygen warrants the following process issues could not be overcome.

i. Burning of with pure oxygen may result in extremely high furnace temperatures which exceed the limits of available refractory materials.
ii. Using pure oxygen should ideally be carried out at O_2 : SO_2 ratio close to 0.5 to minimize the oxygen cost. This results in SO_2 concentrations well above 60% which cannot be handled using vanadium catalyst in conventional adiabatic converter as exit gas from the first bed would exceed upper limit of catalyst.

Taking advantage of this CORE reactor as shown in **Figure 11,** Chemetics has developed a new process named as CORE-SO_2™ process by using pure oxygen. The process has following main features.

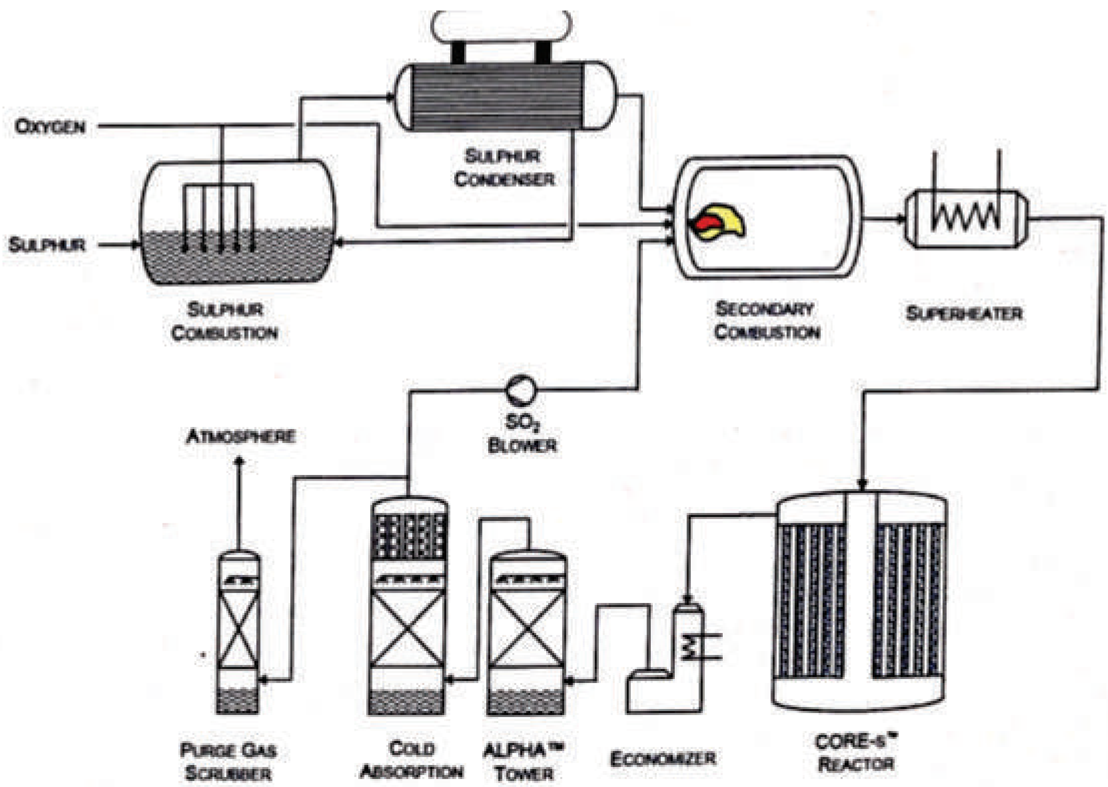

Figure 11. Chemetics CORE-SO_2™ process

i. Pure oxygen reduces the gas volume and hence equipment size by more than 70%.

ii. Main blower not required as oxygen is received under pressure saving power.

iii. Drying tower system eliminated as oxygen contains no moisture.

iv. Low temperature submerged combustion allowing all metal construction,

v. High SO_2 to SO_3 conversion in a single pass in the molten salt cooled CORE- SO_2^{TM} Process

vi. Single absorption system hence no reheat exchangers and secondary absorption system.

vii. Enhanced energy recovery produces more steam.

11.1 Sulphur Combustion System

The major problem of high temperature during combustion of sulphur in pure oxygen is solved by using submerged combustion system where pure oxygen is sparged into molten sulphur. Combustion energy is transferred to liquid sulphur allowing part of sulphur to evaporate thus maintain constant temperature of combustion system. The resulting process gas containing mixture of gaseous sulphur and SO_2 from sulphur combustion at approximately 460 ºC which is boiling point of sulphur at that operating pressure. These units have been designed by Comprimo Sulphur Solutions, a world leader in sulphur technology which is part of Worley Parson (Parent company of Chemetics).

11.2 SO_2 conversion system

The process gas containing all SO_2 and small amount of residual sulphur is then sent to secondary combustion. The at $O_2 : SO_2$ ratio of gas is maintained to 0.5 resulting gas in to 60% SO_2. This gas goes to CORE-S^{TM} system where approximately 70% of gas converts into SO_3.The molten salt coolant maintains the process gas below 630 ºC to prevent catalyst damage. A specially catalyst mixture with heat transfer capability is used to avoid hot spot. In the molten salt 90% of heat is transferred and its flow is designed to operate below 450 ºC therefore no special material is required in CORE-S system **(Figure 12)**. Cooling of molten salt is achieved by superheating steam from sulphur condenser.

After leaving CORE-S reactor, process gas is cooled in the economoser. The cooled gas is then directed to absorption system where the SO_3 is further converted into sulphuric acid.

11.3 Absorption System

The SO_3 formed in CORE reactor is absorbed in ALPHA^{TM} system to produce hot concentrated sulphuric acid and MP steam at 10 bar. This system is constructed from SARMET^{R} HT/HT^{+} alloy for long and reliable service life. Approximately 90% of SO_3 is absorbed in ALPHA tower which is higher than for conventional plant. The process gas leaving ALPHA tower is directly recycled to secondary combustion after mist removal without need to remove remaining SO_3. Water is added to ALPHA pump tank to maintain sulphuric acid concentration to normal 98%. A small purge system from absorption tower is as incoming oxygen is 99.5% pure and therefore inert gas is to be removed

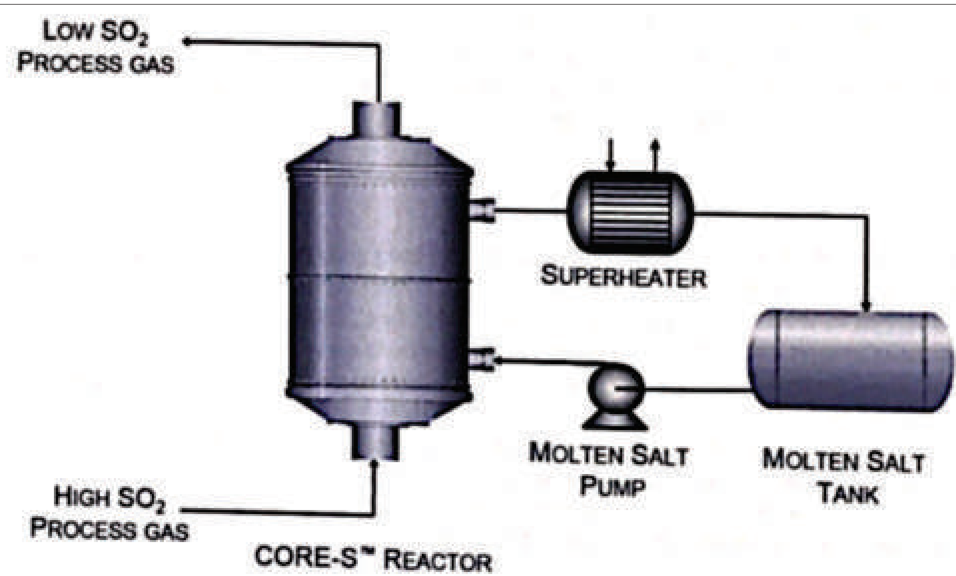

Figure 12. SO_2 conversion systems

Table 3. Comparison of CORE-SO2TM vs conventional sulphuric acid plant

		Conventional using ambient air	CORE-SO2TM using oxygen
Acid Plant			
Investment cost		100	30
Plot area		100	55
Maintenance cost	(@2.5% per year)	100	35
HP Steam production	(60 barg/500 °C)	100	107
MP steam production	(10 barg/200 °C)	100	110
Power consumption		100	17
Cooling water	(@10 °C △T)	100	20
Emissions	(at 100 ppmv in stack)	100	<2
Power production	(at power generator)	100	107
Power production	(after internal use)	100	124
Acid Plant + Oxygen Plant			
CAPEX		100	72
Operating & Maintenance cost		100	60
Power Production	(after internal use)	100	86
Cooling Water Consumption	(@ 10 °C △ T)	100	95
Amortized Annual CAPEX (15 yr @8%) + Annual O&M Cost		100	69
Annual income excluding suffer purchase & H_2SO_4 sales			
Without sale of Nitrogen/Argon		100	116
Including sale of Nitrogen/Argon		100	155
Return on investment (Annual income/invested capital)		100	216

from system. Several options exist for tail gas treatment, the simplest is to produce weak sulphuric acid and then used as dilution water in absorption unit. SO_2 emission can be achieved below 100 ppm.

11.4 Case Study: 10000 MTPD MEGA Sulphuric Acid Plant

The comparison was done on investment cost, steam production and utility consumption. It was further assumed that all steam produced was used to produce power. It was determined that all nitrogen produced by oxygen plant and 50% of argon could be sold into local market.

For investment costs, only sulphuric acid plant and oxygen plant were considered. Any investment required for sulphur melting and power generation were not included as these were deemed to be the same for both options. Capital cost was assessed on US gulf coast basis. Amortization of capital was based on 15 years @ 8% interest and sales value of electrical power, nitrogen and argon was set @ 89, 10 and 75 USD/MT respectively.

The comparison given in **Table 3** shows the results of the study. For each parameter, the performance of conventional sulphuric acid plant is taken as 100 and CORE-SO2TM performance relative to those numbers.

It is clear from results that investment cost in this process is less than to that of conventional air based plant.

The CORE-SO_2 process offers the following advantages over conventional sulphuric acid plant designs:

i. Smaller footprint with lower investment cost
ii. Simplified process with fewer rotating equipment
iii. Patented and proven technologies in a new process configuration.
iv. Virtually no emissions
v. Low OPEX
vi. High value byproducts from air separation unit can be sold.
vii. Increased operating income due to lower CAPEX and OPEX.

13. Conclusion

All steps in the production of sulphuric acid from elemental sulphur are exothermic. The liberated heat is dissipated under controlled conditions in such a way so as to maintain optimum gas temperatures in the convertor system, drying and acid absorbing systems, thereby, minimising SO_2 at the stack outlet. In the typical flow diagram of energy balance, it is observed that out of the total energy input, 97% is accounted for as energy released in the conversion of S to H_2SO_4 and 3% of energy is consumed in driving the gas through the plant. Upto about 60% of the available energy is normally utilised for generation of high-pressure steam and the remaining 40% is usually lost as waste heat. The waste heat system is completely integrated in DCDA plants. In economisers that cool the gases from third & fourth bed of converter, heat is utilised for preheating feed water for WHB system. Heat generated in Sulphur furnace, heats up this feed water and steam is generated at about 250 ºC temperature. This steam is superheated to about 400 ºC for cooling the first stage out converter gases. This superheated steam can be used for generating power and saturated steam for process heating.

Over the past few decades, energy recovery in sulphuric acid plants, like the contact process itself, has stabilized around a few key design features. Most companies require the recovery of as much process heat as possible to produce high pressure steam, which can be used to produce power or run other turbines in the plant. The development of low temperature economizers in the 1980s caused sulphuric acid plant energy efficiency to peak. With approximately 70% of available heat converted into high pressure steam, and with the remaining 30% lost to the atmosphere or to cooling water in the strong acid system, the industry seemed to have reached maximum energy efficiency.

The different commonly available sulphuric acid plant designs all have their own relative merits and drawbacks. The system can easily be retrofitted in existing sulphuric acid plants as it is designed to permit the shutdown of the revamped system while the intermediate absorption tower remains in full operation. Additional production of low-to-medium pressure steam is achievable, depending on the plant configuration. Thus, with the latest heat recovery technology system, a large percentage of the "low-level" heat generated in the absorption section of the acid plant is transferred into valuable steam while the cooling water consumption is reduced by the same degree. In case of a greenfield project, the system can be further optimized to produce the maximum amount of steam possible by incorporating latest waste heat recovery options now.

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Fertilizer Use Efficiency Research : Looking Back to Move Forward

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Abstract

The paper deals with a review of the fertilizer use efficiency (FUE) research to come up with a futuristic plan for boosting its current status. It begins by describing value and state of fertilizer use (includes N, P and K fertilizer nutrients) and its role in sustaining food security. Then it goes on to highlight that FUE pertains primarily to fertilizer N use efficiency (FNUE or NUE). Exclusive focus on FN is justified, since it tends to exit the soil plant system and get lost to pollute surface/underground water or become a cause of global warming. Currently, NUE hovers around 30%. Based on this information, the review traces the pathways of fertilizer N (FN) loss and assesses adoption status of the technologies already recommended to maximize NUE. Finally, the paper suggests a holistic FN management strategy, which aims to reduce FN use by maximizing use efficiency, supplementation by manures and biological N fixation and induction of precise agronomic methods. Holistic N management plan is designed to direct and innovate result-oriented pathways leading to farmer-centric, but a time-bound credible action plan on improving future FUE records.

Key words: Fertilizer use efficiency, fertilizer N use efficiency, pathways of N loss, holistic fertilizer N management

Introduction

Fertilizers: Fertilizers are synthetic chemicals. They supply plant nutrients, indispensable for plant growth. These are materials containing pre-defined quantity of single or more than one essential plant nutrient. Fertilizers are applied to build soil fertility, necessary for nurturing initial plant growth and later development. These can also be spread on the foliage as liquid sprays to cure any happening deficiency. Fertilizers are manufactured and marketed in the form of (IFA, 2013): solids (in granules or powder from), liquids (solution or suspension) or pressurized gas as liquids. These can be single nutrient carriers or straight fertilizers (urea), multi-nutrient combinations (di-ammonium phosphate), multi-nutrient mixtures of two or more fertilizers, also called bulk blends (containing N, P and K, *e.g.*, 12-32-16) or complex fertilizers in which two or more nutrients are combined chemically (nitro-phosphate).

Compared to 100-year history of fertilizers, composted or fresh residues of plant and animal origin, called organic manures, have been utilized to boost soil fertility since the dawn of agriculture - some 10,000 years ago. However, progressive shift from area-extensive to area-intensive agriculture, pushed natural sources to back seat. This happened because organic manures were lacking in amounts that could replenish mined fertility – an aftermath of nutrient removals by back to back cropping. Also, their limited and uncertain ability to readily supply nutrients when needed the most, relegated their position in soil fertility management. Nevertheless, it must be borne in mind, if not as nutrient source, organic manures stay on top of total soil health management – an imperative of sustainable intensification of agriculture itself.

Fertilizers: A Vital Element of Food Security: Based on the evidence generated thus far, fertilizers (include N, P, K fertilizers) have played key role in sustaining the tempo of food grain production. Since 1960 and up to 2016, global NPK use multiplied ~6 times (from 31.7 M tons to 185.8 M tons) and food production expanded 3 folds (from 0.8 B tons *versus* 2.2 B tons). Also, developed world in 1960 consumed 88% of the fertilizers; in 2016 that proportion was 45%. Corresponding figures for the developing world are 12% and 55%. Attracting growth in fertilizer consumption coincides with the wondrous rise in food production, leading many developing countries to become food self-sufficient. India is an outstanding example. Rise in fertilizer consumption has been a key factor turning India's famished state to that of a food-secure nation. Here, the fertilizer consumption multiplied ~90 times between 1960 and 2016 (0.29 M tons *vs* 26 M tons) and food grain production grew 340% (77 M tons in 1960-61 vs 276 M tons in 2016) (**Figure 1**). India is not only self-sufficient in food grains but has also become an exporting country since early 2000s. Needless it is to mention that contribution of and alliance with high yielding varieties, irrigation and standard agronomic practices was necessary in accomplishing this feat.

Quantitatively, intensification of fertilizer use is singled out, claiming at least 50% credit in marvellous growth of food grain production. A blog entitled,

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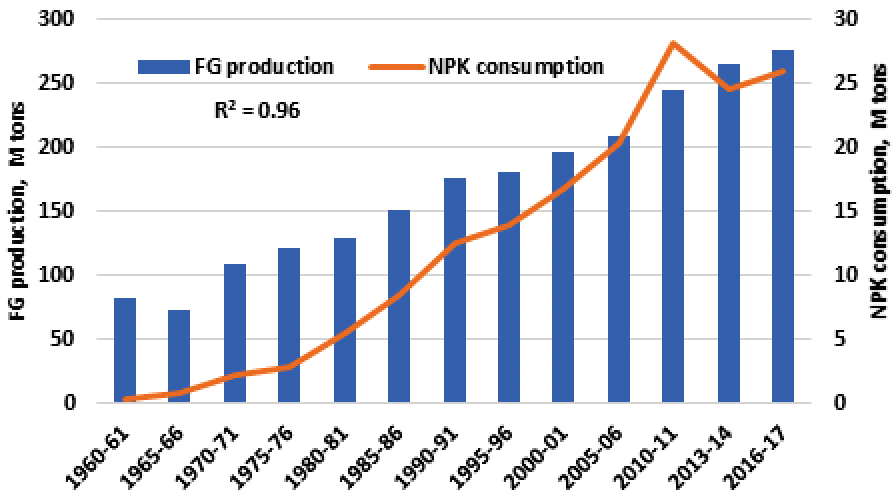

Figure 1. Food grain (FG) production *vis a vis* NPK consumption (Data source: GOI, 2017 and FAI, 2018)

"How many people does synthetic fertilizers feed?" (Ritchie, 2017), informs that in 2000, 44% of the global population was being fed by N fertilizers. This figure expanded to 48% in 2008 and rose to 52% in 2015 (**Table 1**). This means that in 2015, N-fertilizers (together with P and K) supported 3.5 billion people that otherwise would have died of starvation. The estimates presented in **Table 1** further indicate that nurturing food-security will continue to rely on growth in fertilizer use. since natural nutrient sources would be found wanting to meet the growing demand for essential nutrients. Observed Parliamentary Committee on Estimates (2015), 'against a requirement of 710 M tons of organic manures, only 105 M tons is available'. Even in China, whose reliance on exploiting natural sources is well-known, share of man-made fertilizers has progressively increased. In 1961, animal manure plus biological N fixation and synthetic N fertilizer, respectively accounted for 70.9% and 6.8% of the total N input; these values changed to 15.7% and 74.0% in 2012 (Yuan and Peng, 2017). In 2016, China and India with a consumption of 48 and 26 M tons of NPK fertilizers, respectively occupied 1st and 2nd position in the world (FAI, 2017-18). Focusing typically on India, where field wastage spurred by causal approach to fertilizer management is common, the tempo of fertilizer consumption is less likely to slow-down in future also.

Without exception, infertile soils and deficient crops need nutrient supplements for maximizing farm productivity. And sustainable growth of agriculture becomes an oxymoron without optimum management of soil fertility. Accumulated over the years, wide-spread incidence of multi-nutrient deficiency constraints, India is faced with an uphill task of sustaining necessary productivity growth, since possibility of lifting production by expanding crop area has already been exhausted. Additionally, population-driven surging demand for food - ~3 M tons/year, remains unrelenting. According to one revelation, only 3% of world soils are fertile and India is no exception to that. While organic manures are vital, their paucity, at the best qualifies them playing a complimentary role and not good enough to replace fertilizers. Smil (1999) found that animal manures have capacity to provide only 11% of the total N required for global food production. In view of the monumental deficit in fulfilling the demands of high intensity farming (Parliamentary Committee on Estimates, 2015), arable cropped area must rely on fertilizer treatment for building soil fertility – a fundamental requirement mitigating threat to food security, raising farmers' income and preserving environmental safety.

Table 1. World population (billion) supported with and without fertilizer use (Ritchie, 2017)

Element	2000	2008	2015
Population	6.15	6.79	7.38
No of people supported by synthetic fertilizers	3.44	3.53	3.54
No of people likely to starve without synthetic fertilizers	2.71	3.26	3.84
% people likely to starve without fertilizers	44	48	52

Even rain-fed crops need fertilizer care, since dryland soils are nutrient-hungry like these are water-thirsty. Furthermore, dependence on fertilizer use is projected to grow in future for sustainable intensification of production per unit of cultivated area. India without expanding the use of fertilizers would require at least 160% more arable area for remaining food self-sufficient.

***Sustainable Fertilizer Use Necessitates Efficient Management*:** Fertilizers are expensive. Majority of the resource-poor 500 million (M) small and marginal (S&M) farmers world-wide (~120 M in India) find it difficult to make investment for their optimum use. S&M farmers in India spend ~30% of the output value on input costs (NSSO, 2014). In order to inspire fertilizer use, governments across the globe provide subsidy on market price of fertilizers. However, this well-intended pecuniary support at times is at odds with the balanced use of nutrients - so important for deriving maximum returns from fertilizer use. For instance, in India the extant nutrient based subsidy (NBS) scheme promotes over-use of fertilizer-N. Relatively cheap N, in turn, offsets the recommended use of P and K (and other nutrients) fertilizers, causing diminishing returns and growing damage to soil health and ecological equilibrium. Besides, farmers' illiteracy and weakening technology transfer apparatus constrain application of right and soil-test based balanced fertilizer treatment. These imperfections, in turn, limit nutrient use efficiency by weakening potential economic response to less than 50%; damage to soil, water and air quality is beyond costing. Often alleged harmful consequences of fertilizers to land eco-system are, thus, *not because of fertilizer use but because of misuse* (overuse, imbalanced use and exclusive use). Results of long-term fertilizers are witness to that. It, therefore, binds research and development agencies to educate farmers in managing fertilizer treatment smartly to minimize income loss and no harm to quality of natural resources (soil, water, biodiversity and air). Maximizing effectivity of fertilizer treatment is the way forward to achieve these objectives. In pursuance of that goal, economic output must multiply with less use of fertilizers, but without causing drain to the environmental services. Said differently, the use efficiency of added fertilizer nutrients must rise substantially beyond the existing figure of < 50%.

The subject of fertilizer use efficiency (FUE) is not new. Available information confirms that research on FUE in India coincided with the spurt in fertilizer consumption, beginning Green Revolution era - some 50 years back. First research paper on N balance and use efficiency (to this author's knowledge), involving N^{15} (heavy isotope of common nitrogen or N^{14}) labelled FN and lowland rice, was published in 1971. Findings exhibited that the use efficiency of fertilizer N could be as low as 38% (Datta et al., 1971). Despite heavy investments in FUE research, since then sordid state of FUE numbers has been haunting research and development machinery to offer impact creating technologies. This report reviews the past information to design, direct and innovate result-oriented pathways leading to practicable, but a time-bound credible action plan on improving future FUE records. Subject of FUE, a forgotten object of fertilizer research, has once again gained prominence. Revival of interest is largely driven by association of FUE with deteriorating land quality, dwindling farm income and rising global warming. Share of agriculture (excluding land use shifts and livestock) to global warming is ~7%; of which one- third is due to poor handling of fertilizers.

Synonymity of Fertilizer Use Efficiency (FUE) and Fertilizer-N Use Efficiency (FNUE)

Data on FUE are summarized in **Table 2**. Particularly, nutrient loss figures (column 3) give an impression that following treatment, NPK vanish from plant's use point. Analysed from transformations which fertilizers undergo in soil, the answer is both 'yes' and 'no'. In the first place, loss begins with the kind of breakdown products of fertilizer compounds into simple radicals. Secondly, proportion and residence time of resultant entity decides utilization by crop or loss from soil. The change is either bio-centric (aided by soil microbes, example: fertilizer-N) or physico-chemical (assisted by physical and chemical processes going on in the soil (example fertilizer-K/P). Typically, fertilizer-K on conversion gets adsorbed on negatively charged soil particles or enters the clay structure and gets fixed. Whereas, P changes to sparingly soluble forms depending on the soil pH. Either way, in response to this metamorphosis, K and P fertilizers become temporarily locked up and rendered unavailable to crop receiving application. The loss data shown on P and K is, thus, like a fixed deposit, which is progressively drawn by the subsequent crops in rotation. From that angle, use efficiency (UE) of K and P fertilizers is not dented and is nearly 100%. However, a sporadic distortion is believed to happen with P use efficiency, if transformation products get transported by runoff. Compared to P and K, fertilizer-N mutates in ways that the products of breakdown (ammonium, ammonia, nitrate, nitric oxide, nitrous oxide, N_2 gas) largely exit the soil plant system, stamping thereby permanent unavailability to crop receiving application or even that follows. Conclusively, reference to FUE means fertilizer-N (FN) use efficiency (FNUE) or simply nitrogen use efficiency (NUE). Since FNUE/NUE has hardly shown any credible improvement, this subject, even today,

Table 2. Fertilizer nutrient use efficiency and loss (%)

Fertilizer nutrient	Nutrient use efficiency (%)	Nutrient Loss (%)
N	30-60	40-70
P	20-30	70-80
K	5-60	40-50

Source : Several data sources

Table 3. Comparison of NUE (%) estimates for world and countries consuming maximum amount of FN

Reference	China	India	US and Canada	World
Lassaletta et al. (2010) (Data pertain to 2009)	28	32	70	47
Zhang et al. (2015) (data pertain to 2010)	25	30	68	42
Omara et al. (2019) (data pertain to 2015)	30	21	41	35

remains the centre of research and development agenda. This report begins by defining the term FNUE/ NUE covering views of diverse stakeholders. Then it goes on to delineate pathways of FN escape from soil plant system and ends by suggesting means and site-specific management practices plugging the exit routes.

FNUE/NUE – Definition

FUE has been variously described. It is computed using a wide range of methods. In simple terms, translation of a fertilizer nutrient absorbed by the crop into yield increase describes the efficiency of investment on fertilizers. If applied fertilizer nutrient utilized by the crop produces bigger response, it indicates a superior state of use efficiency - more output per unit of fertilizer nutrient input. With reference to N, when contribution of fertilizer-N (FN) to crop growth and yield is singled out, then it is called 'fertilizer N use efficiency' (FNUE). Contrarily, while constructing 'nitrogen use efficiency' (NUE), contribution of soil N pool (biologically fixed N + organic manures + aerial deposition) and FN to growth and yield is added together. Mathematically, NUE and FNUE are represented and calculated as follows:

- NUE – fraction of total N output (N in harvested product, grain + straw) to that of input (FN + soil N pool). NUE is dimensionless ratio of the sum of all N removed in harvested crop products divided by the sum of all N inputs to a cropland (Zhang et al., 2015). This index of NUE is also expressed in per cent (NUE index X 100) and is calculated as follows:

  NUE = Total N in harvested crop/total N input (FN + soil N pool).
- *Agronomic efficiency (AE)* – if yield gain arising from FN is measured; expressed as kg grain or any other economic produce per kg of fertilizer N. It is termed response to FN also. Calculated as: (kg grain yield of fertilized plot – kg grain yield of unfertilized plot)/ kg FN applied
- *FNUE/FN recovery efficiency (FNRE)* – if proportion of applied FN absorbed by the crop of that applied is worked out; expressed as % N absorbed by crop biomass as % of FN applied. In the studies on FN recovery efficiency, ^{15}N tagged fertilizers are employed. When normal FN (^{14}N) is used to calculate recovery efficiency, then it is called 'Apparent FN recovery efficiency' (AFNRE) and is calculated as follows: (N uptake by fertilized crop - N uptake by unfertilized crop)/FN applied.
- *Production efficiency or Physiological efficiency* – if value of FN recovery translated into agronomic efficiency is measured; kg yield gain/kg fertilizer N absorbed by the crop and is calculated by dividing AE with AFNRE.

***NUE**:* Data on NUE (pertaining to 2010) show that N input is utilized less efficiently in China (25-28%) and India (30-32%) than that in the world (42-47%) (**Table 3**). NUE in China (compared to world) is propelled by relatively higher allocation of FN to fruits and vegetables (30% in China *versus* 9% in the world). These crops are known to utilize N input least efficiently (~15%) (Zhang et al., 2015). As far India is concerned, the inferior NUE, though common across all field crops, is aggravated by dominance of lowland rice. This crop shares ~35% of the total FN consumption with use efficiency seldom exceeding 30%. More disturbing is the fact that instead of improving, NUE exhibited a declining trend with time. For instance, with reference to India, a drop has been reported from 32% in 2010 (Lassaletta et al., 2014) to 21% in 2019 (Omara et al., 2019). The explanation seems to coincide with the implementation of Nutrient Based Subsidy (NBS) Policy beginning 2010. NBS promoted preferential subsidy support to urea N, which made its market price 3 to 5 times less expensive than P and K fertilizers. Availability of relatively cheaper urea attracted farmers towards its over-use and misuse. Introduction of NBS seems to have spurred striking fall in NUE from 32% in 2010 to 21% in 2019. It may just not be a coincidence, since cheaper urea N invited its preferential use, creating thereby circumstances leading to imbalanced application of NPK. Distortion in near ideal consumption ratio of 4.2:2:1 of 2009-10 to current use ratio of 6.6:2.8:1 is the witness to that situation. This shift apparently was largely responsible for estimated plunge of 10% points in NUE. Emerging picture is also a reflection on continuing waste of potential productivity growth, financial resources and a cause of serious concern on pollution of soil, air, and water with ammonia, nitrates, and nitrous oxide. More worrisome is the fact that over the years, despite technological advancements, globally NUE has fallen from 68% in 1961 (Lassaletta, et al., 2014) to 35% in 2019 (Omara et al., 2019). During the same period FN use increased from 99 M tons (2010) to 105 M tons (2016) (FAI, 2017-18). There seems a negative influence of rising N application in regions where farmers are already applying more N than crop needs. Rice in NW India (Punjab) is typical example, where application rates (> 200 kg N/ha) exceed crop requirements, resulting in poor NUE. Statistics on N consumption from India (**Figure 2**) confirm this negative relationship. This misalliance makes it incumbent for research and development (R&D)

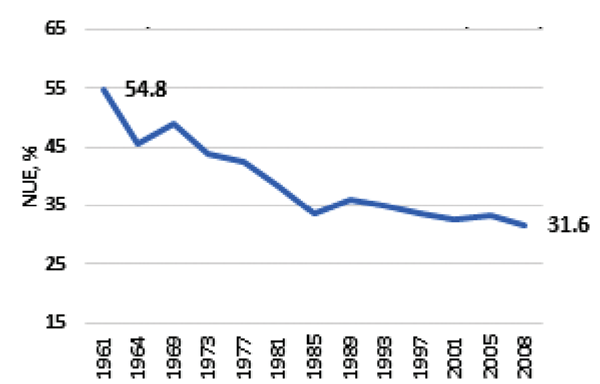

Figure 2. Time series data on NUE (%) - India (Data source: Lassaletta et al., 2014)

institutions to suggest practicable action plan on resurgence of NUE by maximizing plant uptake and its translation into productivity. Besides rationalizing N application rates as per soil test-based crop needs, adoption of standard agronomic practices including precise management of that applied is a prerequisite for minimizing waste – a step necessary for exploiting full potential of FN treatment.

FNUE/FNRE: Based on the available information on N budgets constructed across diverse farming situations, Finck (1992) and Katyal (1993 and 2016) estimated that the crop receiving FN treatment, on an average, absorbs between 30% and 70% (mean ~50%) of that applied. Remainder either joins the soil N pool (~20%) or is lost (range 10% to 50%) beyond roots' uptake range. Even the segment of FN left in the soil has hardly any measurable impact on the following crop (Katyal, 1993). Rather its accumulation poses problem for surface and groundwater pollution. In general, irrigated/rainfed upland crops (wheat, maize, sorghum) lose less proportion of FN (range 10% to 30%) than lowland rice (range 30%-50%) (**Table 4**). Also, under the well-managed conditions of research farms, compared to farmers' fields, typically those in developing countries, more FN is utilized and less is lost (Cassman et al., 2002) (**Table 5**). Also, cultivators who adopt holistic fertilizer management practices obtain higher FN recovery/agronomic efficiency than those who adhere to routine management methods. Higher FN utilization causes positive impact on productivity and vice versa. On the other hand, FN loss downgrades economic benefit arising from its use. More importantly, it adversely influences quality of soil, water, biodiversity and environment (details in a subsequent section)

Agronomic efficiency (AE): AE is a simple means to describe NUE. It is equated with partial factor productive efficiency of fertilizers. AE measures crop yield per unit of FN applied at an economically optimal rate. Expressed as kg grain yield per kg of FN, AE is the most relevant index from farmers' point of view, who are concerned primarily with the profit they get from the investment on fertilizers. Based on a wide range of experiments spread over diverse agro-eco regions of the world, the FAO in 1984 considered that "it is reasonable to assume that 1 kg of fertilizer ($N+P_2O_5+K_2O$) produces around 10 kg of cereal grains" (FAO, 1984). Indian data (**Figure 4**) demonstrated that each kg of NPK produced ~12 kg additional yield in 1970s. With the passage of time, however, the response to fertilizers declined. Between 2010 and 2017, the average value was reduced to 5 kg grain/kg of NPK. Falling response ratio signals drop in partial factor

Table 4. Findings of FN recovery efficiency (% ^{15}N) – Indian experience (Source: Katyal, 2016)

Source	Soil	^{15}N recovery	^{15}N loss	Reference
Lowland Rice				
Ammonium sulfate	Inceptisol	28	35	Khind and Datta (1975)
Ammonium sulfate	Inceptisol	28	46	Katyal et al. (1985)
Nitro-phosphate	Inceptisol/	38-60	30-50	Datta et al. (1971)
Urea	Inceptisol	20	55	Khind and Datta (1975)
Urea	Vertisol	22	68	Shinde et al. (1985)
Urea	Inceptisol	23	48	Katyal et al. (1985)
Urea	Inceptisol	31	39	Goswami et al. (1988)
Urea super granules	Inceptisol	9	76	Katyal et al. (1984)
Sulphur coated urea	Inceptisol	42	28	Bijay-Singh and Katyal (1987)
Irrigated Wheat				
Urea	Vertisol	24	60	Shinde et al. (1985)
Urea	Inceptisol	35	30	Katyal et al. (1987)
Potassium nitrate	Inceptisol	65	5	Katyal et al. (1987)
Rainfed sorghum				
Urea	Vertisol	55	6	Morghan et al. (1984a)
Urea	Alfisol (deep)	64	8	Morghan et al. (1984b)
Urea	Vertisol	56	7	Hong et al. (1992)
Urea	Vertic Ustochrept	41	29	Hong et al. (1992)
Urea (basal)	Alfisol (shallow to medium deep)	22 (only grain)	-	Abu Gyamfi et al. (1996)
Urea (top dress)	Alfisol (shallow to medium deep)	32 (only grain)	-	Abu Gyamfi et al. (1996)

Table 5. FN recovery efficiency by maize, rice, and wheat crops based on data obtained from on-farm measurements (Cassman et al., 2002)

Crop	Region	No. of farms	FN rate (kg N/ha)	N recovery efficiency (%)
Maize	North-Central USA	57	103	37
Rice	Asia farmers	179	117	31
Rice	Asia researchers	179	112	40
Wheat	India, poor weather	23	145	18
Wheat	India, good weather	21	123	49

productivity of fertilizer use leading to decline in productivity growth and rise in cost of cultivation. Deteriorating trends in AE as the time went by are in sync with the drop in NUE (**Figure 3**). Coincidentally, collapsing AE and NUE, as narrated earlier, signal growing wastage of fertilizer input, amplifying ecological damage manifested as decline in quality of soil, water, biodiversity and air. Post-application information on budgeting (**Table 4**) presents a very dismal picture on proportion used by the crop and that exiting the soil plant system.

FN Loss and its Consequences

Currently, respective world production and consumption of FN stands at ~ 123 and ~105 M tons. China and India together appropriate 41% of that produced or consumed globally. FN is utilized in several forms. Of these, urea dominates FN consumption scene - ~57% of the total N consumed (www.fertilizer.org). In India, its proportional use exceeds 80%. Cereals account for 55% of the total N consumed in the world (Heffer, 2013). Huge diversity,

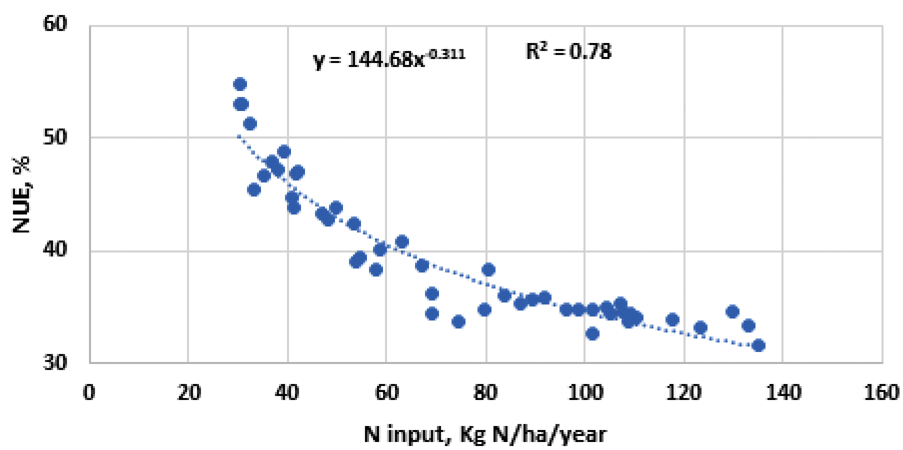

Figure 3. Relationship between NUE and N input - India (Data source: Lassaletta et al., 2014)

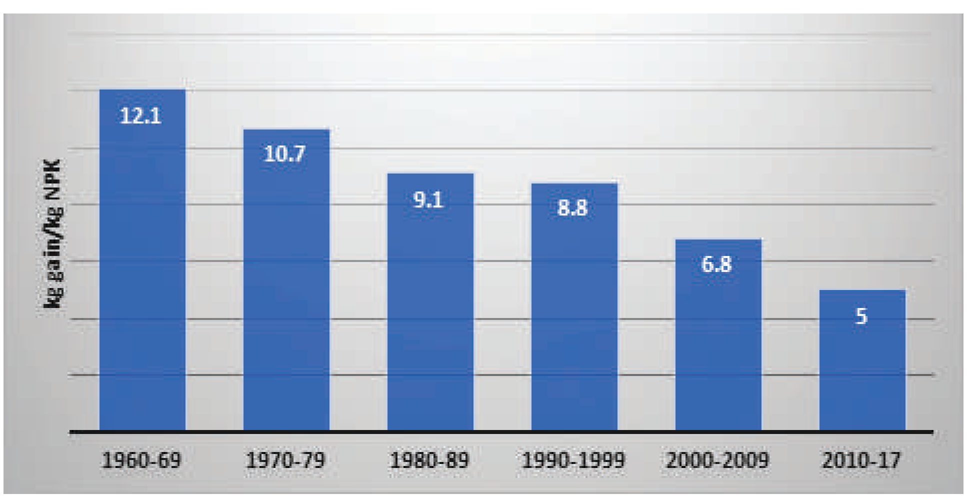

Figure 4. Trends in response to NPK (kg grain/kg NPK). Author's calculations with data from FAI Fertilizer Statsitics)

however, exists when it comes to crop-wise allocation of FN across countries. For instance: maize in US 50%, fruits and vegetables in China >30%, rice and wheat in India 64% (Heffer and Prude'homme, 2016; Katyal, 2016) appropriate total FN use. The stats on trends in FN consumption have significant influence on direction of FNUE research. No wonder, dominating urea remains the focus of research involving cereals like maize, rice, wheat and sorghum.

Once in soil, microbial transformations promote rise of FN forms that guide it to become: (i) associated with the soil-organic matter pool (immobilization), (ii) vulnerable to displacement from the point of application (runoff), (iii) liable to move away from the rooting zone (leaching), and (iv) exiting the soil-plant system as vapours (ammonia, NH_3 volatilization) or gases (mainly nitrous oxide, N_2O).

Review of findings to date from a wide range of studies has established that NUE (proportion of fertilizer-N recovered by the crop and translated into yield) seldom exceeds 50%. Even immobilized FN (~20%) retained in the soil, hardly inspires any useful influence on productivity of crops in rotation (Katyal, 1993). This happens because breakdown products of soil organic matter (mineralization) are subjected to same processes that cause displacement to the point beyond the reach of plant roots. Nevertheless, mineralization remains important, since it serves as native N supply chain for plant growth.

Globally, therefore, no more than 50% of the FN is translated into outcome for which it is intended - productivity gain. Unutilized residual FN is exposed to loss by NH_3 volatilization, de-nitrification, leaching and runoff.

***Ammonia Volatilization*:** Ammonia (NH_3) is the first product of urea-N breakdown, changing quickly – within 2 days, to ammonium (NH_4^+) ions. Ambient state of soil decides further transformations of NH_4^+ ions. Under poorly drained waterlogged anaerobic conditions, as is common with the submerged rice soils, NH_4^+-N continues to dominate. However, on mingling and mixing with flood water, it becomes unstable. There, day-time algal photosynthetic activity drives pH of floodwater towards alkalinity, making NH_4^+-N to change to NH_3 and exit as vapours. This process is termed '**NH_3 volatilization**'. In comparison, if breakdown of FN takes place under aerobic upland soil environment, NH_4^+ ions follow another transformation route. There NH_4^+-N turns out transitorily as nitrite (NO_2^-) followed by change to nitrate (NO_3^-). This biotransformation, driven by *Nitrosomonas* and *Nitrobacter*, is known as '**nitrification**'. However, if the conditions reverse - oxic soil becomes anoxic – then NO_3^- reduces to nitrite (NO_2^-) to nitrous oxide (N_2O) and then finally transforms to N_2 gas. Together, these events are known as '**denitrification**' and are accomplished by a wide variety of soil microbes. While the transformation routes described thus far are biological in nature, there are some other processes, whose regulation follows physico-chemical attributes of the native soil or emerging N entities. It is pertinent to mention, that breakdown products - NH_4^+-N (cation) and NO_3^--N (anion) behave differently on their stay in soil. Former is attracted by negatively charged soil, while the latter is repelled because of the same charge as that of soil. Resultantly, NH_4^+-N remains in the root zone. The NO_3^--N, on the other hand, tends to move down with water – called '**leaching**'.

Initiated by enzyme urease, NH_3 formation is the result of urea (NH_2-CO-NH_2) hydrolysis. The product ammonium carbonate decomposes readily to give rise to ammonium (NH_4^+) and CO_2. Ammonium (NH_4^+) ions thus released when face oxidized sites change to NH_3. Simultaneously, other product of urea hydrolysis - CO_2, is a source of global warming. If this change happens on the surface soil, as is with commonly followed method of broadcast application in India, NH_3 swiftly escapes as vapours. High temperatures, moist soil conditions, alkaline pH, wind speed and ready supply of NH_4^+ for NH_3 formation accelerate rate of volatilization. Dominance of urea for field use in India assures NH_4^+ supply, providing thereby a kind of pre-organized delivery favouring NH_3 volatilization. This explains relatively high FN losses from Indian soils. Incidentally, urea-N exhibits, respectively 6- and 2-times greater vulnerability to NH_3 volatilization to ammonium nitrate urea ammonium nitrate (Yara, 2018).

The pro-volatilization conditions, described above, are encountered across rice paddies; accordingly, NH_3 volatilization is exceptionally high – reaching up to 50% (Bouldin and Alimagno, 1976; Freney et al., 1981; Fillery et al. 1983; Katyal and Carter, 1989). On the other hand, Katyal and Gadalla (1990) observed minimum rate of NH_3 emissions, if the surface broadcasted FN was moved deep into the soil. They accomplished subsurface transfer by timing the fertilizer treatment before irrigation. Infiltrating water moved down FN, since it is the NH_3 concentration in floodwater that sustains volatilization. Existing conventional FN application following irrigation of upland soils and after puddling of lowland soils contribute to skin-deep presence of NH_3, exposing it to volatilization. High rates of basal treatment increase NH_3 concentration in floodwater and further intensify rise in volatilization. Bouwman et al. (1997), in fact, reported that regions emitting highest NH_3 vapours are found in the Indian subcontinent and China, where the intensity of synthetic fertilizer use is among the highest in the world and its broadcast treatment on moist surface or in floodwater is a common method of basal-N management. Later they reported (Bouwman et al., 2002) that developing countries contribute 2.5 times more NH_3 volatilization than industrialized nations (18% *versus* 7%). Besides loss to investment, NH_3 plays a key role in the formation of atmospheric particulate matter, corrosion, visibility impairment and aerial deposition of N across open ecosystems like surface water bodies (lakes); contributing thereby to climate change.

***Denitrification*:** Nitrous oxide (N_2O) is the prominent gas emitted on FN transformations in soil. It is the act of denitrification - a several step microbial process - that generates this Greenhouse gas. Apart from presence of NO_3^-, absence of oxygen and a good supply of organic C are essential for denitrification to take place. Former is required to trigger the reaction, since de-nitrifiers use NO_3^- as electron acceptor (reduction) and organic matter as electron donor (oxidation). Therefore, anaerobic conditions found in submerged rice soils are conducive for denitrification, though not essential, since de-nitrifiers are largely aerobes (facultative anaerobes) (Firestone, 1982). This also explains occurrence of denitrification in saturated micro-sites of irrigated upland soils. Another factor that encourages denitrification in submerged rice soils is the near neutral pH they attain following a couple of weeks of submergence. Otherwise, acidic pH is known to inhibit its progress.

Although extent of FN loss through denitrification can be as high as 50% (Aulakh and Bijay-Singh, 1996), from environmental angle relative abundance of N_2O to N_2 is more relevant. Preferential attention to N_2O is due to its role in global warming and depletion of stratospheric ozone shield (Crutzen, 1982). Since 1750 (Park et al., 2012), N_2O levels in the atmosphere have risen by 22% from 270 ppbv level to 329 ppbv in 2016. Compared to that just between 1964 and 2016 the increase has been 16% (change from 286 to 329 ppbv) (https://www.n2levels.org). Essentially, this period coincided with the spurt in FN consumption following the invention of high input responsive dwarf rice and wheat varieties. Park et al. (2012) attributed the rise in N_2O to dramatic surge in FN consumption (6.5 folds increase between 1964 and 2016); of the 80% escalation in N_2O emitted from agricultural lands almost one-half is contributed by FN. A positive relationship, observed by Bremner et al. (1980), between intensity of denitrification and FN supports this opinion. Also, global level data on FN consumption and N_2O emissions, captured graphically (**Figure 5**), adds weight to this thesis. Although lowland rice soils are believed to lead in N_2O emissions, but largely as N_2 gas (Cady and Bartholomew, 1960). Sahrawat and Keeney (1986). Katyal et al. (1989) confirmed inconsequential proportion of N_2O to molecular N (N_2O/N_2) to be no more than 1.5%. In contrast, developing wet conditions following irrigation and continuing saturated pockets during drying phase of otherwise aerobic soils add far greater proportion of FN in the form of N_2O.

Despite lesser atmospheric load of N_2O than CO_2 (327 ppbv *versus* 400 ppm), its global warming potential is nearly 300 times higher (gtr.rcuk.ac.uk/projects?ref=BB/H013431/1) on a time scale of 100 years.

***Leaching*:** Leaching is not of much consequence, if leaked FN stays within the reach of plant roots. It becomes serious when NO_3^- arising from nitrification of FN or that escaping de-nitrification travels with percolating water following rain or irrigation. Increasing rate of FN application and flood irrigation, as is common across ~10 M ha of rice-wheat cropping in the Indo-Gangetic plains covering Pakistan, India and Bangladesh, drive NO_3^- leaching. Since percolating water moves faster in light textured sandy soils, leaching of NO_3^- is more serious there. Typical examples are loamy sand soils dotting floodplains of Punjab and Haryana. Progressively with regular cropping and repeated FN treatment, concentration of NO_3^- in the underground water builds up. When the level exceeds 50 mg NO_3^- L^{-1} (11.3 mg NO_3^--N L^{-1}) (WHO, 2011), the water becomes unsafe for drinking. This situation has already arisen in Indian state of Punjab, where dominantly soils are loamy sands and annual intensity of FN consumption is highest in the

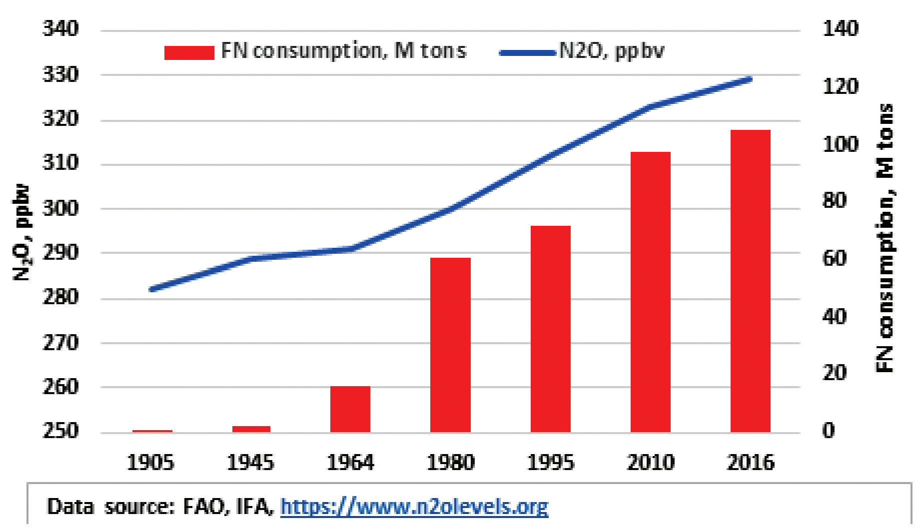

Figure 5. FN consumption and atmospheric N_2O

country - range spans between 270 and 400 kg N ha^{-1}. (http://www.greenpeace.org/india/global/india/report/2009/11/chemical-fertilisers-in-our-wa-2.pdf). Blue baby syndrome and stomach cancer are two diseases associated with continued exposure to NO_3^- contaminated waters.

***Surface Runoff/Erosion*:** Erosion, dislodges FN (and other nutrients) from soil. Typically, erodible part of residual fertilizer P and N end up in rivers, ponds and lakes (Johnston, 1997). Progressive enrichment of lake/pond waters with N and P promotes eutrophication - a process causing quick death of algal blooms and aquatic life. Left to nature, eutrophication is a slow-aging condition of a water body. But led primarily by inefficient conservation of soil and fertilizer N and P has greatly speeded up the process, which damages climate pacifying role of water bodies; contributing thereby to global warming.

In summation, it appears that NH_3 volatilization, denitrification and leaching are the prominent ways of FN exit from soil plant system and source of abysmally poor NUE. On an average, these routes cause about one half of the FN dose to move beyond the reach of plant roots and get lost by entering air as vapour/gases or leak into groundwater as soluble ions. Higher rate of application than recommended is the single most important element of FN loss by any of the three ways listed above. Broadcast of FN on surface of soil or flood water drives NH_3 volatilization; deep placement minimizes its occurrence. Contrarily, placement is not able to counter denitrification, which happens in response to lack of oxygen, which is common to flooded or saturated soils. Light texture intensifies leaching. Based on this broad and brief synthesis of past research findings, strategies have been developed in the past to diminish the role of FN loss pathways to boost NUE. In this pursuit, not only has the right dose, timing and method of application been developed, but sources alternative to urea have also been synthesized. Details on FN management and new urea constructs are presented in the following section.

Strategies on Improving Fertilizer Use Efficiency

Looking back, role of FN has been unquestionable in unshackling India from food insecurity. Looking forward, this role is going to be far more crucial in future due to rising demand for food from shrinking area per caput. Since inefficient use of FN has disturbed and continues to disturb sustainable growth in productivity (production/unit area), future success in assuring food security will, therefore, hinge upon how efficiently the FN is managed. Over the 50-year history of Green Revolution from where the FN use took off, Indian scientists have been concerned about increasing the FNUE, which has stayed extremely low. They devoted sizable research effort on discovering optimum treatment dose with fertilizers that was: (i) divided over cropping period, (ii) crop- /variety-specific, (iii) soil test based, and (iv) aligned with disparate soil and crop growing environments. Urea was the prime focus of this research with rice in the centre of these investigations. Additionally, substantial energy went into exploring the alternative sources of FN that decelerated NH_3 volatilization, denitrification, leaching and erosion. Induction of urease and nitrification inhibitors, slow release N carriers, urea in the form of super granules and soil conditioners were employed to lessen the vulnerability of urea to these processes. Scientific efforts undoubtedly provided possibilities on improving the state of weak FNUE. Balance of information available thus far indicates following major findings:

A. Fertilizer Nitrogen Management Approaches (Agronomic)

A.1. Royal Commission on Agriculture (1929) observed, “The question has been much argued whether the soils of India are to-day undergoing a progressive decline in fertility. Such experimental data as are at our disposal suggest the view that, in an overwhelming proportion of lands in India, a balance has been established and no further deterioration is likely to take place under existing conditions of cultivation”. Today, the situation on bad state of soil fertility is no different than it was in the 1920s. Available scientific findings point out that the extent of nutrient deficiency (% soils/soil samples deficient) is: N 99; P 80; K 50; S 41; Zn 36; B 23; Fe 13...Apparently, N deficiency is universal in Indian soils. Compared to that, deficiency of other nutrients is sporadic and its distribution is soil and situation specific. Balancing FN treatment with application of other deficient nutrients is fundamental to achieve high NUE. In order to decide the level of FN treatment (or other nutrients) soil test-based applications are necessary. Generally, soil organic matter as proxy of soil available N, nitrate-nitrogen credit from the previous crop and yield goal including N credit for manure and irrigation water are employed to estimate N availability and corresponding rate of FN application. Farmers seldom adopt calibrated applications matching these soil test-based recommendations. This misalliance is a leading cause of consistently low NUE.

A.2. *Split application* of FN has invariably been more efficient than one-time application (Prasad, 2013). By and large, including basal treatment, recommended FN dose is divided, respectively into 2 and 3 top dress applications with upland wheat/maize/sorghum and lowland rice. it is the superior contribution of top-dress FN that makes the difference (**Table 6**). And,

Table 6. Recovery efficiency of ^{15}N urea (%) in individual doses of 30 kg N/ha applied to sorghum

Time of application	^{15}N recovery plant	^{15}N recovery soil	^{15}N loss
Basal	34	23	43
Top dress	57	26	17

Source: Hong et al. (1992)

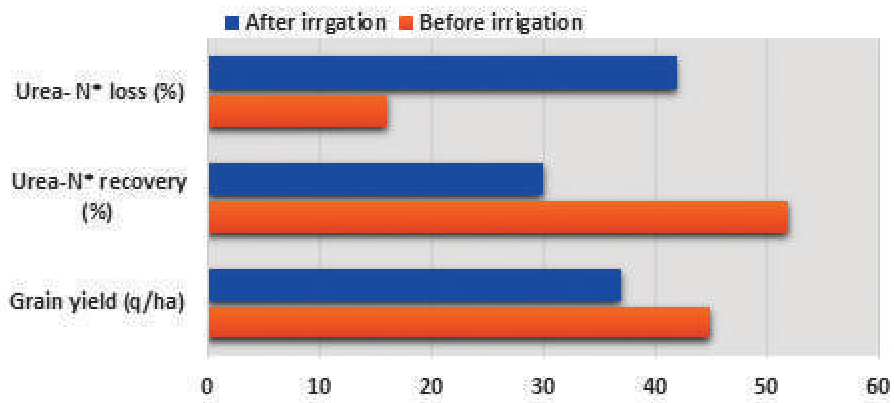

Figure 6. Influence of timing of top dress urea treatment *vis a vis* irrigation

gains in terms of N recovery efficiency and yield from top-dress FN to standing crop grow with concomitant fall in FN loss, if applied before irrigation than broadcast after irrigation as is the general practice (Katyal et al., 1987) (**Figure 6**).

Recent research has generated credible evidence that omitting basal treatment produces additional benefit equal to ~15% rise in agronomic efficiency (kg grain/ kg FN) (Yadvinder- Singh et al., 2007). In fact, research findings from China and IRRI confirm possibility of a quantum leap in agronomic efficiency in high intensity farmed areas (Peng et al., 2006), like N-W India, by lessening share of basally applied FN.

A 3. Management of Top Dress FN: Since FN requirements of an established crop vary due to unequal spread of patches exhibiting deficiency and sufficiency within the same field, precise management (of FN) necessitates real time adjustment in top dress rates as per crop condition, instead of commonly recommended blanket rate of broadcast. Differentiated applications are made possible with the use of a pre-calibrated leaf colour chart (optical sensors like Green Seeker, Holland Crop Circle…) that recognizes spatially variable spots needing preferential FN treatment from those that do not. Findings from several farmer-field investigations conducted in rice growing areas of Punjab (**Table 7**) have proven up to 45% gain in response and 25% rise in FN recovery efficiency (Yadvinder-Singh et al., 2007).

Table 7. Leaf colour chart (LCC) guided urea-N management: Response of rice

Method of application	Response to FN (grain/kg N)	FN recovery (%)
Recommended method	11.3	39.8
LCC based	16.4	52.7

Source: Yadvinder-Singh et al. (2007)

A 4. Placement of FN: Ammonia generated during breakdown of urea lying on the moist surface or that found in the standing water of rice paddies is vulnerable to ready escape. It means urea decomposition taking place below the soil surface hinders NH_3 exit, enhancing thereby its use efficiency. Experimental results confirm that placement of urea-N deep in the soil had clear advantage in terms of agronomic efficiency compared to broadcast application on the surface (Katyal, 2003; Prasad, 2013). Mohanty et al. (1993) reported increase in FNUE due to reduced NH_3 volatilization of deep placed FN. Since placement is difficult in puddled soils, Katyal and Gadalla (1990) proposed application of FN to dry soil followed by flooding and puddling. Fast percolating water in un-puddled dry soil encouraged natural deep placement and led to clear advantage in terms FN recovery efficiency (**Figure 7**). These findings gain

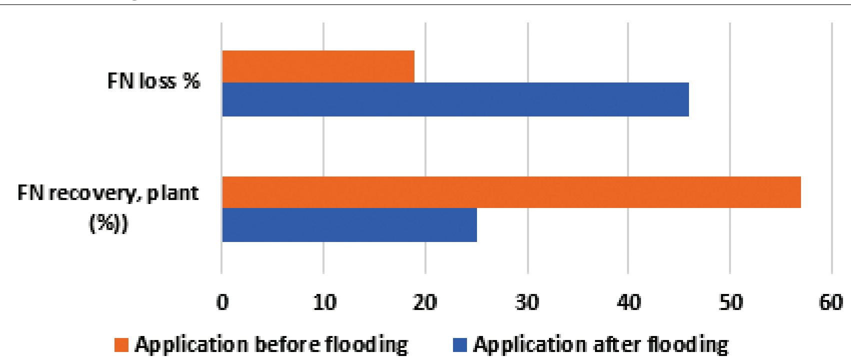

Figure 7. FN management in flooded rice soils

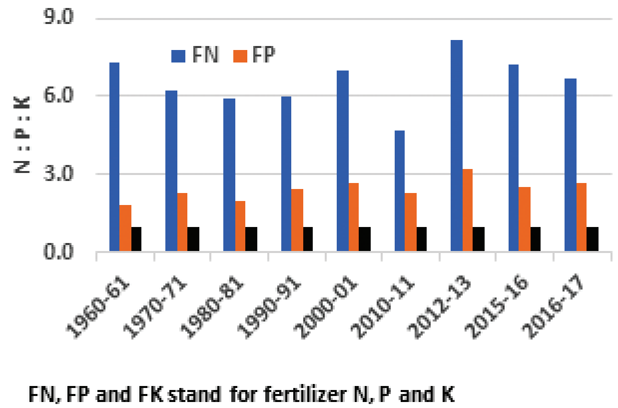

Figure 8. Fertilizer N, P and K consumption ratio (Data source: FAI)

specific currency as the shift from transplanted to direct seeded rice becomes necessary due to rising labour shortages and high cost of hiring.

A 5. Balanced application: Balanced application of fertilizer nutrients (N, P, K , including all other deficient nutrients) in adequate amounts and proportion is essential to maintain high level of use efficiency and sustainable productivity growth. Keeping in view the theme of current report, state of balanced use of NPK remains the epicentre of examination. In 2016-17, NPK use ratio of 6.6:2.8:1.0 did neither correspond to actual crop uptake pattern i.e., 1.0:0.3:1.3, nor it matches with the perceived NPK consumption ratio of 4:2:1. This imbalance is not new. It has continued over the years (**Figure 8**). Distorted use ratios confirm that K additions in typical lag crop removals. (Katyal, 2016) estimated that consistent mining of soil K by harvested food grains (straw included), year on year basis leaves a virtual gap of 7 M tons. Crop removals exceeding additions have spurred deficiency of K in soils – a situation which was rare ~30 years ago. FN-slanted use diminishing agronomic efficiency of NPK (**Figure 4**) confirms just that. Furthermore, despite advancements in crop genotypes and agronomic management practices, NUE has remained stubbornly unmoved. It is reaffirmed that NUE continues to hover around 30%. Besides weakening influence of technology transfer apparatus on inspiring balanced NPK application, the main factor contributing to the dismal state of one-sided use has been and continues to be the policy on subsidy extended to NPK fertilizers. Extant nutrient based subsidy (NBS) scheme - introduced in 2010, tilts far more towards N from the point of price support. Resultantly, P and K fertilizers have become more expensive than urea N. Price differential jolted NPK use ratio. Being cheap, farmers got tempted to use more N than their crops really need. By over-using urea N, they downgrade the use efficiency further. Data in **Figure 9** (Singh et al., 2012) confirm that NUE with wheat as test crop increased as complete complement of NPK was applied. This was true whether the wheat was grown on an Inceptisol (Ludhiana) or an Alfisol (Palampur). Quantitatively, the gain in NUE due to enriching fertilizer treatment with P over N ranged between 141% and 396% (**Figure 10**). Corresponding rise in NUE by adding K to NP treatment varied between 61% and 41%. Supplement of FYM to 100% recommended NPK dose enhanced NUE by additional 12% (**Figure 10**). It means **that** by balanced use of NPK, NUE gets maximized; integration with FYM lifts it (NUE) higher. Resultantly with balanced NPK use, cost of fertilizer input decreases, making farming more profitable. Also, degradation in the health of soil, pollution of groundwater and rise in global warming get automatically contained, which are otherwise fueled

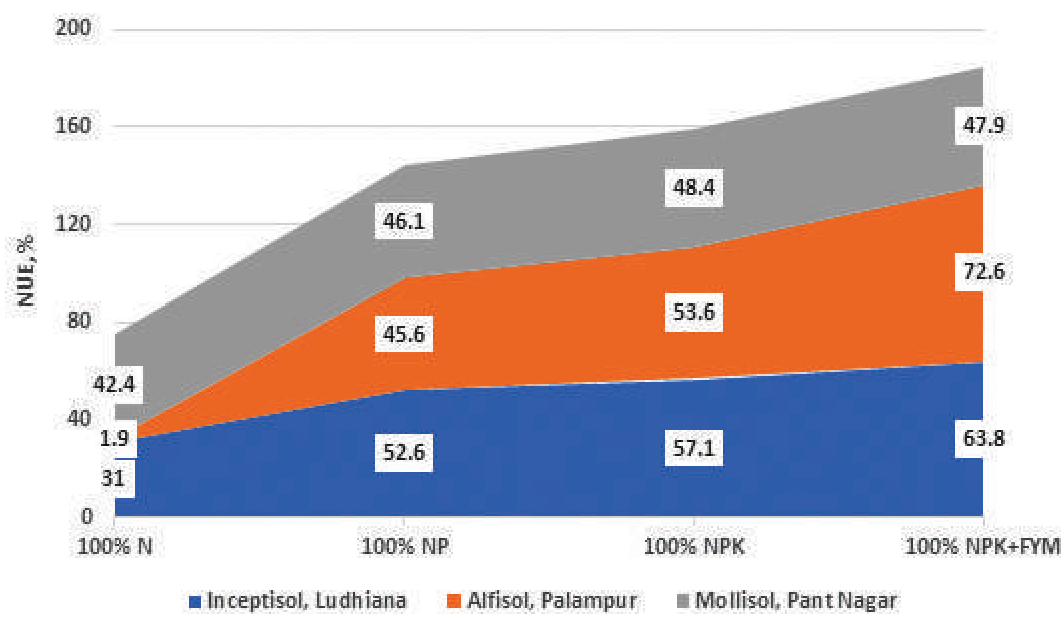

Figure 9. Influence of balanced and integrated NPK on NUE - wheat (Data source: Singh et al., 2102)

Figure 10. Gain in NUE (%) due to balanced and integrated NPK management (Data source: Singh et al., 2012)

by imbalanced use of NPK and by excluding organic manures in total soil fertility management.

From the above review, it is evident that there exists a wealth of time-tested practicable no-cost methods of FN management by application of which NUE is possible to boost by 20% to 30%. However, farmers largely turned a blind eye when it came to their adoption. An analysis of why farmers ignore these doable practices is tabulated as follows (**Table 8**):

Table 8. Farmer-perceived cumbrances in adopting urea-N management practices and suggestions to minimize their influence

Recommendation	Farmers' response, reason and result	Suggestion
Apply N-dose as per soil test value.	Generally higher dose is applied, since farmers believe that suggested levels are insufficient for expected yields.	Strengthen technical advisory with evidence-based data.
Divide the application into basal and top dress with minimum as basal (<20%).	Divide the application, but generally apply more as basal due to belief that higher basal application is necessary for early growth.	Influence farmers' mindset by consistent advisories and laying out adaptive research trials with their involvement.
Place basal dose of N, P and K together deep in soil.	Followed by those having seed-cum-fertilizer drills, majority of S&M farmers broadcast due to non-availability of machinery.	Support establishment of custom-hiring centres; support by sharing cost of renting (50/50 basis).
Applytop dress dose before irrigation (tube-well irrigation and upland crops).	Ignore because of misconceived notion that application before irrigation will leach beyond root zone.	Lay out farmers' involved action research and intensify technical advisories.
Balance N dose with P and K (S, Zn, B...) treatment as per soil health card recommendations.	Farmer's response is partial, as he is attracted to over apply N because of its cheaper cost and quick visible response.	Correction in NBS policy is necessary to minimize disparity in prices and improve extension advisories on value of balanced crop nutrition.
Distribute top dress urea-N as per leaf colour chart (LCC) readings.	Farmers are either unaware on the value of LCC in saving urea N or find it unmanageable to apply as per LCC; subsidized urea-N being cheap makes it hardly inspiring to save it.	Layout farmers' involved demonstrations to prove extent of savings *vis-a-vis* extra cost/difficulties in adopting LCC; correction in NBS policy to rationalize urea prices is needed.
Adopt precise agronomic practices necessary to harness full potential of balanced nutrition.	Application of standard agronomic practices is partial because of non-availability of requisite inputs (timely availability of seeds/fertilizers/ machinery or seed of duration-right varieties, timely release of canal water...) or ignorance on what exactly the location specific precision agronomic practices are?	Strengthen timely input supply and technology transfer on exact requirement of precision agronomic practices (seed treatment, date of seeding, seeding geometry, critical weeding time, irrigation...).
Adoption of integrated nutrient supply and management system	Farmers are not well-versed on the role of manure integration in sustaining soil health, express insufficient availability as an alibi not to use and view extra urea-N treatment as replacement	Build farmers' adaptability by: (i) education on value of organic manures not just to save N but to build total soil health, (ii) extend support for creating at least one compost pit/ landholder, (iii) assure availability of seeds of multi-purpose crops free of cost inspiring green manuring, and (iv) emphasize returning maximum crop residues back to soil by supporting hiring of machinery for total straw management.

B. *Urea Modification/Fortification for Improving NUE*

In order to elevate use efficiency of urea N and reduce the influence of farmer-perceived management cumbrances, several alternative products have been designed and developed. Customized fertilizers (CFs), micronutrient fortified fertilizers, modified urea (sulphur- coated urea or SCU, neem-coated urea or NCU, urea treated with nitrification/urease inhibitors), urea super granules (USG), water soluble fertilizers (WSF) are some chosen examples. It is the NCU whose production and consumption (~3 M tons in 2016-17) gained momentum since 2014-15. In March 2015, GOI made it mandatory for domestic manufactures of urea to produce 75% (changed to 100% in May 2015) of their total production of subsidized urea as NCU and allowed them to charge an extra MRP of 5% (pib.nic.in > newsite > PrintRelease). Subsequently, imported urea was also notified to be *neem* coated. A synthesis on state of acceptance and spread of selected modified urea products is presented in **Table 9**.

Customized Fertilizers: Customized fertilizers (CFs) are manufactured by combing necessary proportions of requisite fertilizers. In pursuance, wet or dry granulation processes are adopted. With wet granulation a slurry of needed fertilizers is made followed by drying and granulation. Drying of wet slurry is energy expensive. In comparison dry granulation involves densification of a powdered mixture of needed fertilizers by subjecting it to compression with a compacting and granulation machine. Bulk blending is another technology that involves physical mixing of required fertilizers. Segregation of mixed materials is a serious drawback of bulk blends. Of the three methods, single step dry compaction and granulation is simple to handle and energy saving.

Compaction allows preparation of small batches with ease. This facility specifically suits diverse production systems and varying soil fertility conditions that necessitate synthesis of a range in products. In fact, tailored CFs by compaction enable precise handling of location-specific treatment of nutrient deficiencies. Since experience on large-scale production of CFs has failed, synthesis must be decentralized and developed as a start-up/SME/franchise of a fertilizer manufacturing company in the heart of a major production system catchment. In pursuance, it is recommended to dry granulate by compressing together the calculated proportions of requisite nutrient sources. A compacting machine (somewhat like tabletting machine) fuses together powdered fertilizer sources in sheets/tubes followed by disintegration/cutting as granules of requisite sizes.

Purakayastha and Katyal (1998) specifically compacted urea with other fertilizer sources capable of generating acid micro-sites. Fertilizers that are

Table 9. State of acceptance and spread of modified urea carriers

State of use and acceptance	Issue	Recommendation
SCU: agronomic superiority; near zero use and production	Economically unattractive	Disband future production
USG: gain in agronomic efficiency no more than 10%; benefits over urea neither uniform nor universal; limited use and production	Lack of policy allowing extra pricing to cover granulation cost; no practical ways of placing USG in puddled soils. Highly vulnerable to leaching in percolating soils.	Introduce pricing policy to cover granulation cost; design and develop efficient and practicable means of placement; recommend only if leaching of N is not a problem.
NCU: excellent policy support, wide-spread use and production since 2015.	Sparse experimental data from real-life situations to realistically confirm extent of superiority over urea across diverse crop-growing environments; gain in NUE hangs around 5% to 7%.	Lay out large number of farmer-field experiments to establish credible gains in NUE across diverse crops and cropping systems.
Zincated-urea (ZnU): agronomically superior, began production and use in 1990, zero production since 1992 because of GOI control on MRP.	GOI fixes MRP, NBS is inadequate to cover cost of fortification; no production over the last 27 years.	Free MRP from GOI control; introduce a pricing mechanism that at least allows covering manufacturing cost
Water soluble fertilizers (WSF): higher use efficiency of N and other nutrients, currently 6 WSF are available in the market (extent 90%); further increase in number of WSF grades since notification of specification in FCO; use and production expanding fast (15% to 20%/year).	Despite higher efficiency, slow growth due to limited spread of micro-irrigation (MI), which is prime driver of expansion in production and use of WSF	Accelerated MI spread is necessary for expanding manufacture and use of WSF.

Table 10. Comparison of NH_3 volatilization from urea and some compacted materials

Source	% NH_3 volatilization	Relative NH_3 loss (Urea = 100)
Urea	41	100
Urea + ammonium chloride	23	56
Urea + muriate of potash	33	72
Urea + zinc sulfate	32	70

Source: Purakayastha and Katyal (1998)

known to create acidic conditions included ammonium chloride, muriate of potash, zinc sulphate…This innovation with urea as the base significantly reduced NH_3 volatilization (**Table 10**). The gain in NUE is estimated to range between 7% to 14%, which is equivalent to reduction in NH_3 volatilization. It is reiterated that this approach holds promise in terms of economics. Blends of dry granulated materials involve the in-use fertilizer sources; hence no cost of additives. Low cost of compaction machinery (~ US $ 20,000) and manufacturing (~ 10%) are other attractions of this technology. Also, this approach offers unique possibility of balanced fertilizer use supporting site-specific nutrient management. What is required would be establishing small scale compaction facilities across dominant production tracts of the country by decentralizing and distributing manufacturing facilities.

Policy hurdles on manufacture of local-level CFs must be minimized to inspire site-specific production of wide variety of nutrient combinations. The guidelines for production of CFs were formulated in March 2008 under clause 20-B of Fertilizer Control Order (FCO, 2019). These directives mandate manufacturers to seek permission from appropriate authority in the Ministry of Fertilizers and Chemicals before marketing a CF. It is a time-consuming process. Need is to simplify the approval and notification procedure for CFs manufacturing so that approval and notification is hassle-free. Since there is no provision for procuring subsidised fertilisers (except urea) used as raw material for manufacturing of CFs, the benefit of subsidy, it is recommended to extended to all fertilizers as is available to urea.

Following action plan is suggested**:**

- Allow synthesis of CFs as a start-up/SME/franchise of IFFCO/KRIBHCO in a production catchment; simplify operation of clause 20 B of FCO 2008.
- Extend benefit of procuring all fertilizers, constituting a CF at subsidized rates as is available to urea.
- Provide financial support for purchase of complete set of compaction machinery and building to house it under "credit guarantee fund trust" scheme.

Moving Forward

Despite clear understanding on efficient management of fertilizers, improving FUE continues to be an enigma. One prominent explanation seems that scientific findings were poorly aligned to farmers' situation and/or the native biophysical soil attributes and limitations. In general, research objectives seldom provided space accommodating farmers' needs and views; particularly the constraints faced by the S&M farmers. Rarely did scientists attempt to work hand in hand with this category of farmers to validate practicality of their findings on improving the conventional methods of fertilizer management. Also, when it comes to transfer of technology, observed Feder and Zilberman (1985), S&M farmers remain the least preferred group to interact with. Incomplete adoption of a technology package till date remains the patent source of persisting gulf between the NUE obtained in the researcher managed on-farm trials and the NUE accruing in the farmers' run fields (**Table 5**). It is reasonable to believe that at least 20% fall in NUE is assigned to partial application of standard management practices. Need is to devise and induct a new look extension system, which besides being multi-agency, on the one hand will facilitate availability of inputs as per technological demands and on the other will offer advice on improved soil, water and input management. Then NBS scheme, if not rationalized, will continue to promote unbalanced NPK use mediated deterioration in NUE.

It is re-constated that inefficient use of fertilizers, besides lost economics, degrades health of soil, pollutes groundwater and fuels rise in global warming. Worried, perhaps, by these anti-development outcomes, Honourable Prime Minister (PM) in November 2017, gave a call to reduce urea N use to one half of the existing level by 2022. In order to meet that challenge, the way forward is increasing NUE by maximizing role of organic manures and biological N fixation in soil fertility management, induction of precise agronomic methods of crop and FN management, FN delivery through fertigation, diversification with N-efficient crops, new products and correction in NBS.

A study made by Zhang et al. (2015) has projected, if India's surplus N [difference between (inorganic + organic N additions) - N removals] in 2010 has to nearly half in 2050, it would be necessary to raise fertilizer-N use efficiency (FNUE) from 30% to 60%. With these estimates in forefront, it seems less straightforward to cut the urea-N consumption to less than one half by 2022, the target year set by the Hon'ble PM. Affecting that big reduction would not only mandate raising the bar of NUE but would also necessitate supplementing the discounted urea consumption with manures and biological N fixation. Otherwise, it would spell disaster for already declining productivity growth of wheat and rice, which form food security basket of India. In order to elevate FNUE to 60% from the current value of ~30%, necessary it would be to: (i) bolster complementary role of organic manures and biological N fixation, (ii) replace casual FN handling with precise crop, soil and FN management practices, (iii) minimize basal urea N treatment by replacing the recalibrated dose with the application of customized products and (iii) rationalize NBS scheme minimizing excessive pitch towards urea N consumption.

The total strategy harmonizing precision agricultural practices for elevating NUE and lessening urea-N consumption by stepping-up inclusion of native resources and biological N fixation is manifestation of a holistic nutrient management concept or what IFA calls 'nutrient stewardship' (IFA, 2013). Either way, it is a leap forward to sustain target productivity growth that country's food security demands, zero harm to soil health, environmental integrity and well-being of other natural resources. In approach, holistic N management/nutrient stewardship attempts to weld together precise agronomic methods, integrated nutrient supply and management, balanced fertilizer applications, site specific fertilizer choices and treatment regime for cutting current FN use to about one half. Organically, proposed holistic strategy harnesses the potential of partnership between farmers, extension and R&D institutions for arriving at relatively quick and basic solutions to improve NUE. Following work plan is suggested.

a. Strengthen supply of N though organic resources and biological N fixation. India annually generates a total input of about 15.6 and 4.1 M tons of N through manures of all shades and biological N fixation (Prasad et al., 2002). Of the total input of 19.7 M tons N, fertilizer equivalent would be around 8 M tons (1ton organic N a" 0.4ton FN). In order to create a sustainable native N supply system: (i) embark on a massive campaign on raising use of organic manures by subsidizing establishment of one compost pit/ landholder, (ii) provide free seed of location and duration right seeds of intercrops to intervene after wheat harvest and before rice planting; alternatively provide free seed of dual-purpose legumes (pods for vegetable and green mass for turning into soil) for raising green manure and (iii) incentivize those farmers who do not burn but return maximum crop residue back to soil.

b. Launch a mass-movement to spread the concept of holistic FN management by creating awareness, adaptability by bridging knowledge and skill gap, acceptance by action research and application by initial handholding in the form of necessary inputs and use of machinery. Strengthen extension-research interface by promoting role of private partners as change agents with farmers as nucleus. Place special emphasis by facilitating:

- timely guaranteed availability of region-specific quality seed of N-efficient HYVs,
- diversification by supporting infusion of legume intercrops as part of prevalent cropping systems,
- strengthening of water use efficiency apparatus for enhancing water productivity,
- adoption of precision agronomic practices (seed treatment, date of sowing, timely weed/ pest management…),
- availability of seed-cum fertilizer drills, enabling placement,
- minimize application of urea N as basal dose,
- time top-dress application before irrigation of upland crops in areas having on-farm water facility and distribute top-dress amount as per leaf colour chart readings and
- manufacturing of water-soluble multi-nutrient products for placement via fertigation; accelerating spread of drip irrigation would be a prerequisite.

Critical elements promoting holistic FN management are given in box below:

Critical areas of work plan on holistic N management for lessening urea N use and enhancing NUE:

♦ Maximize organic manure supply by extending guidance on scientific composting and supporting financially to establish one compost pit/ landholder.

♦ Guide to create enough biological cover by incentivizing turning of crop residue or by raising cover crops for biological N fixation.

♦ Substitute blanket fertilizer advisories by cropping system-based recommendations using soil health card and target yield potential in area-specific production zone.

♦ Minimize basic fertilizer dose and whatever little is recommended be made mandatory to be placed at the bottom of the plough furrow in a continuous band by subsidizing hiring of seed-cum- fertilizer drills

♦ Top dress fertilizer before irrigation and its application rate to be calibrated as per leaf colour chart readings

♦ Promote fertigation system in a phased manner starting from high value and high water-requiring crops like sugarcane to cereal crops and extend NBS benefit to WSF as is available to urea.

c. Customized fertilizers (CFs) are a way forward to auto-inspire balanced application of requisite nutrients. In that way, appropriately constituted CFs are a response serving the needs of site-specific soil fertility management. It is recommended to decentralize manufacture of CFs in the heart of a dominant production system. Allow synthesis of CFs as a start-up/SME/franchise by fertilizer manufacturers like IFFCO/ KRIBHCO in a production catchment; modify operation of clause 20 B of FCO 2008 by simplifying the approval and notifying procedure. Extend benefit of procuring necessary fertilizer sources at subsidized rates as available to urea. In order to attract use of CFs, it is recommended to pay for environmental services generated, like climate mitigation products e.g., reduced N_2O generation.

d. Reforms in NBS**:** Existing NBS policy is an impediment to reach the goal of balanced application of nutrients. Hence, its rationalization is necessary. First suggestion is to extend the NBS scheme to all fertilizer nutrients (not fertilizer products as it exists) including urea-N in the interest of sustaining soil health and ensuring viability of domestic fertilizer manufacturers. An alternative route reforming NBS policy could be that government exercises only necessary control and command on production, distribution, marketing, and pricing. Market self-serves the interest of fertilizer producers and farmers - typically big farmers who produce mainly for market. As this proposal precludes the interest of S&M farmers, specifically those who have little surplus to participate in the market, it is suggested to build their otherwise *limited purchasing power* to buy a critical input like fertilizer (and seeds). Such farmers could be given well-designated vouchers to receive an assigned amount of fertilizers. The kind of fertilizer-buying assistance could be guided by the general soil test values given in the soil health-card.

And finally: No action plan on improving NUE can have any chance of success, unless millions of S&M farmers of the country accept its objectives, share in its making, regard it as their own and are prepared to make contributions in implementing it. Apparently, technology transfer apparatus must become more proactive and involved so that farmers, organized preferably as Farmer's Field Schools on Fertilizer Use, get advice and input support from a single window. Since, integrated N supply and management systems do not show immediate visible response, in order to convince members of a farmer's field school, the scientists and technology transfer agents ought to actively work with them facilitating mindset change. Intimate interface of R&D institutions and farmers groups must gain momentum because lack of literacy stands in the way of absorbing and applying holistic solutions on N management, noted India's Economic Survey 2017-18.

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Sustainable Farmer-friendly Technologies for Management of Natural Resources in Eastern India

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Abstract

The present paper identifies the major natural resource constraints of eastern and north-eastern regions of India to promote sustainable agriculture. Technological options available in three areas, namely, utilization of water resources; managing degraded soils, especially the acid soils; and soil health maintenance over the years, have been discussed. Important technologies for water use, such as rain water harvesting and water conservation, water management in hilly and sloping areas, land shaping for crop diversification, zero tillage, mulching, besides some novel agro-techniques have been presented in detail. Soils under upland and medium land physiography of eastern India suffer from soil acidity constraints, which drastically reduce crop productivity and soil health. Farmers grow rice in these lands and leave major part as fallow during the post-rainy season, as the region is primarily rainfed. Technology of lime application in furrows either singly or with organic manure along with balanced use of fertilizers has been successful in several states of India with the farmers. This practice needs to be promoted among the farmers of the acid soil regions, based on the soil-health cards being provided to the farmers. Other soil-health-related-constraints responsible for the low agricultural productivity of the region include large scale promotion of soil test based balanced nutrient use, soil organic matter maintenance through use of quality organic manures and crop residues, restoration of degraded soils, checking soil erosion and soil pollution etc. Technologies to address these problem areas with farmers' participation have been discussed in the light of the area-specific needs and perceptions. It is a must to adopt a mission-mode approach for rapid transfer of some of these technologies for doubling farmers' income without adversely affecting the natural resource base of the country.

Key words : Soil health, soil acidity, water resources, eastern India, technologies, agriculture

Managing Water Resources for Agriculture

Eastern region, a water resources rich region (**Table 1**), is considered to be agriculturally backward because of widespread poverty, low crop productivity and poor irrigation development. Due to poor storage capacity, large area is prone to floods in *kharif* season and drought in *rabi* season. Groundwater development is less than 30% as compared to more than 100% in many pockets of the country. Annual rainfall of this region varies from 1091 to 2477 mm with an average of 1526 mm, which is sufficient for growing any crop. Assam gets mean annual rainfall of 2477 mm which is the highest in the region, followed by West Bengal (1750 mm), Odisha (1451 mm), Chhattisgarh (1430 mm), Jharkhand (1277 mm), Bihar (1204 mm) and eastern Uttar Pradesh (1091 mm) (Kumar, 2012). Bulk of the rain (about 80%) occurs during the monsoon season. It has erratic temporal and spatial distribution with considerable year-to-year variations. High intensity and heavy rains cause frequent floods in plains and coastal deltaic area. Coastal areas are also vulnerable to seawater intrusion and cyclones.

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I. Assessment of Available Water Resources in Eastern India

a) Surface Water Resources

Total available surface water in different river basins of the country is 188 Mha-m per year. Three major river basins in the eastern region excluding Assam are Mahanadi, Brahmai-Baitarani and Subarnarekha. The annual surface water available in these three basins is 11.2 Mha-m and the total annual monsoon runoff is 11.7 Mha-m. Annual utilizable surface water in the three basins is estimated at 8.8 Mha-m. It has been observed that due to (i) non-availability of suitable storage sites in hills and plains, and (ii) extreme variability in precipitation, which disallows storage of flash and peak flows, all the stream flows cannot be stored in the reservoirs. The live storage capacity under completed projects in the country is 20.65 Mha-m, out of which the share of eastern region is 2.92 Mha-m. The annual per capita water availability in Mahanadi, Brahmani-Baitarani and Subarnarekha basins is 2067, 2388 and 1982 m^3, respectively. Groundwater potential of Ganga, Brahmaputra, Barak and other basins has been estimated at 171725, 27857 and 1795 Mm^3, respectively. In Subarnarekha,

Table 1. Status of water resources in the eastern region of India (Source: CWC, 2010)

Particulars	Water availability (BCM year^{-1})		
	Eastern region*	India	Share (%)
Utilizable surface water#	68.9	690.32	10
Available surface water#	31.53	315.98	10
Annual replenishable groundwater resources	130	433	30
Net annual groundwater availability	120	399	30
Annual groundwater draft	36	231	16
Irrigation	31	213	15
Domestic and industrial uses	4	18	22
Groundwater availability for future irrigation	82	161	51
Stage of groundwater development (%)	27	58	-
Total utilizable water (surface + ground) resources	199	1123	18

*Comprising of West Bengal, Odisha, Bihar, Chhattisgarh, Jharkhand and Assam
#Chopra and Goldar (2000)

Brahmani-Baitarani and Mahanadi basins, groundwater potential is estimated at 2185, 5879 and 21293 Mm^3, respectively.

b) Groundwater Resources

The region also has a large groundwater potential. Total utilizable groundwater resource for irrigation is estimated at 19.5 Mha-m yr^{-1}. However, average utilization of this resource is only 29%. It varies from 6% in Chhattisgarh and 9% in Assam to 46% in Bihar and 47% in eastern Uttar Pradesh. Thus, there is an ample scope for further exploitation of groundwater resource. However, utmost caution is needed in coastal belts to avoid seawater intrusion. In several areas endowed with thick but relatively less pervious clay layer at the land surface (*e.g.*, Midnapore district of West Bengal), over-exploitation of groundwater has caused substantial fall in water table. The actual groundwater exploitation level is less than 20% in 25 districts of Odisha, 6 districts in Bihar, all the districts of Chhattisgarh and Assam, 6 districts of West Bengal, and 12 districts of Jharkhand.

Irrigation Status in Eastern India

Net irrigated area in eastern India is 14.89 Mha, out of which the net irrigated area of 4.2 Mha is in eastern UP, 2.51 Mha in Bihar, 2.69 Mha in Odisha, 3.91 Mha in West Bengal, 1.26 Mha in Chhattisgarh, 0.20 Mha in Jharkhand, and 0.17 Mha in Assam (**Table 2**). On an average, 60% of the created irrigation potential is utilized for irrigation. In Assam and Jharkhand states, utilizable irrigation potential is below 50% level.

II. Technological options for Efficient Use of Water in Agriculture

In general, the eastern region receives adequate rainfall and has favourable ground water reserves. However, the amount and timing of precipitation is highly erratic. Drought is a frequent event in the plateau due to erratic distribution of rains. Some areas do not receive enough rainfall, and many areas face scarce groundwater availability. Waterlogging occurs in the deltaic alluvial area near the sea coast due to high rainfall, reverse flow from canal irrigated highlands and the saucer-shaped

Table 2. Irrigation status in eastern India

State	Irrigation status							Ground-water resource (Mha-m)	Ground-water development (%)
	Irrigation potential created (Mha-m)	Net irrigated area (Mha)	Per cent utilisa-tion	Irrigated area in *rabi* (Mha)	Source-wise irrigated area, % of total irrigated area				
					Canal	Well	Others		
West Bengal	4.94	3.91	79.08	1.91	23.5	57.6	18.9	2.31	38
Bihar	4.55	2.51	55.20	1.03	28.4	54.0	17.6	2.70	46
Jharkhand	0.43	0.20	46.30	-	48.9	51.1	-	0.65	33
Odisha	3.62	2.69	74.25	-	64.8	14.8	20.4	2.10	23
Chhattisgarh	1.82	1.26	69.20	0.89	65.2	13.1	21.7	1.61	6
Assam	0.51	0.17	33.33	0.12	87.1	1.2	11.7	2.47	9
Eastern UP	5.88	4.20	71.67	1.68	27.7	68.4	3.9	8.11	47
Eastern India	21.75	14.89	59.78	-	49.4	37.2	13.4	19.95	29
All India	81.10	72.90	89.90	-	30.4	57.9	11.7	36.03	42

Source: Ministry of Water Resources (2000-2001) and Irrigation Departments, Govt. of Chhattisgarh, Assam, Bihar, West Bengal, Odisha, Jharkhand and Uttar Pradesh physiographic nature of the land. Large temporal and spatial variations with co-existence of acute scarcity and excess of water call for immediate action (Sikka et al., 2009). Number of technologies have been developed for efficient use of water resource in agriculture in this region. These include appropriate integrated land and water management practices like i) soil-water conservation measures through adequate land preparation for crop establishment, rainwater harvesting and crop residue incorporation, ii) conservation tillage to increase water infiltration; reduce runoff and improve soil moisture storage; and iii) adequate soil fertility to remove nutrient constraints on crop production for every drop of water available through either rainfall or irrigation. In addition, novel irrigation strategies such as supplementary irrigation (some irrigation inputs to supplement inadequate rainfall), deficit irrigation (omitting irrigation at times that have little impact on crop yield), and drip irrigation (delivering irrigation water to plant rooting zones) can also minimize soil evaporation thus making more water available for plant transpiration. In sandy soils of low fertility, nutrient deficiencies often override water shortage as the main factor limiting crop productivity. Some of the selected low-cost and eco-friendly water saving technologies which have proved effective in different parts of the region are briefly discussed hereunder.

I. *Rainwater Harvesting and Water Conservation Technologies*

i) Moisture storage pits technology for coastal areas of West Bengal

The coastal areas of the eastern region, particularly the Sunderbans in South Bengal, suffer chronically from scarcity of soft/fresh water. The Sunderban Development Board of Govt. of West Bengal launched a project involving excavation/re-excavation of ponds/ tanks for harvesting of rainwater. It was implemented by a local NGO 'Tagore Society for Rural Development'. So far more than 1000 ponds, tanks, canals, *nullahs,* etc. have been excavated in the Agar, Basanti and Gosaba blocks in South 24 Parganas district and water storage capacity has been substantially enhanced. In addition to excavation/ re-excavation of ponds/tanks, etc. the society has adopted small plots for introducing 'moisture storage pits technology' in uplands and midlands by dividing large stretches of land into small plots. The moisture storage pits are dug at the lowermost corner of each plot to collect runoff rain water. Through farmers' initiative, large number of such runoff water storage pits have been dug all over the islands. The technology has yielded several benefits, *viz.*, improved groundwater level in low lands, harvested rain water for most part of the year, increased irrigation and farm productivity, promotion of sweet water fishery, and creation of employment opportunities. All the Village Users Committees/ Self Help Groups have now taken over the use and maintenance of the community assets ensuring sustainability of the project.

ii) Rainwater harvesting and water conservation technology in drier tracts of West Bengal

The Heerbandh Development Board in Bankura district, West Bengal introduced this technology to farmers to harvest rainwater by excavating small tanks under 30-40 model (*i.e.*, 30 ft x 40 ft plots) on their own land.

Principles and benefits of this technology are:

- During the monsoon season, rainwater is harvested in small tanks dug and used to irrigate the *rabi* season crops. As a result of introduction of this method, an area of about 100 acres (40 ha) has been brought under double cropping comprising of *kharif* paddy followed by low water requiring *rabi* crops like oilseeds.
- Tube wells sunk in the area 5 years earlier, which had dried up and rusted due to lowering of water level, have started functioning now due to recharging of groundwater level.
- Using this technology, many farmers are now raising mango orchards to augment their income.
- The technology has provided farmers with means of not only a better livelihood but also for water conservation and green cover development.

iii) In-situ *rainwater conservation in paddy fields for multiple uses*

Directorate of water management (DWM), Bhubaneswar standardized the technology for *in-situ* rainwater conservation in paddy fields for multiple uses. In 8% of the total paddy field, small dugout ponds of 2.5 m depth and 1:1 side slope have been found to be beneficial. The pond is used for short-duration aquaculture during monsoon and its embankment is used for growing horticultural crops. The conserved rainwater in the pond is used for giving supplemental irrigations to *kharif* paddy and irrigating *rabi* crops. Total cost for construction of a pond in 800 m^2 in 1 ha area will be about Rs. 67,000/- involving labour input of total 900 man days. The yield of *kharif* paddy increased from 1.8 to 4.9 t ha^{-1}; in addition, it also gave fish yield of 1.4 t ha^{-1}. The cropping intensity increased up to 200%.

iv) Subsurface water harvesting structures for coastal lowlands

High to very high salinity of water is the major constraint to agricultural production in the coastal lowlands of eastern region. Fresh water floats above the saline water below ground in such areas which could be tapped through construction of subsurface water harvesting structures (SSWHS) to meet the irrigation demand of *rabi* season crops as well as pisciculture. To extract water from these structures, pump of capacity up to 2 HP is suitable to avoid saline water ingression into the fresh water layer. The depth of structure should be restricted up to 5 m below ground within sandy zone. To create a water harvesting structure of 4000 m^3 capacity in an area of 0.1 ha with 4 m depth, 550 man days of labour will be required. Average cost for construction of SSWHS is Rs. 14 m^{-3}. It results in higher area of irrigation and higher cropping intensity and crop productivity. Average water productivity of SSWHS involving pisciculture and *rabi* vegetables is Rs. 36 m^{-3}. Participatory approach of implementing SSWHS improves the financial status of the poor farmers living below poverty line in coastal waterlogged areas and also gives better employment opportunity.

II. Rainwater Conservation and Management in Sloping Land

i) On-farm rainwater management technology for sloping land

Rainwater is harvested through construction of small scale water harvesting structures (WHS) called on-farm reservoirs (OFR) along the slope of farmers' fields. Ground water structures like dug wells and ditches are also excavated to store the runoff rainwater. This technology has been successfully implemented in Keonjhar district of Odisha and Darisai (Ghatshila) block of Jharkhand.

Benefits of the OFR technology are:

- The OFR technology helps in conservation and utilization of harvested rainwater. Groundwater level in the project area has improved due to recharge.
- Stored water in the OFRs can be used both for saving *kharif* rice during drought and also to raise *rabi* crop, thus increasing cropping intensity.
- The cost of this technology could be recovered by additional income generated from the project in three years with adoption of improved packages of practices for *kharif* paddy and *rabi* crops like gram, wheat and vegetables.

ii) Rainwater management in Chhattisgarh

The model of rainwater harvesting in the farm ponds at different toposequeces developed by IGKV Raipur depicted below (**Figure 1**) have helped the rainfed farmers of Chhattisgarh state immensely. Construction of on-farm reservoirs (OFRs) in series from top to lower level, helps in harvesting excess runoff. Water harvested in the OFRs also recharges the ditches, wells and ponds located in the recharge zone. This system helps in drought mitigation in *kharif* and growing second crop in *rabi* season.

iii) Rainwater harvesting technologies for eastern plateau region ('Jaldhar' models)

Located in the eastern plateau region, Purulia district is characterized by soil with low water retention capacity, low and erratic rainfall, undulating landscape with high runoff, high soil erosion and depleted vegetative cover. All these factors have caused frequent water stress/ droughts affecting agriculture. In this soil and agro-climatic situation, rainwater harvesting and moisture conservation through 'Jaldhar 30 x 40 Model' and 'Jaldhar 5% Model' were found to be effective and encouraged the farmers to adopt the technology in their own fields.

This Jaldhar model has been designed and implemented by an NGO, PRADAN, working in the

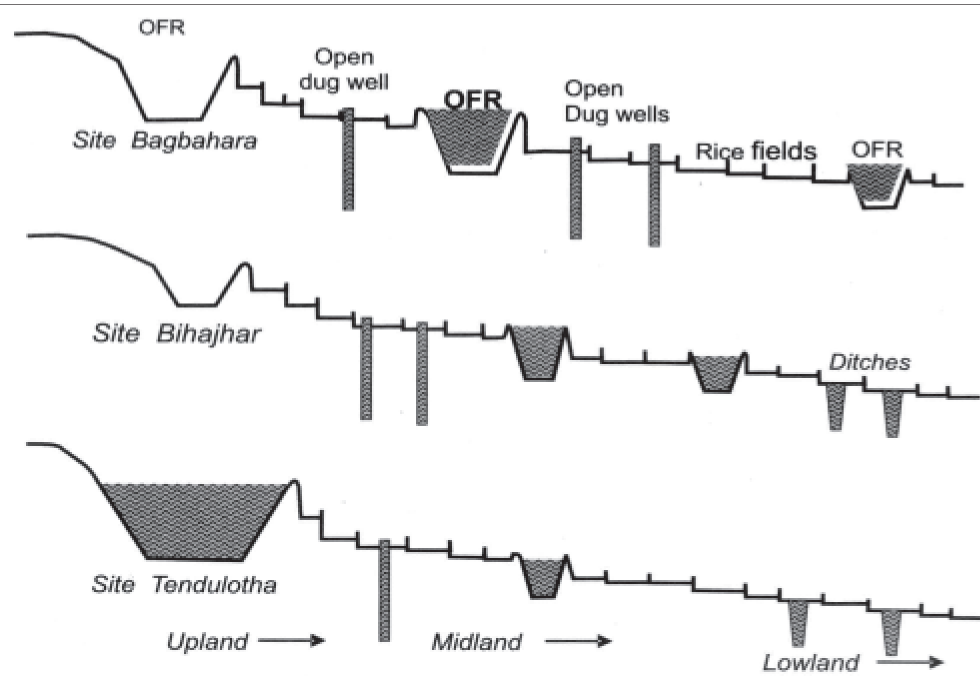

Figure 1. Location wise on-farm reservoirs (OFR), open dug-wells and ditches at Bagbahara in Chhattisgarh

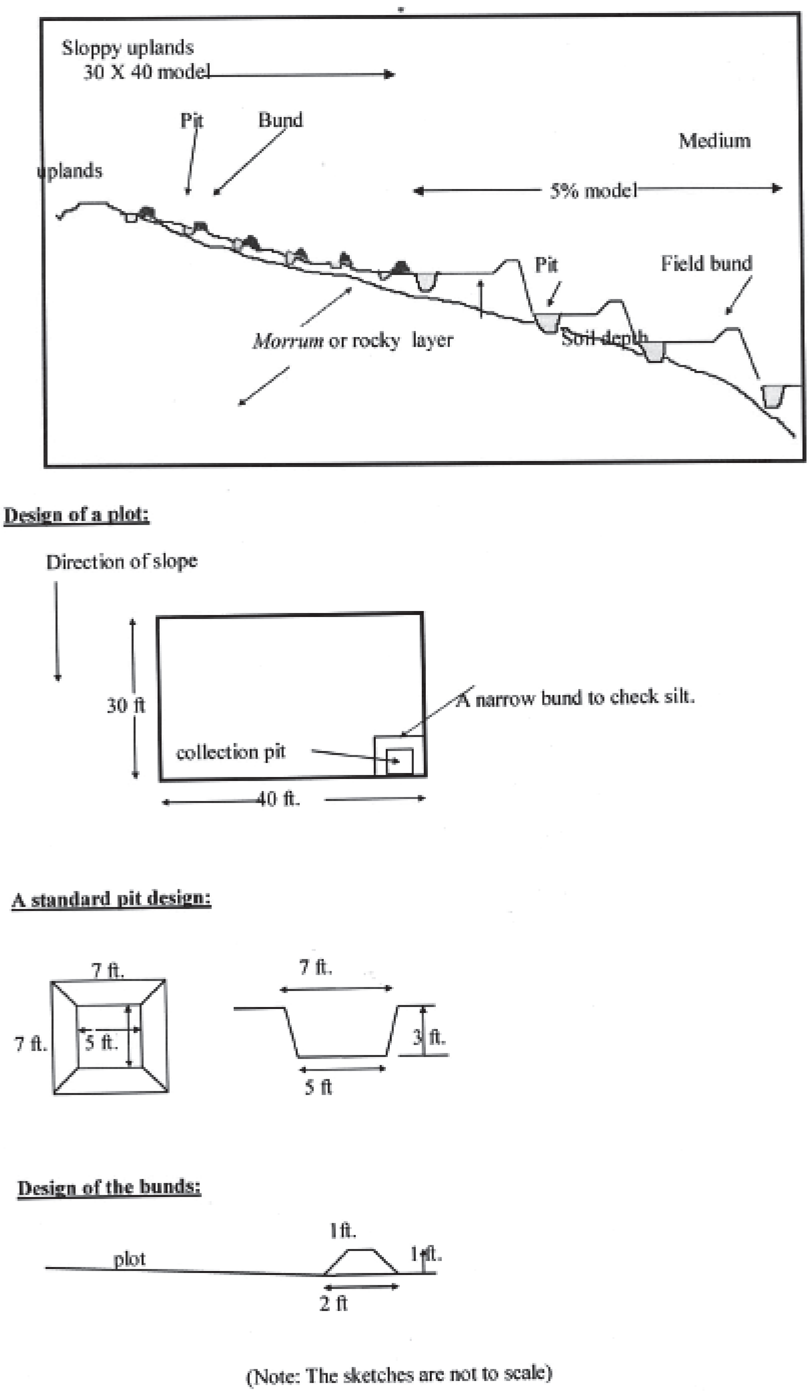

Figure 2. Design of plot, pit and bund under 30′ x 40′ and 5% Jaldhar model of rainwater harvesting in the plateau region (Note: The sketches are up to scale).

dry land plateau areas in the eastern region. They originally designed the model more than a decade ago. Since then, the model has undergone modifications and its utility has been continually enhanced (**Figure 2**). These technologies are user-friendly and within the financial reach of poor farmers. They have large scale replication potential in water-scarce plateau land. Salient features of the Jaldhar water saving technologies are given below.

a) Jaldhar 30 × 40 model: Unterraced and unbunded upland with varying degrees of slopes is divided into smaller plots, each 30 ft along and 40 ft across the land slope. Hence, each plot is 1200 sq ft. In each plot, water collection pits are dug at the lowest point of the plot. The volume of each pit is about 100-110 cubic feet. The earth excavated out of the pit is used to construct bunds on the plots. The pit area is not more than 3-4% of the individual plot. Layout of the plot is designed in staggered fashion as far as possible to facilitate uniform seepage of water collected in the pits across the slopes. This technology helps in arresting runoff rainwater from the plots. The runoff water gets deposited in the pits. Water from large number of such plots travels below the earth downstream to recharge the aquifer. It has made possible the growth of permanent agroforestry as well as raising of good upland paddy, vegetables, pulses, oilseeds and several other crops.

b) Jaldhar 5% model: Here, water bodies (pits) are dug at the lowest point of each plot covering only 5% of its area. Minimum depth of each pit is 5 ft. But most of the farmers who are raising a second crop after paddy may choose to dig pits with a depth of even 10 ft. Such pits of larger depths under 5% Model have been preferred for implementation under government-sponsored programmes like MNREGA, RKVY and others.

Jaldhar technologies are user-friendly, within the financial reach of poor farmers and have large scale replication potential in water-scarce plateau land. Many farmers in the drier tracts of West Bengal in the districts of Bankura and Purulia have adopted this technology. With small pits dug in 5% area of a farm of 1200 to 2000 sq ft. may increase farmers' income by Rs 15,000 to 25,000 (through intensified cultivation of rice and vegetables). Many farmers have even switched from low yielding *kharif* rice to high value vegetables for higher income. Application of this water harvesting pit technology in large number of contiguous plots has enhanced the moisture regime in the area and often pits at the lower reaches exhibit the characteristics of perennial water sources.

iv) Micro level water resource development through tank-cum-well technology

For rainwater harvesting and utilization, the tank-cum-well system technology along the drainage line in a watershed is recommended for plateau areas having 2 to 5% slope. Developed by the Water Technology Centre, Bhubaneswar, this technology involves a system of tanks and dug wells in a sequence. While tanks store runoff water, which is recycled for irrigation, the open dug wells harvest water seeped in from tanks. Application site for the technology is selected in such a way that the area has a well defined valley where the runoff flows either as overland flow or channel flow. The well is constructed about 100 to 300 m downstream of the tank to tap the water that is lost by seepage from the tank. A set of 15 tanks and wells is required for a catchment area of 500 ha to irrigate 60 ha area. With an investment of Rs 55,000 ha^{-1} of net command area, it can increase the cropping intensity to 166%. Rupees 30,000/- extra gross income ha^{-1} yr^{-1} can be achieved with an additional employment generation of 115 man days. Farmers in Keonjhar district of Odisha have successfully raised a second crop through the irrigation facility created by the harvested rainwater in tanks and wells. Farmers could recover about 80% of total investment on this technology by the second year. This system can be constructed and maintained by locally available skill, rendering it easily adoptable.

III. Land Shaping Technologies for Crop Diversification

i) Land Shaping Technology for Low-lying Coastal Region

Krishi Vigyan Kendra (KVK) of the Ram Krishna Mission conceptualized and developed the 'Land Shaping Technology' in 1980 to address the twin problems of raising the level of cultivable land and harvesting rainwater in Sunderban area of West Bengal for multiple cropping. Over the years, the technology has undergone modifications and fine-tuning through collaborative participation of the farmers and KVK scientists. This is a multi-faced method by which HYVs of rice replace the low yielding indigenous rice in rainy season and makes growing of high value vegetable crops possible during winter season. At the same time, pisciculture and duck-rearing in ponds and growing of fruit crops are possible on the embankment developed by the dug-up soil.

Principles of land shaping are

- Excavation of 1/5th area of the lowlands up to a depth of 9 ft
- Height of the adjoining lowland raised up to 1.5 ft
- Pond embankment dimension: 5 ft wide and 4 ft high
- Land embankment around the area: 3 ft wide and 2 ft high
- About 6 to 9 acre inch of rainwater can be harvested and stored in the pond.

Benefits of the technology are

- Engineering solution for productive use of the lowland
- Three dimensional (land, water, air) option for cropping
- Diversified cropping possibilities with integrated approach
- Introduction of double and triple crops

- Additional crop in ponds and land embankments
- Off-season crops fetching higher market price
- Water and energy saving module

This technology has made significant impact on agriculture, ecology and economy of the coastal areas in Sunderban. Farm income has increased several times. The technology requires an investment of about Rs 20,000/- for a farm of 1.5 bigha (0.2 hectare).

ii) Raised and Sunken Bed Technology for Medium and Lowlands

In medium and lowlands of eastern India, saturated and oversaturated soil conditions do not permit cultivation of any crop other than lowland rice. Productivity of water in rice cultivation is very low and rice farming as such, is not very remunerative. To make farming more remunerative in such areas, this technology has been developed by Directorate of Water Management, Bhubaneswar. The land is converted into alternate sunken and raised beds (1: 1) each of 30 m length and 5 m width. Different vegetable crops of local importance are grown on the raised beds. Sunken beds are used for growing lowland rice or other aquatic crops like colocasia. Fish spawn can also be raised up to fingerling stage in the sunken beds together with rice. Adoption of this technology increased the productivity (rice equivalent yield) of farm. Singh et al. (2005) reported 600% enhancement in the productivity with adoption of this technology at small and marginal farms of Khurda district, Odisha (0.36 kg m^{-3} for rice cropping, and 2.62 kg m^{-3} for diversified cropping). In addition, fish yield of 1 t ha^{-1} was obtained. Additional income of Rs. 60,500 ha^{-1} yr^{-1} can be achieved.

iii) Farm Pond-based Agricultural Diversification Model for Rainfed Areas

For rainfed medium and lowlands, rainwater harvesting system was designed and agricultural diversification model (on-dyke horticulture, fisheries, cultivation of diversified field crops, short-term fruits like papaya, banana, floriculture like marigold, tube rose etc.) with harvested rainwater was developed by the Directorate of Water Management, Bhubaneswar for small and marginal farmers through multiple use of water. Cost of developing the water harvesting system is about Rs 40 m^{-3}. The model was implemented in Bahasuni watershed of Dhenkanal, Odisha and cropping intensity could be increased up to 200% with its adoption. Due to harvesting of spring water and rainwater, irrigated areas of two villages of the watershed increased from 3.2 to 26.5 ha, where 55 tribal farm families were benefited. Additional income garnered was Rs. 25,000-30,000 ha^{-1}. The technology has been included under the Mahatma Gandhi National Rural Employment Guarantee Act (MGNREGA) for implementing in watersheds of eastern states of India.

iv) Pond-based Farming System for Deep Waterlogged Areas

Due to poor drainage, saucer-shaped topography and high monsoon rainfall, some parts of east coast of India remain waterlogged (>1 m water logging above surface) and unproductive. To stabilize and enhance the net income from such waterlogged ecosystems, pond-based farming technology (deep water rice in *kharif* + salt tolerant vegetables like watermelon, ladies finger, spinach, chilli in winter + on-dyke vegetables-fruits + fish inside pond) was developed and implemented in deep waterlogged areas (1-2.5 m water depth) of coastal Odisha. It increased cropping intensity to 200%, gave water productivity of Rs. 7.2 m^{-3} and generated additional income of Rs. 25,000 ha^{-1} yr^{-1}.

IV. Technologies for Conservation of Soil Moisture and its Efficient Use

i) Vegetable Cultivation on Bunds of Paddy Fields Utilizing Retained Soil Moisture

Bunds or '*ails*' of paddy fields are raised and broadened to conserve soil and water. On an average, 5-10% of the field is available for vegetable cultivation. Nimpith Krishi Vigyan Kendra, West Bengal provided technical support to farmers to grow vegetables on the bund or '*ails*' of paddy fields. The farmers modified and developed some practices including crop varieties, nutrient use, intercropping and multi-tier cropping system according to their individual situations. Seeing the benefits, farmers of the neighbouring villages have started adopting this technology. An annual income of Rs 15,000/- from 1×400 m bund is reported by farmers.

ii) Zero Tillage Technology for Water Management

This technique aims at enhancing and sustaining farm production by conserving and improving soil, water and biological resources. Essentially, it maintains a permanent or semi-permanent organic soil cover (*e.g.*, a growing crop or dead mulch) that protects the soil from sun, rain and wind, and allows soil microorganisms to take on the task of 'tilling' and soil nutrient balancing. After harvest of *kharif* rice, wheat is sown on the rice field with minimum or zero tillage. This is facilitated by the increased moisture content in the soil due to mulch debris kept on the field from the preceding crop. It also helps minimize the soil erosion.

In a field study on the effect of sowing time and method on water productivity of *rabi* horse gram conducted at Balipatna in Khurda district, Odisha, water productivity was found to be higher under minimum tillage than under no tillage. Then, within the minimum tillage treatment, early-sown crop recorded higher yield and water productivity obviously due to better utilization of residual soil moisture and/or efficient tapping of water from shallow water table. Thus, when irrigation water is not available for raising dry-season crops, early sowing of seeds using minimum tillage can enhance the water productivity.

Following are the benefits of zero tillage technology:

- The zero tillage technology helps in retaining soil moisture content at 26 to 32%, which is required for germination of wheat seed within the normal sowing period i.e. in November.
- Twenty-five per cent irrigation water can be saved as compared to conventional tillage system.
- Grain yield is also increased by more than 50%.

iii) Mulching for Reducing Evaporation Loss of Soil Moisture

Comparative effects of using one 30 mm irrigation and paddy-straw mulch @ 5 t ha^{-1} on field surface on water productivity of sweet potato during *rabi* season were studied at Balipatna in Khurda district. Water productivity of the crop was highest under straw-mulch treatment. While the early application of irrigation water produced moderate benefits, late application of irrigation had no significant effect on tuber yield and water productivity of the crop. Use of mulch thus can enhance water productivity several folds during dry season, when no irrigation water is available.

V. Novel Agro-techniques for Judicious Water Use

i) Reducing Water Use in Rice Cultivation

Dominant system of rice production in India is transplanting in the puddled land that is kept continuously submerged with 5-10 cm floodwater throughout the growing season. Water requirement for land preparation consisting of soaking, ploughing and puddling of soil is theoretically 150–200 mm, but it can be as high as 650-900 mm when the duration of land preparation is long, *i.e*. 24 to 48 days (Bhuiyan et al., 1995). Water input during crop growth varies from 500-800 mm to more than 3000 mm. Water outflows from a rice field through evaporation, transpiration, seepage, percolation and surface run-off. Of various outflows of water from a rice field, only transpiration is productive as it directly results into crop growth and yield formation. Seepage is the lateral flow of water through field bunds and percolation is the vertical flow of water to below the root zone. It has been estimated that seepage and percolation together account for 50-80% of the total water input to the field (Sharma, 1989) and these flows are unproductive as they do not contribute to crop growth and yield. For a rice crop of 100 days' duration, total water requirement varies from 675 to 4450 mm, depending on the season and soil characteristics. Water requirement for rice growing in many lowland areas is 1500–2000 mm. Irrigation water requirement of rice crop depends on several factors. Soil texture and percolation losses play a major role in this respect.

ii) Saturated soil culture and alternate wetting and drying

The 'water-saving irrigation techniques' for rice production aim at reducing seepage and percolation rates by i) reducing the depth of floodwater in field, or ii) keeping the soil just saturated, or (iii) alternate wetting and drying, *i.e*., allowing the soil to dry out to a certain extent before re-applying irrigation water. Water-saving irrigation techniques, however, run the risk of reducing rice yield from possible drought-stress effects. Establishment of relationships between water input and rice yield is needed to know the extent of water input reduction without reducing yield and to optimize the use of scarce water in rice production. The optimum intermittent period for delaying irrigation and saving of irrigation water in *kharif* rice has been worked out. Optimum period is 2 days for locations with light textured soils, 3 days for locations with medium-textured soils and as high as 5 days for locations with silty loam soils. Intermittent flooding saves 21-66% water as compared to continuous flooded condition. In saturated soil culture, soil is maintained as close to saturation as far as possible by providing shallow irrigation (to obtain about 1 cm floodwater depth) a day or so after the disappearance of standing water. In alternate wetting and drying treatments, irrigation water is applied to obtain 2–5 cm floodwater depth after certain days of disappearance of ponded water.

iii) Aerobic rice

With the development of suitable varieties and improved management practices, there is growing interest in aerobic rice cultivation. In a field study conducted in Deras Irrigation Command Area in Khurda district of Odisha, grain yields of rice under aerobic condition were 2.57–3.95 t ha^{-1} and there was a yield reduction of 18.7–47.1% compared to flooded condition. Irrigation water input was 540-700 mm under aerobic and 1250 mm under flooded soil conditions. As reduction in water use was more pronounced than that in the grain yield, water productivity under aerobic cultivation increased by 22.4–45.0% compared to flooded condition.

iv) Supplemental and Deficit Irrigation for Rainfed Areas

Deficit irrigation, a strategy which maximizes the productivity of water by allowing crops to sustain some degree of water deficit and yield reduction, holds promise for severely water-shortage areas. The ICARDA studies in Syria have shown that applying 50% of the supplemental irrigation requirement only reduces yields by 15%. For deficit irrigation to function as a realistic strategy, we need to understand better the relationship between yield and water deficit and we need to identify the types of support and incentives that farmers need to adopt the practice. Increased water productivity of field crops in the dry season may be achieved through proper irrigation scheduling at critical growth stages.

v) Improved Irrigation Methods

Performance of drip and conventional furrow irrigation methods in maize, cowpea, sunflower and tomato was evaluated at Deras Minor Irrigation Command in Khurda district, Odisha (Mandal et al., 2013). Though the crop yields under drip and furrow irrigation methods were similar, substantial saving of irrigation water was recorded under the drip method. Saving of water under drip against the conventional furrow irrigation method was 29% in maize and 30% in tomato. Use efficiency of irrigation water increased by 36% in maize and 32% in tomato when water was applied by drip than conventional furrow method. About 40% irrigation water in cultivation of medicinal plant stevia (*Stevia rebaudiana* Bertoni.) following rice could be saved in Khurda district, Odisha by practicing drip compared to conventional surface irrigation method (Behera et al., 2012).

Constraints Experienced by the Farmers in Adoption of Water Management Technologies

Eighty per cent of the farmers have reported the following constraints which bottlenecked the adoption of recommended scientific water management technologies in their specific farming systems (Ghosh et al., 2005):

- Adoption of soil and water conservation measures requires a community approach, which is still not common in practice as response of community is often poor.
- Unassured supply of irrigation water in canal command and unpredictable water availability during rainy season hinder the adoption of scientific irrigation schedules for different crops.
- Free-flooding method of irrigation leading to uncontrolled supply of water in irrigation command often does not allow the following of scientific water management practices.
- There is a high initial expenditure to construct water conservation/harvesting structures.
- Farmers prefer to grow rice crop instead of low duty crops because of their marketability and management practices and their house-hold food security.
- Regulation of irrigation/drainage is not feasible at individual level and requires group action.
- Farmers face difficulty to get inputs like mulching material, lining material, etc.

For efficient management of water in agriculture, farmers' participation through formation of local level water user institutions *viz.*, *pani* panchayat/ water users' association (WUA) is vital. The equity concept of water distribution assumes importance under the irrigation commands. Benefits and cost sharing will form the basis of water distribution in future. The central and state governments in collaboration with other institutions and line departments have already formulated policies for participatory irrigation management (PIM). Overcoming the energy constraints by an individual is a difficult proposition, especially in the case of small and fragmented holdings. Formation of farmers' groups in term of pump users group, tube well users group, etc. is of paramount importance in this regard. Participatory operation and maintenance of resources also ensure sustainability.

Soil Acidity Management Technology

Acid soils occupy about 18.0 Mha of land in India (NAAS, 2010). These soils have been categorised under exclusively acid soils (pH <5.5) with an estimated area of 5.09 Mha, acidic (pH<5.5) and water eroded soils (5.72 Mha) and acid soils under open forest (< 40% canopy) with an area of 7.13 Mha. Such soils are spread in the states of Kerala, Nagaland, Manipur, Tripura, Mizoram, Meghalaya, Assam, Arunachal Pradesh, Chhattisgarh, Jharkhand, West Bengal, Odisha etc. (**Table 3**).

Table 3. States with large area under acid soils in eastern and north-eastern India (Source: NAAS, 2010)

State	TGA (km^2)	Area ('000 ha)				
		Acid soils (< pH 5.5)	Acid soils under water erosion	Acid soils under open forest	Total	Area (% of total)
Nagaland	16,579	17	45	1,454	1,516	91
Manipur	22,327	115	86	1,396	1,597	72
Tripura	10,486	101	83	525	709	67
Kerala	38,863	1,961	378	87	2,426	62
Mizoram	21,081	150	0	1,013	1,163	55
Meghalaya	22,429	52	175	796	1,023	46
Assam	78,438	411	1,319	265	1,995	25
Arunachal	83,743	300	501	968	1,769	21
Chhattisgarh	134,805	812	1,383	147	2,342	17
Jharkhand	79,714	226	394	115	735	09
West Bengal	88,752	240	165	13	418	05
Odisha	155,707	107	51	45	203	01

Table 4. Degree of soil acidity and the pH range as per Soil Science Society of America (1987)

S. No.	Soil category	pH range
1	Extremely acidic	< 4.5
2	Very strongly acid	4.6 – 5.0
3	Strongly acid	5.1-5.5
4	Moderately acid	5.6-6.0
5	Slightly acid	6.1-6.5
6	Neutral	6.6-7.3

Health of Acid Soils and Crops

The indicators of health of acid soils in order of importance are soil pH, exchangeable Al^{3+}, available P, water holding capacity, CEC, exchangeable Ca^{2+}, soil texture, soil organic matter, and microbial population. In hilly terrain, extent of soil loss and nutrient loss are important (Panda et al., 1996; Sarkar, 2013).

Most of the acid soils are deficient in a number of plant nutrients, both macro and micro, indicating poor soil health. A recent study on the sulphur (S) and micronutrient status of acid soils of eastern region, indicated widespread deficiency of S, boron (B), and zinc (Zn) (Anonymous, 2017), which is highest in soils of Jharkhand, probably because of lighter texture and poor organic matter content. Information regarding availability of molybdenum (Mo) in acid soils of India is quite meagre; Mo deficiencies to the extent of 55 and 59% in acidic soils of Jharkhand and Odisha have earlier been reported. Reduced base saturation causes nutritional problems, especially in animals, such as milk fever and grass tetany. Nodulation in legumes and symbiotic nitrogen fixation are adversely affected by deficiencies of Mo, calcium (Ca), magnesium (Mg) and phosphorus (P) in acid soils.

Crops perform differently in acid soils depending on their preference to grow well in a certain range of soil pH. In general, yields of pulses, oilseeds, maize and wheat are poor in low pH soils (Mandal et al., 1975). On the other hand, rice, minor millets, potato, *mesta*, niger, mustard and plantation crops, such as tea, coffee perform well under acidic soil environments. Crops like soybean, pigeonpea, potato, cotton and vegetables respond to liming, indicating their sensitivity to soil acidity.

Degree and Forms of Soil Acidity

Extent of soil acidity depends on different factors, such as rainfall, slopy terrain, soil type, fertilizers, crop removal of basic cations, and organic matter status. Interaction of these factors influences the amount and speciation of nutrient ions in the soil solution and ultimately determine their availability for plant growth. Degree of soil acidity is measured in terms of soil pH in a soil testing laboratory **(Table 4)**.

Acid Soil Management

The two-pronged strategy of liming acid soils to neutralize soil acidity and adding fertilizers to ensure adequate supply of nutrients to crops holds great promise to enhance the productivity of acid soils. Liming should be practiced only to neutralize the low magnitude active acidity which is due to hydrogen and aluminum ions in the soil solution and part of the exchange acidity. The active acidity influences most of the plant root and the microbes around the rhizosphere. Only a small amount of lime is required to neutralize this acidity. Liming may not be done to neutralize the reserve acidity.

Earlier approach of liming of soils based on lime requirement (2-4 t ha^{-1}) and broadcast method of application proved to be uneconomical and resultantly was least popular with the farmers. On the contrary application of lime @ 1/10th of lime requirement of soils in furrows along with the fertilizers turned out to be economical and acceptable to farmers.

Crop Response to Lime and Fertiliser Use

Altogether, 871 experiments on farmers' fields were conducted under ICAR Network Project on Acid soils (2000-2005) involving lime, fertilizer, FYM, and crops in different states of India with large area under acid soils (**Table 5**). Lime @ 2-4 q ha^{-1}, which was 1/10th of the lime requirement (LR) of the soil, was applied at

Table 5. Effect of liming and fertilization on crop yields in different acid soil regions of India

State	Crop	FP	FP + Lime	Rec. NPK	Rec. NPK + Lime
Assam	Rapeseed	7.3	8. 6 (18)	10.5 (43.8)	12.9 (76.7)
	Green gram	10.1	11. 5 (14)	12.3 (21.6)	15.1 (49.0)
Himachal Pradesh	Maize	23.5	27. 4 (17)	34.0 (44.7)	37.5 (59.6)
	Wheat	17.4	20. 2 (16)	27.9 (60.3)	31.7 (82.2)
Jharkhand	Maize	17.1	21.5 (26)	25.1 (46.9)	29.6 (73.3)
	Pigeonpea	7.4	10.0 (34)	12.0 (61.3)	15.2 (105.3)
Kerala	Black gram	3.5	4. 4 (26)	4.0 (14.8)	5.6 (58.3)
Maharashtra	Groundnut	14.2	16.7 (18)	19. 9 (40.1)	24.3 (71.2)
Meghalaya	Maize	10.6	13.8 (30)	21.1 (99.1)	30.6 (189.2)
Odisha	Groundnut	8.6	12.5 (45)	14.3 (66.3)	17.9 (108.1)
	Pigeonpea	10.5	15.1 (44)	16.4 (56.2)	20.2 (92.4)
West Bengal	Mustard	4.8	6.5 (35)	7.0(45.8)	9.1 (89.6)
	Wheat	10.2	15.5 (52)	15.0 (47. 1)	19.0 (86.3)

*Figures in ( ) indicate % increase over farmer's practice

Figure 3. Application of lime in line-sowing

the time of sowing in furrows (**Figures 3** and **4**). Results showed that lime with recommended fertilizer dose increased crop yields by 49 to 189% over farmers' practice. Response of crops to the combined application of NPK and lime was more than the individual effects of lime and fertilizer, indicating synergy and benefit of a combined application. Results of the field studies have been presented earlier in an ICAR publication (Sharma and Sarkar, 2005). Conjunctive use of FYM in lime + NPK plots resulted in higher crop yields and better soil health compared to the lime + fertilizer plots. This could be due to the fact that organic manures reduce Al concentration in soil solution due to precipitation of Al ions by OH ions released from the organic ligands.

Benefit: cost ratio followed the order: Farmers' practice (FP) < FP + lime < 100% NPK < 100% NPK+ lime (**Table 6**). The benefit: cost ratio in lime + NPK plots varied from 1.4 to 4.3 with different crops and locations. The net returns, therefore, were Rs. 0.4 to 3.3 per rupee invested depending on the extent of soil acidity and crop response.

Extensive work on different vegetable crops, pulses, and oilseeds in Odisha show the benefit of such a practice in acidic soils (Jena, 2008, 2013; Pattanayak and Sarkar, 2016). Long-term studies of Ranchi have validated the benefits of lime application in soybean-wheat and maize-wheat sequences (Mahapatra et al., 2018).

Technology of lime application in soils which has emerged out of the network study is given in the box below.

Target area: Rainfed/irrigated uplands and medium lands (pH <5.5)

- Crops: Pigeonpea, soybean, groundnut, lentil, pea, cotton, maize, wheat, linseed, mustard etc.
- Rate: 200 to 500 kg lime ha^{-1} in furrows (10% of LR for monocots & 20% of LR for dicots), mixed with compost. The rate may be high for fine textured and organic matter-rich soils.
- Source: Locally available lime source, cheap with good neutralizing value. Materials, such as basic slag, paper mill sludges, limestone/dolomite or, marketable lime may be used depending on the availability, price etc.
- Method: To be applied in furrows along with recommended fertilizer doses manually or through seed-cum-fertilizer drills at sowing of each crop. Crops and cropping sequences: Pigeonpea, soybean, groundnut, lentil, gram, pea, cotton, maize, sorghum, wheat, linseed, mustard etc. Any prevalent cropping system may be followed as lime is to be added to every crop as per lime requirement of the soil.

Soil Amendments and their Use

Several materials have been identified as good soil

Table 6. Benefit : cost ratio of liming and fertilization of crops in acid soils

Acid soil region / State	Crop	Farmers' practice (FP)	FP + Lime	100% NPK	100% NPK + Lime
Assam	Rapeseed	2.30	2.72	2.77	3.40
	Summer green gram	2.36	2.69	2.71	3.19
Himachal	Maize	1.15	0.97	1.99	1.73
	Wheat	0.73	1.02	1.46	1.79
Jharkhand	Maize + Pigeonpea (Maize equivalent yield)	1.52	1.85	1.97	2.37
	Pea (pod)	1.70	1.87	2.39	2.78
Kerala	Black gram	1.47	1.63	1.36	1.84
Maharastra	Groundnut	1.25	1.40	1.61	1.76
Meghalaya	Maize	1.00	1.27	3.58	3.45
	Mustard	1.00	0.63	1.32	2.35
Odisha	Groundnut	0.76	1.03	1.17	1.37
	Pigeonpea	1.13	1.48	1.59	1.80
	Groundnut + Pigeonpea	1.64	2.27	2.56	2.93
West Bengal	Mustard	1.70	3.20	3.00	4.30
	Wheat	1.40	2.70	2.20	3.00
Mean of all crops		1.41	1.78	2.11	2.54

ameliorant for acid soils. These are agricultural lime, dolomite, industrial wastes, such as basic slag, paper mill sludges, carbonated pressmud from sugar industry etc. At present, there is no arrangement in place, for ensuring timely supply of soil amendments to farmers in different acid soil regions. Though the material is available, but its grinding, bagging, transport, marketing and quality control have not been arranged by the State Governments. What is needed is that the state Governments should ensure that lime/dolomite/paper mill sludge/basic slag (choice based on local availability/price/quality etc.) is made available at block/panchayat level (preferably in small packing of 10-25 kg as per the average land holding in the area). Close linkage with industry is necessary. Quality assurance is necessary before supply of the material (size, Ca content, neutralizing value etc.).

Soil testing facilities in most of the laboratories are inadequate. This has resulted in poor transfer of data from soil testing laboratories (STLs) to the farmers. This issue needs to be debated and addressed with all seriousness.

In acid soil regions, lime dose is fixed based on the lime requirement of the soil. It is necessary that STLs have a ready reckoner for deciding on the dose of lime for crops, based on pH, organic carbon and soil texture of major soil groups in the state. Further, periodic monitoring (every 3 years) of soil test values must be done to make adjustments in doses of lime and available plant nutrients, especially the ones which are often deficient. Linking of soil health cards with lime and nutrient application recommendations will bring about perceptible changes in the crop performance in acid soil areas.

Sustainability Issues

For a long-term solution, one has to think about a combination of measures to tackle the problem of soil degradation on account of acidity keeping in view the location-specific problems faced by the farmers and implement them involving all the stakeholders. Some such measures are: i) creation of a database of soil acidity at block level along with crop production constraints of the farmers; ii) prescriptions on use of soil amendments and other plant nutrients deficient in the area based on soil health card being prepared for the farmers; iii) ensuring supply and availability of locally available, cheap and efficient soil amendments to the farmers for use; iv) balanced nutrient use for crop production, with special emphasis on P, N, Zn, B and S; v) use of compost for crop production, especially in the areas where soil organic matter content is low; vi) managing available water resources to provide irrigation to crops for successful crop production; vii) creating awareness and management skills among extension functionaries; and viii) integration of efforts at block/ village level for the success of the programme.

Soil Health Management

Of all the natural resources endowed upon mankind, soil cover on the mother earth has been one of the most important basic resources, which plays a strategic role in determining the living standards of human beings. However, the pressure on this vital resource has increased to such an extent that the relationship between the living beings and the soil has become critical. This has resulted in various kinds of land degradation, environmental pollution, and decline in crop productivity and sustainability.

Eastern states present extreme variability in climate, topography, soil, vegetation and other physiographic features such as river, lake, hill etc. About 30% of the total geographical area suffers from one or the other degradation problem. Among the different degradation problems, soil erosion is dominant in the states of Orissa and Jharkhand. In Bihar and West Bengal, drainage problems pose a major concern. Salinity and sodicity problems occur to a considerable extent in West Bengal, whereas soil acidity problems occur in as much as 15% of the geographical area. Coastal soil salinity is a major problem in the states of West Bengal and Odisha (**Table 7**).

Soil Resources

Soils of eastern India are represented in six soil orders and in order of their relative presence these follow a sequence : Inceptisols (33.92 Mha) > Alfisols (19.67) > Entisols (14.46 Mha) > Vertisols (2.94 Mha) > Ultisols (0.39 Mha) > Mollisols (0.16 Mha). In general, 22-75% area in different states is under Inceptisols. Soils of the eastern UP, West Bengal and Odisha have more than 50% area under Inceptisols. In Chhattisgarh

Table 7. Degraded lands of Eastern India (Area in '000 ha)

Eastern states	Types of degradation (%)				
	Water erosion	Physical*	Chemical	Land affected by more than one problem	Total (%)
West Bengal	19.7	8.0	-	3.2	30.90
Bihar and Jharkhand	23.3	11.51	1.32	-	36.14
Orissa	34.4	4.4	0.50	-	39.30
Assam	17.7	13.0	-	45.9	76.70
Sikkim	32.2	-	-	-	33.03
Andaman and Nicobar Islands	22.8	-	-	1.1	23.90

*Physical degradation includes waterlogging and flooding; Chemical degradation includes salinization
Source: NBSS&LUP (2010)

Figure 4. Limed farmer's field

state about 50% area is under Alfisols. More than 40% area is covered by Entisols. About 3 Mha area of the eastern region, largely in Chhattisgarh, is under Vertisols. Hilly areas of Chhattisgarh and eastern UP have 0.09 and 0.07 Mha, respectively under the soil order Mollisols. In Assam, 0.39 Mha area is covered by the soil order Ultisols. Soils of the region under various subgroups are characterized largely by sandy loam to clay loam texture which retain good amount of moisture which is available to post-monsoon crops, poor drainage conditions, and moderate erodibility. However, the soils belonging to Entisols, Inceptisols, Vertisols and Mollisols have high to very high erosion index, indicating an urgent need for adoption of soil conservation measures (Kundu et al., 2013). Intensive studies on various aspects of major soil groups of the region have been carried out by Singh and Kundu (2008a, 2008b, 2010) and Singh et al. (2008, 2009a,b, 2010). In Orissa, Inceptisols are the dominant soils covering 48.8% area of the state, followed by Alfisols (33.52%), Entisols (10.16%) and Vertisols (5.52%), respectively.

Major Soil-related Problems

Soil Acidity

Soil acidity is an important constraint responsible for low productivity and other associated soil-related problems in eastern India. The extent and degree of soil acidity in different states are presented in **Table 3**. More than 50% of the area of eastern region is affected by the problem of soil acidity. About 27.44, 10.47 and 0.17 Mha areas of the region are categorized as slightly, moderately and strongly acidic soils, respectively. Strongly acidic soils occur in the states of Chhattisgarh and Assam. About 70% of the soils in Orissa are acidic in reaction. As much as in 45% of area, soils are of red loam and red sandy loam and another 35% are of mixed red and yellow type.

Out of total cultivable area (about 7 Mha) of West Bengal, about 2 Mha and 1 Mha soils are acidic and coastal salt-affected, respectively with varying intensities. On an average, about 43% of total soils are problematic posing major constraints for crop production and hence require suitable agricultural management practices.

Soil Fertility

Due to intensive agricultural practices and high nutrient mining, soils are becoming deficient in plant nutrients with simultaneous decrease in soil productivity reflected in physical and biological indices of soil quality. Soils of Chotanagpur plateau region are, by and large, sandy loam to clay loam in texture with moderate water holding capacity (35.9 to 52.2%) and medium to low bulk density (1.21 to 1.51 Mg m^{-3}). Soils are very strongly acidic to near neutral (pH 4.8 to 7.0), low to medium in organic carbon (5.8 to 10.5 g kg^{-1}) and poor in cation exchange capacity (CEC) [5.2 to 8.8 cmol(p^+)kg^{-1}], low to medium in available N (145.5 to 298.7 mg kg^{-1}) and K (21.5 to 86.3 mg kg^{-1}), and low in available P (8.0 to 36.0 mg kg^{-1}). Acute acidity, low activity clays, richness in hydrated oxides of iron and aluminium in the sorption complex lead to phosphate fixation, leading to nutrient imbalances (especially in red and lateritic soils). Deficiencies of N, P, Zn and B create nutrient imbalances. Sulphur and Mo deficiencies are more acute in red and lateritic soils. Frequent short spell droughts in the *kharif* season and frequent occurrence of gullies on the land surfaces create hindrance in land leveling needed for normal agricultural practices.

Long-term fertilizer experiment of ICAR conducted at Orissa clearly showed declining trend of soil productivity, even with the application of recommended NPK fertilizers due to emergence of deficiencies of secondary nutrients like S and micronutrients like Zn (Nambiar and Abrol, 1989). As per estimates made by Biswas and Tewatia (1991) on nutrient balance in 5 agro-climatic zones of eastern India for 1988-89, crops removed annually 33 to 60 kg of N, P_2O_5 and K_2O ha^{-1} over and above the fertilizer nutrient additions in this region; depletion of soil fertility was highest in the Eastern Plateau and Hill regions.

Most of the farmers in Orissa practice rice-fallow cropping system. Fields remain fallow during the dry season due to inadequate water availability and 30-90 kg NO_3-N ha^{-1} gets accumulated. Kundu et al. (2004) studied the accumulation of NO_3-N build up in the 0-60 cm soil profile under three different field management practices which ranged from 52.5 to 86.0 kg ha^{-1} (mean of 66.8 kg ha^{-1}) for ploughed clean, from 35.2 to 57.0 kg ha^{-1} (mean 46.3 kg ha^{-1}) for zero-ploughed weedy, and from 20.0 to 41.4 kg ha^{-1} (mean 30.4 kg ha^{-1}) for horsegram grown fields. After flooding and puddling operations and just before planting *kharif* rice, little NO_3-N remained in the soil profiles and got lost mostly through denitrification and leaching. Such losses of NO_3 every year from a field not only deplete N fertility but also contribute to the pollution of ground water.

Soil nutrient mining is a continuous and destructive process leading to deterioration of soil health and decline in crop productivity. Available data on nutrient mining per unit of gross cropped area indicates that mining of N was highest (62.2 kg ha^{-1}) in hill zone followed by Barak Valley (62.7 kg ha^{-1}). This might be due to low addition of nutrients in the hills. Lowest mining of N was in the Central Brahmaputra Valley Zone and Upper Brahmaputra Valley Zone due to higher nutrient consumption, despite very high cropping intensity. Nutrient mining was highest in case of K in all the zones. Higher mining is obviously due to very less use of K. More use of N and P *vis-à-vis* K is counter-productive. Balanced and soil test based nutrient application is a viable option to sustain soil health and crop productivity (Borkakati et al., 2001). Long-term fertility studies conducted with rice-rice system on Typic Endoaqualfs of Regional Agricultural Research Station (RARS), Assam Agricultural University indicated that declining crop yields were due to reduction in the nutrient availability. Physico-chemical and biological parameters determined at the end of 12^{th} and 13^{th} crops in rice-rice rotation under rainfed conditions involving 5 treatments *viz*., control, 100% N, 100% NP, 100% NPK recommended dose, and 50% N (urea) + 50% N (FYM) +100% PK revealed that 100% N and 100% NP treatments deteriorated the soil structure and reduced the organic C content in soil (Anonymous, 2003).

Soil quality index (SQI) of tea soils of Assam under continuous tea cultivation was found to be highest in the category where tea cultivation was practiced for less than 15 years. In deep, fine loamy well drained soil, SQI was 14.11 for less than 15 years of continuous tea cultivation, 10.35 for 15-30 years, 12.15 for 30-45 years, 10.28 for 45-60 years of continuous tea cultivation and 8.04 for more than 60 years. Most sensitive soil quality indicators identified in deep, fine loamy, well drained soil were available nitrogen for less than 15 years and 45-60 years of continuous tea cultivation, total nitrogen for 15-30 years and 30-45 years, and exchangeable Ca for more than 60 years of continuous tea cultivation (Baruah et al., 2017).

Agriculture is the backbone of Bihar's economy and about 81% of workforce is engaged in agriculture. About 17.4 Mha area of the State comprises of fertile alluvial soils and sedentary soils. *Diara* areas usually developed in between natural levees get inundated for different periods of time also need special management practice. Soil quality is mainly governed by flooding, salinity and sodicity in most of the parts of Bihar.

Quantitative evaluation of soil quality in North Eastern Himalayas of India under various dominant land use and soil management types *i.e*., dense forest (DF), bun cultivation (BC), pine forest (PF), shifting cultivation (SC), and abandoned land after shifting cultivation (AS) revealed significant variations in soil quality following the sequence: 0.91(DF) > 0.69(SC) > 0.63(PF) > 0.57(BC) > 0.37(AS). This soil quality degradation was attributed to the anthropogenic activities. Soil organic carbon was observed to be a powerful soil indicator under prevailing land use and thus was key to improving the soil quality (Hinge et al., 2019).

Soil Erosion and Degradation

Land degradation results from displacement of soil nutrients mainly through run-off and from biophysical and chemical deterioration. Rapid population pressure forces the poor to clear forestlands for cultivation leading to deforestation. Further, the increased dependence on intensive agriculture and irrigation results in degradation of land. Inappropriately managed or excessive irrigation leads to waterlogging, salinization, and sodification of the soil. There is also a loss of fertility and productivity of irrigated lands due to an inappropriate use of fertilizers and pesticides. Such processes in turn reduce the agricultural productivity. Extent of soil degradation in eastern India under various categories is presented in **Table 7**. It is interesting to note that Assam and Chhattisgarh suffer from severe soil degradation problems to the extent of 76.8 and 53.7% of the total land area, respectively. Extensive loss of top-soil is a common feature of degradation in all the states of eastern region. Waterlogging and flooding are the other major concerns. Singh et al. (2003) and Singh and Kundu (2009) studied on various aspects of managing the salt-affected soils of the eastern region. Severe land degradation in Orissa is mainly due to soil erosion and degraded forests, severity of which could be attributed mainly to rapid rates of deforestation, poor irrigation and drainage practices, inadequate soil conservation, steep slopes and over grazing. Soil degradation due to water erosion and physical deterioration together occurred on 37.8% of the total geographical area of Assam. Major type of soil degradation is due to soil erosion *i.e*., loss of top soil (1.39 Mha) followed by physical deterioration by way of water logging (0.2 Mha) and flooding (0.829 Mha) and of chemical deterioration due to loss of nutrients and acidification (0.385 Mha). Estimated soil loss under shifting cultivation may be to the extent of 40 – 50 t ha^{-1} yr^{-1}, leading to the enormous loss of nutrients.

In Jharkhand, soil degradation in about 30% of cultivated soils is a major concern. Major soil-related constraints in Jharkhand are undulating topography with varied slopes, light to coarse textured soils with high permeability leading to low/ very low water holding capacities, shallow soil depth at places, surface encrustation and susceptibility of moderate to severe soil erosion hazards leading to gully formation, abundance of gravels and coarse subsurface texture as well as high bulk density, and low available water capacity (AWC).

Fertilizer Consumption Status

Fertilizer consumption in the eastern region is lowest in the country. Nutrient consumption in the states of West Bengal, Bihar, Jharkhand, Odisha and Assam was 160.1, 216.0, 114.4, 103.8 and 61.7 kg NPK ha^{-1}, respectively **(Table 8)**. Average consumption is less than the national average of 134.0 kg NPK ha^{-1}. Primary cause for low fertilizer consumption in eastern states is waterlogging by surface flooding during *kharif* season and *rabi fallow* due to non-availability of irrigation water. Studies have clearly indicated that while fertilizer use in *kharif* rice has been negligible, farmers often use more than recommended doses of fertilizers in irrigated rice during the *rabi* season (Kundu et al., 2013).

Traditionally, low fertilizer consumption in eastern states has been responsible for decline in the available nutrients and organic C content in soils which in turn have triggered deterioration of soil quality.

Soil Pollution

Besides the problems of soil acidity and soil salinity in West Bengal, majority of fertile alluvial soils covering districts of Malda, Dinajpur (North and South), Murshidabad, Nadia, Burdwan, 24 Parganas (North and part of South), and Hooghly are in the trap of arsenic (As) contamination. Arsenic is highly hazardous to human and animal health. As small as 0.1 g of arsenic trioxide (As_2O_3) can prove lethal to human. Arsenic is the causal factor of several physiological disorders in humans, namely, edema, skin lesions, hyperkeratosis, skin cancer and even death (Sanyal and Naser, 2002). Presently, 8-9 million population is affected by arsenic toxicity due to consuming arsenic contaminated groundwater. However, out of the total contaminated groundwater used in affected belt of West Bengal, less than 10% accounts for drinking purposes and rest 90% finds its use in the agricultural sector to meet the crop irrigational requirements. Despite this, almost entire effort is being directed towards solving As problem in groundwater-derived drinking water sources, while very little has been done to explore the influence of arsenic-contaminated groundwater used as irrigation source on soil-crop system. Due to agricultural activities, soils exhibited a progressive As build-up in the soil and such a build-up might be due to the leftover of As-rich roots in the soils. Arsenic phytotoxicity is expected to be greater in sandy soils than in the clay soils because of lower amounts of Fe and Al oxides in the former.

Soil quality and crop production in the Birbhum district of West Bengal have been adversely affected due to fluoride contamination in the groundwater used for irrigation purposes. Analysis of the groundwater of north-western part of Birbhum district showed the cations to be in the order: Na^+ > Ca^{2+} > Mg^{2+} while the sequence for anions was HCO_3^- > Cl^- > SO_4^{2-} > NO_3^-. Fluoride (F^-) concentration

Table 8. Fertilizer consumption in different states of eastern India (Source: FAI, 2018)

States	Fertilizer consumption in *kharif* + *rabi* (kg ha^{-1})			
	N	P_2O_5	K_2O	Total
West Bengal	78.8	46.0	38.9	163.7
Bihar	145.1	50.3	20.6	216.0
Jharkhand	37.5	28.6	5.9	72.0
Odisha	41.6	18.0	9.2	68.7
Assam	37.4	11.9	10.7	60.0
Manipur	27.0	12.7	13.3	53.0
*Mizoram	17.5	3.1	2.4	23.0
Tripura	22.2	8.0	8.5	38.7
Nagaland	3.3	1.9	1.2	5.8
Eastern India	45.6	20.0	12.3	77.8

*Mizoram Fertiliser Statistics data of 2016-17 varied from 0.01 to 18 mg L^{-1} in pre-monsoon and 0.023 to 19 mg L^{-1} in the post-monsoon period. Eighty-six per cent of the samples showed low F^- content (<0.60 mg L^{-1}) whereas, 8% exhibit elevated concentration of F^- (>1.2 mg L^{-1}) which occurred mainly in the central and north-central parts of the study area at a depth of 46 to 98 m. The prime water type is $CaHCO_3$ succeeded by F^- rich $NaHCO_3$ and NaCl waters. The suitability analysis revealed that the water at about 81% of the sampling sites was unsuitable for drinking and at 16% sites it was unsuitable for irrigation. Results suggest that chemical weathering along with ion-exchange is the key process, responsible for mobilization of fluoride in groundwater of north-western part of Birbhum district (Batabyal, and Gupta 2017).

Industrial effluents released into the crop fields alter the soil properties and consequentially affect both plant and animal lives. Use of Nagaon paper mill effluents significantly increased the electrical conductivity (EC) of soil (3.07 dS m^{-1}) as compared to unaffected soil. Exchangeable Na^+ content of soil increased by 70%, resulting in increase in exchangeable sodium percentage (ESP) of the soil. Available nutrients *viz.*, N, P, S and exchangeable and water soluble basic cations *viz.*, Na^+, K^+ Ca^{2+} and Mg^{2+} were also increased whereas available P decreased due to effluent irrigation. Chloride content increased by 3-7 folds and microbial biomass carbon (MBC) reduced by about 10-37%. Chaffy grain of rice increased by 38% in affected soil due to poor uptake of K (Baruah, 2003).

State of Orissa has large deposits of ores and minerals of heavy metals namely, Fe, Mn, chromium (Cr), lead (Pb) and nickel (Ni). Soils around the mining areas contain 100-300 ppm Fe, 60-100 ppm Mn, 60-75 ppm Cu, 30-100 ppm Cr, 50-150 ppm Ni, 10-20 ppm Pb, and 200-250 ppm Zn which contributes towards the contamination of soils of vicinity with heavy metals. Combustion of coal through thermal plants adds large amounts of pollutant elements to the soil and water. The fly ash released from Talcher thermal plant contains total 424 ppm Fe, 34 ppm Zn, 39 ppm Cu, 241 ppm Mn, 33 ppm Pb, 13 ppm Cr and 4.5 ppm cadmium (Cd). About 15% of these heavy metals from the ash pond seep into the flow of river Nandira and pollute its water. Surface soil samples in and around the chromite mines at Sukinda of Jajpur district were found to be contaminated with Cr^{6+}. Medium and low lands adjacent to the lateritic uplands as well as the lands close to the Fe-ore mining areas suffered from Fe toxicity (Sahu, 2003).

Sustainable Farmer-Friendly Technologies for Managing Natural Resources

Considering the issues of sustainability, land degradation, global warming, livelihood of the rural poor, sustaining productivity of agriculture and availability of natural resource the following technologies should be developed for managing the natural resources of eastern India.

I. Technologies for the Management of Soil Resources

In the light of poor soil health and severe land degradation problems inflicting eastern India, there is an urgent need for developing and harmonizing the viable strategies for sustaining long-term soil productivity and improving the food security of resource-poor farmers of eastern and northeast India.

Soil Test-based Nutrient Use

Soil testing is a unique tool for judicious fertilizer use and a well-recognized practice for sustaining crop production and balanced fertilization. Fertilizer is a key input for achieving the food grain production goals of the country. But, the escalating cost coupled with increasing demand for chemical fertilizers and depleting soil health necessitates the safe and efficient method of nutrient application. Government of India has implemented soil health card (SHC) scheme since 2015 through the Departments of Agriculture of all the States and Union Territories to provide 'Soil Health Cards' to all the farmers. In this scheme, GPS-enabled soil samples are collected at a grid of 2.5 ha in irrigated area and 10 ha in un-irrigated areas following uniform approach in soil testing adopted for 12 parameters viz. primary nutrients (N, P, K), secondary nutrient (S), micronutrients (B, Zn, Mn, Fe, Cu), and other properties (pH, EC and OC) for comprehensiveness. The GPS-enabled soil sampling helps to create a systematic database and allows monitoring of changes in the soil health over the years. In the 1st cycle of SHC scheme which was implemented in years 2015 to 2017, 2.53 crore soil samples were analyzed and 10.73 crore soil health cards were distributed to the farmers. To enable quick soil sample testing and distribution of soil health cards, the soil test infrastructure has been upgraded and 9263 soil testing laboratories have been sanctioned to the states.

As a part of centrally sponsored 'Soil Health Card' scheme, the soil testing laboratory of Palli Siksha Bhavana, Institute of Agriculture, Visva-Bharati University, Sriniketan has been entrusted with the responsibility of analysis of soil samples of farmers' fields of 18 blocks of Birbhum district of West Bengal.

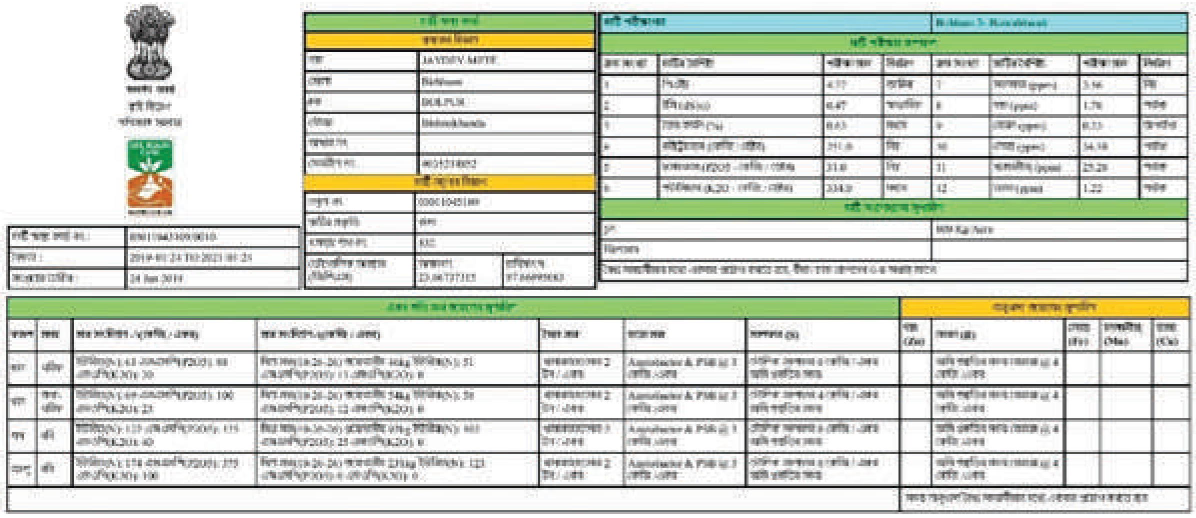

Figure 5. A typical soil health card of a farmer's field soil of Bolpur Block of Birbhum district of West Bengal (Courtesy: Soil Testing Laboratory, Visva-Bharati University, Sriniketan, West Bengal)

A typical soil health card of a farmer's field of Bishnukhanda Mouza of Bolpur Block of Birbhum district and analyzed at Soil Testing Laboratory of is presented in **Figure 5**.

Sustaining Soil Organic Matter

Soil organic matter (SOM) is the mainstay of soil health. Balanced fertilization may meet crop productivity and maintain SOM, but there is an urgent need to improve the sequestration of carbon in all the soils by all available resources including recycling of crop residues, green manuring, composting, zero tillage, resource conserving technologies and other agro- techniques. Annual depletion of 28 Mt of nutrients against addition of 20 Mt leaves a net gap of 8 Mt yr^{-1}, and this deficit has been widening year after year, deteriorating the soil quality (Chand, 2010). Decline in the organic carbon content of the soils occurred due to continuous cultivation of cereal-based cropping systems, for instance rice–wheat, rice–rice and rice–maize, etc. Low SOC concentration in the soil is attributed to ploughing, removal of crop residues and other biosolids, and mining of soil fertility. Important strategies of soil C sequestration include restoration of degraded soils, and adoption of recommended management practices of agricultural and forestry soils (Lal, 2004). Continuous nutrient depletion from the agricultural fields is a severe threat to the soil health. Sub-optimal nutrient application together with poor quality water results in sparse plant cover and low vegetative inputs into the soils. The SOC loss ranged from 0.22% to 6.0% in different cropping sequences of India due to inadequate fertilization, whereas depletion of SOC was far less (0.22% to 2.92%) under balanced fertilization (Anonymous, 2003). Basing his observation on the data from the long-term experiments in India, Goswami (2005) concluded that the application of farmyard manure (FYM) + major nutrients (N, P, K and S) and micro-nutrients increased the crop yield and built up the soil organic carbon. Therefore, enhancement and management of SOC concentration are important to sustainable management of soil and water resources.

Balanced Use of Plant Nutrients

Balanced and judicious use of fertilizers is the key to efficient nutrient use and for maintaining soil productivity. It enhances the fertilizer use efficiency and leads to increase in the crop yields by improving physical, chemical and biological environment of the soil. It also ensures that the plants become more tolerant to drought, cold, insects, pests and diseases. An NPK ratio of 4:2:1 (N: P_2O_5: K_2O) is generally considered ideal and accepted for macro-level monitoring of consumption of plant nutrients for the country as a whole. For producing one tonne of cereal grains about 20-27 kg N, 8-19 kg P_2O_5 and 24-48 kg K_2O are required, and these values are highest for pearl millet producing the lowest grain yield per hectare. Grain legumes remove much more N (two to four times of that in cereals) but most of it is fixed by the *Rhizobium* in their roots and very little N as fertilizer has to be applied, say, 20- 25 kg N ha^{-1} as a starter dose. However, P and K removal is higher in pulses than in cereals. Rapeseed also removes quite a bit of N and very high amounts of K. But in none of these crops NPK removal is in 4:2:1 ratio. Fertilizer recommendations and N: P_2O_5: K_2O ratios for different

Table 9. Fertilizer recommendations and N: P_2O_5: K_2O ratios for different crops / cropping systems in different agro-climatic zones of eastern and north-eastern India

S.No.	Agroclimatic zone	Soil	Crop/ Cropping system	N : P_2O_5 : K_2O ratio	Fertilization recommendation (N - P_2O_5 - K_2O kg ha^{-1})
1	Eastern Himalaya (Assam, W.B., NE states)	Alluvial, Brown hill, Red, Tarai	Rice (K)	4:2:2	80-40-40
			Rice (R)	4:2:2	80-40-40
2	Lower Gangatic Plain (W.B.)	Alluvial, Red & Lateritic	Rice (K)	4:2:2	80-40 -40
			Wheat	6:2:2	120-40-40
3	Middle Gangetic Plain	Alluvial, Red & Black	Rice (K)	4:2:2	120-60-60
			Wheat	4:2:1.3	120-60-40
			Sugarcane	4.5:1.5:1	180-60-40
	Bihar		Rice (K)	6:2:1	120-40-20
			Wheat	6:3:1	120- 60-20
			Sugarcane	5:2.8:2	150-85-60
4	Eastern Plateau & Hills (Jharkhand)	Red & yellow, Red & lateritic, Mixed red & black	Maize (K)	4:2:1	80-40-20
			Wheat	5:2:1	100-40-20
		part of Orissa and Eastern Maharashtra (Bhandera region)	Rice (K)	4:2:1.3	120-60-40
5	East Coast Plains & Hills(Orissa)	Red, Black Coastal Alluvium	Rice (K)	4:2:2	80-40-40
			Rice (R)	5:2.5:2	100-50-40
6	Island region (Andaman & Nicobar)	Coastal Alluvium salty 4:2:1.3 120	Rice (K)	4:2:1.3	120-60-40

crops / cropping system in different agro-climatic zones of eastern and north eastern India are presented in **Table 9** (NAAS, 2009). Application of targeted yield concept can also take into account the application of nutrients applied through FYM or made available through biofertilizers resulting in reduced NPK application ratio.

Residue Recycling

Recycling of crop residues back to fields helps in building stable organic matter in the soil and sustaining yield levels. Studies under AICARP suggested that in some areas incorporation of crop residues made it possible to curtail 25% of fertilizer NPK requirement of rice. Application of extra 10-20 kg N ha^{-1} at the time of incorporation of residues hastened the rate of decomposition, and consequently increased the beneficial effect in terms of grain yield and soil fertility build-up. Since 70-80% of K taken up by these crops is retained in straw component, residue recycling may be the best option to replenish K to the soil and avoid the mining of soil K reserves. Efforts are underway to develop direct drilling and stubble mulching machinery to overcome this problem. A novel promising approach recently developed and tested by Australian and Indian collaborators is the 'Happy Seeder', which combines the stubble mulching and seed drilling functions into one machine. The stubble is cut and picked up in front of the sowing times (which therefore engages bare soil) and deposited behind the seed drill as mulch. Waste decomposer (microbial) is now being encouraged by National Centre of Organic Farming (Ministry of Agriculture and Farmers Welfare, Government of India, Ghaziabad, Uttar Pradesh) and promoted among farmers through KVKs. It has been claimed to be very efficient in decomposing several tonnes of farm wastes into manures within a month.

A large number of farmers in the rice-wheat cropping system belt are burning rice and wheat straw in the field. Although some nutrients (N, S, P, B) are partly lost on burning, metallic plant nutrients (Ca, Mg, K, Fe, Zn, Cu, Mn) are left in soil. Main adverse effects of crop residue burning include the emission of greenhouse gases (GHGs) that contribute to the global warming, increased levels of particulate matter (PM) and smog that cause health hazards, loss of biodiversity of agricultural lands, and the deterioration of soil fertility (Lohan et al., 2018). Crop residue burning significantly increases the quantity of air pollutants such as CO_2, CO, NH_3, NO_X, SO_X, non-methane hydrocarbon (NMHC), volatile organic compounds (VOCs), semi volatile organic compounds (SVOCs) and PM (Mittal et al., 2009). This basically accounts for the loss of organic carbon, N, and other nutrients, which otherwise could have been retained in the soil (Jain et al., 2014).

Integrated Nutrient Management (INM)

Inorganic and organic fertilizers, bio-fertilizers, crop residues and other living materials are to be used in an integrated manner (balance) to enhance the fertilizer use efficiency, increase the crop yields and minimize the environmental risk. Green manuring crops grown *in situ* (*e.g.*, clover, vetch, cowpea, sesbania etc.) or brought from outside (*e.g., Gliricidia*) can be incorporated in soil to improve the crop productivity. Biofertilizers help in improving soil fertility through biological nitrogen-fixation, solubilizing P from native soil and applied sources, and mobilizing micronutrients like Zn and Cu for plant-uptake. Rhizobium strains play a major role in symbiotic N-fixation in legumes. Similarly, blue-green algae, *Azotobacter* sp. and *Azospirillum* sp. help in N-fixation in cereals. The vesicular arbuscular mycorhizal (VAM) fungi have an extensive mycellial network that increase the transport and uptake of P and micronutrients like Zn and Cu. Phosphate solubilizing microbes *e.g*., *Pseudomonas striata*, *Bacillus polymyxa* and *Aspergillus awamori* help in solubilizing native soil P and rockphosphates. Nutrient losses through runoff, leaching, volatilization and immobilization are reduced in INM which ultimately leads to increase in the fertilizer use efficiency.

Soil Health and Crop Quality

Nutrient elements influence crop quality. This is manifested by changes or differences in quality attributes of different crops with different rates of nutrient elements applied or available to various crops. The common quality attributes which get influenced include protein and carbohydrate content of the sink organs of plants, fruit colour, flavour and vitamin-related attributes for example, *beta*-carotene, grain hardness and moisture content at storage of crops such as maize and wheat, potato tuber density and internal colour.

Crop quality characteristics mostly reported to be affected by plant nutrition include: proteins, carbohydrate, sucrose and fructose content in grains, root crops, tuber crops and fruits; vitamins like beta-carotene content in fruits and tubers; moisture content at storage in cereal grains, potato tuber density; and fruit colours, and fruit weight. It has been noted that the essential and beneficial nutrient elements contribute to crop quality through functioning as raw materials for the synthesis of various plant components that have food value to humans and animals. Nitrogen and S are raw materials for protein synthesis. Others like Ca, P, Zn and Fe are involved in enzyme synthesis, activation or as electron carriers while Mg and K are mostly involved in enzyme activation and transportation of materials such as fructose and sucrose from points of synthesis to sites of loading and hence affect quality of fruits, and root and tuber crops greatly. It has been noted that crop quality is also greatly influenced by the synergistic and antagonistic interactions in uptake and utilization of various nutrients. Therefore, balanced nutrition is the best prescription. Crop quality is a very important area to consider while advancing and putting up resources in research since it has a huge bearing on human health and socioeconomic effect on farmers through its influence on marketability of crops and crop products.

Undersupplying and oversupplying of nutrients may lead to reduced crop quality. This can result from the nutrient being a raw material for synthesis of a product but also from its involvement in enzymatic activities, for instance low N (as a raw material) will lead to reduced amount of proteins whereas low K will lead to reduced amount of proteins due to reduced activation of enzymes that metabolize carbohydrates for synthesis of amino acids and proteins. Too much of NH_4-N will suppress uptake of Ca and its functions. On the other hand, low levels of Mg and K will lead to reduced distribution of carbohydrates (Kow and Nabami, 2015). It should be noted that nutrients do not work in isolation; therefore, balanced nutrition is needed to optimize crop quality.

Organic Farming

In view of the increasing consumption of fertilizers and insecticides and their perceived deteriorating effect on soil productivity and soil/animals/human health, the concept of organic farming is gaining importance throughout the world. In most of the eastern states fertilizer consumption is less than 12 kg ha^{-1} (excluding Manipur and Tripura), which account for roughly 15% of the area of the country. Firstly, the use of inorganic fertilizers and chemicals is meager in the region. The farmers of the region, in general and hill farmers in particular, are having apathy towards use of agro-chemicals. Secondly, the fruits of Green Revolution could not benefit the farmers of the hills as the system of production in the hills remained low input-low risk-low yield technology based and the average yield of most of the crop remained far behind the national average. It is assumed that the differences in production gap due to adoption of organic agriculture is expected to be negligible; rather there is a scope for enhancing productivity with good organic management and the organic premiums would boost earning of the hill farmers. Thirdly, it is an added advantage that all the households are maintaining live stock (pig, poultry, cattle, goats, etc.), producing sufficient quantity of on-farm manures, which could be efficiently used for organic agriculture. Moreover, the eastern region is one of the mega-biodiversity rich in plant biomass *viz*., weeds, shrubs, herbs and forest litters. Most of these species could be efficiently used in organic production. The region as a whole is having a potential of 46 Mt of manure, which is almost equivalent to the requirement for organic production in the identified areas (Bujarbaruah, 2004). Vermicomposting, green manuring, growing of leguminous hedge row species *viz*., *Crotolaria, Feringia* sp. in the bunds, farm fences and terrace/risers, recycling the pruned biomass into the field improve the health and productivity of soil.

Restoration of Degraded Lands

Understanding the processes, factors and causes of land degradation is a basic prerequisite towards successful restoration of the productivity of degraded lands. Knowing the category of soil degradation is an important step to restore the soil quality and its productivity by preventing soil erosion, promoting high biological activity, increasing soil organic matter content and increasing rooting depth of plants. Productivity of degraded soils in the eastern India and north-eastern hills can be successfully restored to some extent following mechanical and ecological approaches.

Mechanical Approaches

Mechanical approaches are used in cases of extreme degradation, where other approaches are either not possible or are slow. Mechanical measures include:

- Check dams (masonry, stone, loose rock, log check dams, etc.)
- Level bench terraces, stone terracing
- Contour drains, contour bunds, earthen dam/ reservoirs, gabion, stream channeling, etc. to absorb most of the surface water into the soil before reaching to streams.

By adopting terracing and protected waterways, the steep slopes could be cultivated safely and profitably.

Ecological Approaches

Ecological approaches include vegetative barriers on field boundaries, contour bunds and ridges, appropriate agroforestry practices, vegetative filter strips, live checks etc. to promote *in situ* moisture conservation. Wattling and staking is a combination of mechanical stabilization and re-vegetation on road fill banks and similar areas of base slopes for building new roads in the hilly terrain. It helps to reduce the run-off and its velocity, acts as a barrier or buffer strip for controlling soil and conservation of moisture for stake growth. Agronomical practices like use of cover crops, mixed/ inter/ strip cropping, crop rotation, green manuring and mulch farming are vital practices associated with integrated nutrient management. Growing soybean (*Glycine max*)/ groundnut (*Arachis hypogoea*)/ cowpea (*Vigna radiata*) with maize (*Zea mays*)/ *jowar* (*Sorghum bicolor*)/ pearl millet (*Pennistum glaucum*) is a common example for intercropping in the dry lands.

Transformed Shifting Agriculture

Managing transformation in shifting cultivation areas is fundamental to agricultural development in the uplands of northeast (NE) India and an important element of the Act East Policy. Transformation of shifting cultivation is, therefore, key to the thrust for agricultural transformation in the region. An effective, fairly easy to replicate and scale up approach to transformation is the promotion of home gardens (or extended home gardens). Home gardens allow households to grow many of the crops cultivated in shifting cultivation fields around their household. This not only provides access to traditional food crops and contributes to nutritional security, but also allows for income generating opportunities. Combined with horticulture and animal husbandry, the promotion of home gardens has helped many households to increase their income significantly and improve the economic status.

The intelligent application of modern low cost and energy techniques could be expected to increase the yield of crops under shifting cultivation without affecting the viability of the system. Improved fallow with woody and herbaceous legumes with primary purpose of fixing N as a part of short fallow (2-3 years) tends to increase the accumulation of large quantities of N and provides a residual effect to two or three subsequent crops. The introduction of plantation and horticultural crops like rubber, coffee, tea, banana, citrus, black paper, cashew, spice trees, pineapple etc. on *jhum* fields on sloppy hills are the promising alternatives, providing free food for some time to cultivators to gain confidence. The locals without breaking their traditions can achieve this through a reasonable share of profits after processing and marketing (Rajkhowa et al., 2015).

Strategy for Meeting the Challenges of the Future

The challenges to scientists in the decades ahead can be grouped as under:

- Improving the agricultural productivity of the land that is already under cultivation and developing rational systems of management for new lands for farming, recreation and urbanisation.
- Improving the efficiency of agricultural inputs such as water, fertilizer, energy and pesticides, which are necessary for increasing productivity.
- Preventing soil degradation caused by man's negligence and ignorance. Reducing soil erosion, desertification, salinization and land degradation by ensuring efficient soil and water management systems is needed.
- Restoring and improving productivity and utility of degraded lands to meet the immediate and future needs of society for food, fibre, shelter and recreation
- Monitoring changes in the productivity of land and developing a system of warning, treatment and care

Conclusions

The eastern and north-eastern region of India, comprises of plains, coastal, hilly and plateau regions. Climatic extremes pose a major challenge for agricultural growth in the region. Drought and scanty rainfall in some areas and waterlogging and floods in another part are of common occurrence. Aim of natural resource management should be to reduce and moderate the floods, mitigate the droughts, reduce the soil erosion and arrest the soil displacement. Effective and farmer-friendly technologies are in place for widespread adoption by the farming community which could bring |improvements in the farmers' income. Water resource management encourages the farmers to go in for double cropping and reduce the area under rice-fallows. ICAR-Indian Institute of Water Management, Bhubaneshwar, (previously, Directorate of Water Management) has been tackling several researchable issues, such as rain water management, canal water management, management of groundwater and waterlogged as well as coastal acid-saline areas.

Soil acidity is a major constraint in many of the states in the eastern and north-eastern region limiting soil as well as crop productivity. It can be ameliorated by adopting liming technology to the lime-responsive crops, adding organic manures, and resorting to the balanced nutrient use. Two sets of long-term fertilizer experiments which have been in place for past 40 years or more at Ranchi, have clearly demonstrated the effect of lime + NPK fertilizer use over NPK- only use. Such low cost technologies are boon for the farmers having substantial area under acid soils. Several soil health-related constraints like soil erosion, soil degradation, soil pollution, low soil organic matter etc. have a deleterious effect on crop production in eastern states. A comprehensive knowledge of the crop growing practices *vis-a vis* soil health is necessary for sustenance of crop productivity. Needless to say that better soil health is an important parameter for better crop quality. Need of the hour is to create awareness among the farmers and sensitize them to adopt improved technologies for harnessing higher crop yields of superior quality. This is a science-based prescription for enhancing income of the resource-poor farmers of the eastern region.

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Correcting Micronutrient Deficiencies for Sustainable High Productivity

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Abstract

Micronutrient deficiencies which were sporadic till mid-1960s have now increased alarmingly across the soils, crops, cropping systems, areas or regions of the country. Amongst the micronutrients, the deficiency of Zn (36.5%) is most wide spread followed by that of B (23.4%), Fe (12.80%), Mn (7.10%), Cu (4.20%) and Mo (meagre). The degree of Zn deficiency increased with increase in soil pH or sodicity, $CaCO_3$ and sand content, and decrease in soil organic carbon content. Deficiency of Fe in rice and that of Mn in wheat popped up under rice-wheat cropping system (RWCS) on coarse textured permeable soils. The deficiency of B found mostly in acid leached soils and highly calcareous soils. Matching responses of crops to their application confirm their existence and impacts on sustaining their high productivity. The negative impact of their deficiency to high productivity was halted with the use of identified and developed effective sources of micronutrient fertilizers, organic and green manures (GM) and their integrated management and supply systems. $ZnSO_4$, 2% zincated urea, ZnO, Zn-EDTA for Zn, $MnSO_4$ for Mn, $FeSO_4$ for Fe , borax or granubore for B, $CuSO_4$ for Cu, sodium molybedate for Mo found to be the relatively more effective sources than others for the correction of their respective micronutrients deficiency in diverse soils, crops and cropping systems. Soil application of Zn and B, foliar sprays of Fe and Mn, both of soil and foliar application of Cu and Mo are the most effective methods of application to the field crops at the time of their seeding/sowing and at critical growth stages for foliar sprays that helped combat their deficiency and in attaining high productivity. Application of organic manures @ 2.5 to 10 t ha^{-1} as well as GM alone or in combinations with Zn, Fe, and Mn sources in various combinations and permutations enhanced their supply to and availability in soil and effectively corrected their deficiency and significantly reduced the rates of their fertilizer application from 25 to 100 %. Micronutrient-efficient cultivars have been identified and their adoption can help reduce the rates of their application for getting high sustainable yields.

Key words: Micronutrients, source, methods of application, organic manures, green manure, integrated micronutrient management, micronutrient-efficient cultivars, multi-micronutrients

Introduction

Seventeen elements are essential for the plant growth and constitute the basic component of soil chemical fertility that refers to the inherent capacity of soil to supply these essential nutrients to plants in adequate and right proportion for their optimum growth, thus is one of the key components to determine soil health, quality, productivity and stability on sustainable basis. Micronutrients are as important as the macronutrients as these also play macro role in determining growth and productivity of crops. These micronutrients are boron (B), copper (Cu), chlorine (Cl), iron (Fe), manganese (Mn), molybdenum (Mo), nickel (Ni), and zinc (Zn). Cobalt (Co) is essential only for legumes. In Indian soils, till mid-1960s the deficiencies of micronutrients were sporadic and thereafter these increased alarmingly as a consequence of depleting their resource in soil with the change of environment towards intensive cropping with green revolution HYV of wheat, rice, maize, imbalance use of high analysis NPK fertilizers, and little use of organic manures. Deficiency of Zn is the most common followed by that of B, Mn and Fe and their applications on deficient soils have been giving dramatic responses in field as well as in fruit and plantation crops. A sharp decline in available micronutrients with continuous intensive cropping at recommended dose of NPK application has been widely reported. Field scale deficiency of Zn was first noticed in rice in *tarai* soils (Nene, 1965) and in wheat on sandy soils of Punjab during 1969-70 (Takkar et al., 1971, 1972, 1973), then in most of the intensively cultivated areas. Later deficiencies of Fe in rice, sugarcane, etc., on sandy soils (Takkar and Nayyar, 1979, 1984), Mn in wheat in rice-wheat cropping system (RWCS) on coarse textured soils of Punjab (Takkar and Nayyar, 1981b), and B in chickpea and rice on highly calcareous soils of Bihar (Sakal et al., 1996; Sakal et al.,1988) have been demonstrated and their availability in soils has now become critical to sustain high productivity. Currently 36.5, 23.4, 12.8, 7.1 and 4.2% soils are deficient in Zn, B, Fe, Mn and Cu, respectively. In future if intensification of agriculture has to be followed to feed the burgeoning population, it will further mount more pressure on the finite micronutrient soil resource that would cause the deficiency of other micronutrients to pop

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up besides aggravating the existing ones. Corrections of these deficiencies with the use of specific micronutrient fertilizers, single or multi-micronutrients, as per their specific soil status or magnitude of crop response to their application, and in balance use with macronutrients and organic manures are and would be helping in attaining the sustainable high productivity and stability. Thus, for effectively correcting the micronutrient deficiencies for sustainable high productivity, basic information about the status of their deficiency in soils, factors governing these, the magnitude of crop responses to their application, the right source, mode, rate and time of their application in specific soil-cropping conditions is a prerequisite. Development and use of available genotypes tolerant to specific micronutrient deficiencies and high efficiency of their utilization needs to be given high priority to minimize soil depletion and the use of micronutrient fertilizers. This review is an attempt in this direction.

Evaluation of Soil Micronutrients Resource for Sustainability

The total content of soil micronutrients is not directly available to plants because plant roots absorb these directly from the available fractions/pools. Takkar (1996) shows that Zn will be the most limiting nutrient in future, and is so at present, while considering its removal by the crops and the total amounts in soil. The preliminary estimate indicates that Zn will be just enough for 165 to 384 years, followed by Cu for 149-630, B for 266-558, Mn for 404-771, Mo for 391-419 years, and Fe for 10,131 to 60,392 years to sustain productivity of important cropping systems.

The longevity of sustainable soil productivity was found to be associated with the emergence of zinc deficiency under intensive cultivation and cropping systems. The data of the long term experiments showed that the productivity and sustainability of maize in the wheat-maize-cowpea (fodder) cropping system started declining significantly after 10 annual cropping cycles of the system on a loamy sand soil because of depletion of available Zn pool from adequate level of 1.10 mg kg^{-1} to deficient level of 0.68 mg kg^{-1} (Biswas and Benbi, 1989). Similarly, sustainable high productivity of rice and wheat under intensive cultivation of rice-wheat-cowpea (fodder) cropping system on Hapludoll of Pantnagar started declining significantly after 12 annual cycles (Nandram, 1998) because of depletion of available Zn status from adequate (2.54 mg kg^{-1}) to low/deficient level (0.97 mg kg^{-1}). There is an urgent need to halt any further deterioration of the micronutrient natural resource base and restoring the same through prudent management practices to maintain and sustain the high productivity of Indian soils.

The constraints of micronutrients to high productivity have been alleviated by augmenting the soil resources through addition of chemical fertilizers (off-farm input), and organic manures, wastes, recycling of residues, and cultivation of micronutrients-efficient cultivars (on-farm input). The extent of deficiency, crop responses and correction of micronutrient deficiency are being reviewed nutrient wise below for the sake of continuity.

Zinc

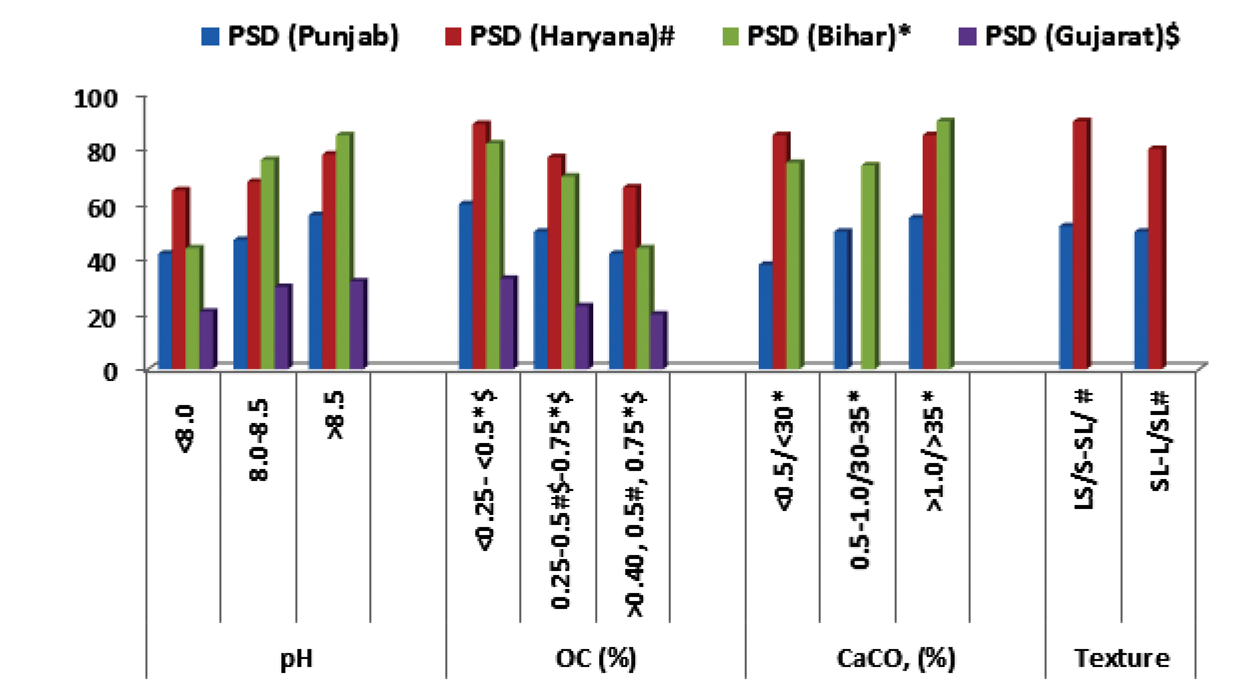
Extent of Zinc Deficiency

In Indian soils, total Zn content ranged between 25-285 mg kg^{-1} and available Zn (DTPA-extractable) varied from 0.25 to 2.58 mg kg^{-1} (Takkar, 1982). Currently 36.5% soils are deficient in available Zn. Its deficiency varied across the states. Zone-wise data on Zn-deficiency status from 1967-87 to 2009-2015 years revealed that its deficiency has markedly declined from 59.5 to 18.5% in northern zone due to regular use of Zn fertilizer and has increased appreciably in south zone from 43 to 52% probably due to intensive cropping with NPK only (Shukla and Behra , 2011; Takkar and Shukla, 2015). Earlier deficiency of Zn was observed more in rice and wheat growing belt and now its deficiency has extended even to coarse cereals and pulse-growing areas (Takkar et al., 1988). Long-term cultivation, for six and a half years of rice-wheat, maize-wheat, *bajra*-wheat and *guar*-potato cropping systems with high analysis NPK fertilizers markedly decrease in all the soil Zn-pools, particularly of weakly adsorbed one. Effect of all the cropping systems was more prominent in the 0-15 cm layer and gradually decreased with an increase in soil depth (Chandi and Takkar, 1982).

Soils which are coarser in texture (sandy/loamy sand), high in pH (>8.5 or alkali/sodic soils) and or low in organic carbon (< 0.4%), or calcareous/high in $CaCO_3$ (>0.5 %) and intensively cultivated are most deficient in Zn and require fertilization with Zn to achieve sustainable high productivity. Takkar and Randhawa (1978, 1980) also showed highly significant relation of available Zn with pH (- 0.95*) and SOC content (0.81) (**Figure 1**).

Responses of Crops to Zn Application

Before 1966 low to medium crop responses to the application of all the micronutrients were observed. But during the years 1967-76, the period of introduction of HYV of Green Revolution crops, responses to Zn application have been spectacular in most of the states. Cases are on record where Zn



Soil properties/data pertains to: # Haryana, * Bihar, $ Gujarat; PDS = Percent deficient soils

Figure 1. Influence of soil properties on the extent of zinc deficiency in the soils of Punjab, Haryana, Bihar and Gujarat (Takkar and Randhawa, 1978, 1980; Takkar, 1982; Takkar et al., 1989)

application decided between the success and failure of the crop. In several instances the increase in yield was many times more when Zn was applied. In view of these spectacular responses, awareness regarding the use of zinc has increased among the farmers and its application has spread to vast areas. In general, summer (*kharif*) crops especially rice, maize and sorghum responded more to Zn than winter (*rabi*) crops like wheat and chickpea (Takkar et al., 1971, 1972, 1973; Randhawa et al., 1974, 1975; Takkar and Randhawa, 1978, Takkar, 1991).

Till today Zn deficiency continues to be one of the key factors in determining the crop production in the country, therefore studies have largely been focussed on this element. Results of 4702 field experiments at the farmers' fields (ECF) revealed responses of almost of all the major crops to application of 5 kg Zn ha^{-1} (25 kg $ZnSO_4.7H_2O$ ha^{-1}) and were as high as 4.7-4.8 t ha^{-1} of wheat and rice and 2.0 t ha^{-1} of maize on soils severely deficient in Zn (Takkar et al., 1989).

A response of more than 200 kg Zn ha^{-1} of grain has been considered as the parameter for isolating the Zn deficient from non-deficient soils as the response beyond 200 kg ha^{-1} grain yield with 5 kg Zn ha^{-1} is economical. Irrespective of the states, rice emerged as the most responsive crop to Zn application. In 72% of the 1875 experiments, the increase in rice grain yield attributable to applied Zn was more than 200 kg ha^{-1}, whereas the increase in grain yield more than 200 kg ha^{-1} of wheat, maize and sorghum was recorded in 56, 52 and 36% of the fields, respectively. The frequency of response was even much less in case of cotton, pearl millet, and finger millet, *i.e.*, 40, 37 and 27% of the fields. And irrespective of the crops studied, 86, 66, 61, 58, 54, 51, 48, and 44 % of the fields indicated Zn deficiency in the soils of Bihar, Tamil Nadu, Uttar Pradesh, Andhra Pradesh, Haryana, Gujarat, Punjab, and Madhya Pradesh, respectively. In most of the cases a matching Zn deficiency of 45, 43, 64, 53, 64, 24, 50, and 65% was revealed by the soil analysis in the corresponding states. Also soil analysis and field response experiments indicated 46 and 61% Zn deficiency, respectively in the soils of the country (Takkar et al.,1989).

Changes in crop responses to zinc with time in experiments at cultivators field have been further analysed. Out of 4,144 trials during 1967-84, 58 and 42% exhibited response and no response to Zn application respectively (Singh, 2001), that is almost the same what Takkar et al. (1989) have reported. The number of responsive trials increased up to 63% during 1985-2001 and 72% during 2001-2010 (**Figure 2**). This indicates that either new cultivars are more responsive to Zn application or its deficiency has magnified due to greater mining of Zn from soil without its replenishment (Shukla and Behra (2011; Takkar and Shukla (2015).

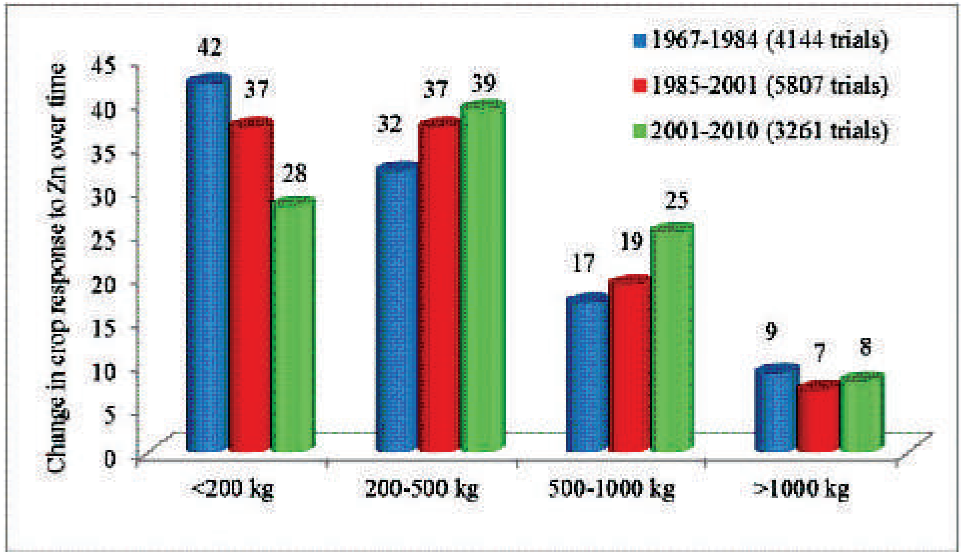


Figure 2. Changes in crop responses to zinc with time in experiments at farmer's field (Singh, 2008; Shukla and Behera, 2011)

Sources of Zinc and their Relative Efficacy

Zinc sulphate ($ZnSO_4.7H_2O$, 21-22% and $ZnSO_4.H_2O$, 35% Zn), ZnO (67-80% Zn), Zn-chelates, ZnEDTA (12-14 %Zn), zincated urea (2% Zn) are the major Zn-containing fertilizers in India and have been brought under the Fertilizer Control Act of Government of India (FCO, 2019). In addition to these other fertilizers multi-micronutrient mixtures containing variable amounts of Zn have also been brought under the state fertilizer control act in some of the states. Besides these other chemicals such as $Zn_3(PO_4)_2.4H_2O$ (44% Zn), $ZnCl_2$ (45% Zn) and $ZnCO_3$ (56% Zn) and by-products of industries such as Zn-frits (11% Zn) and physical mixtures of SSP and $ZnSO_4.7H_2O$ and other nutrient sources such as organic manures, compost, industrial effluents, sewage and sludges (variable Zn composition) have been evaluated,in field and pot-culture experiments with several crops, as a source of Zn supply to correct its deficiency in crops on diverse soils. Some studies on these aspects are reviewed as under.

Multi-micronutrient Mixture as Source of Zinc

In two field experiments, the relative efficiency of Tracel (6.5% Zn, 4.25% Fe, 10.0% Mn, 0.005% Cu), Nu-Spartin enriched with lignin and sugar free organic material in pre-digested form (5.28% Zn, 0.88% Fe, 3.20% Mn, 2.8% Cu), Booster Treat-inorganic salts enriched with life promoting hormones (7.96% Zn, 0.64% Fe, 14.0% Mn, 2.20% Cu) and Sahayield-101, a chelated compound (0.05% each of Zn, Cu and Mn, 0.10% Fe) was compared against $ZnSO_4$ on a Fatehpur loamy sand for correcting Zn deficiency in wheat (Takkar and Bansal, 1987). In both the experiments, 5.6-11.2 kg Zn ha^{-1} rate produced the maximum grain yield and was significantly more than the control and other Zn sources. This resulted mainly due to the lower Zn content in the multi-micronutrient mixtures which were unable to meet fully the Zn requirement of the crops (**Figure 3**). Takkar and Nayyar (1986a) further evaluated the efficiency of foliar sprays of six products sold under various trade names against Zn-chelate, $ZnSO_4$ for wheat on a Zn-deficient loamy sand

Table 1. Grain and straw yield of rice as influenced by Zn coated urea applications (Shivay et al., 2008)

Treatments	Grain yield (t ha^{-1})	
	2005	2006
Prilled urea	4.02	3.95
0 5% ZnO coated urea	4.28	4.22
0.5% $ZnSO_4$-coated urea	4.52	4.37
1.0% ZnO coated urea	4.45	4.47
1.0% $ZnSO_4$-coated urea	4.65	4.68
1.5% ZnO coated urea	4.61	4.75
1.5% $ZnSO_4$ coated urea	4.89	5.04
2 0% ZnO coated urea	4.78	5.12
2 0% $ZnSO_4$ coated urea	5.05	5.26
Separate soil application of 25 kg $ZnSO_4$ ha^{-1}	–	5.18
CD (*P* = 0.05)	0.70	0.52

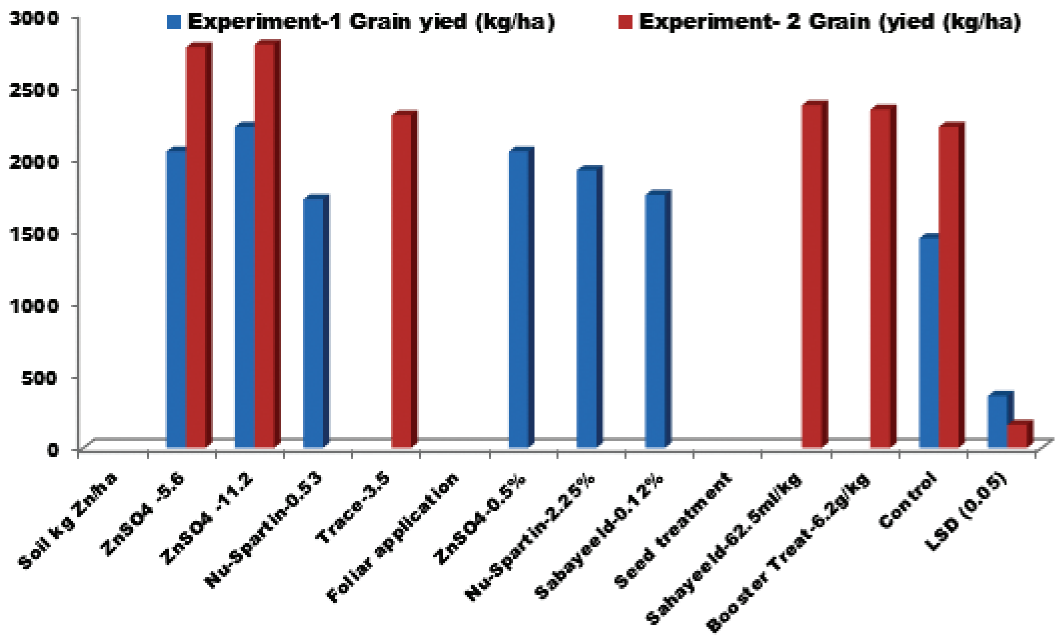


Figure 3. Comparative efficiency of zinc sulphate and multi-micronutrient mixtures in mitigating Zn deficiency in wheat (Takkar an**d Bansal, 1987)**

soil. Both $ZnSO_4$ and Zn chelate proved almost equally efficient and performed better than the remaining products.

Multi-nutrient Mixture/Products as Source of Zinc

The inclusion of micronutrients in macronutrient fertilizers has generally been advocated for their uniform distribution. With this in view, the efficiency of zincated super (mixture of $ZnSO_4$ and superphosphate containing 2.5% Zn) against $ZnSO_4$ for different crops was studied (Takkar and Nayyar, 1986a). The performance of zincated supper was either at par or less than $ZnSO_4$ for rice, wheat and groundnut and is the reason that it could not catch up with the farmers. Relative efficacy of zinc oxide (ZnO) and $ZnSO_4$-coated urea was compared for rice on a low Zn sandy clay-loam soil (DTPA-Zn , 0.68 mg kg^{-1}) by Shivay et al. (2008). They showed that in 2005 a significant increase in grain yield of rice over prilled urea was obtained with 1.0%, 1.5%, and 2.0% $ZnSO_4.7H_2O$-coated urea and 2.0% ZnO-coated urea. In 2006 a significant increase in rice grain yield was obtained with 1.0, 1.5 and 2.0 % $ZnSO_4.7H_2O$ -coated urea or ZnO-coated urea as well as with soil application of $ZnSO_4.7H_2O$ (**Table 1**). Also 2% coating with either material gave higher grain yield of rice than 1% coating of Zn. In both the years, increase in grain yield of rice was more with $ZnSO_4$ -coated urea than with ZnO-coated urea. Also 1.0% $ZnSO_4$-coated urea gave the highest agronomic efficiency (AE) and economic return. In 2006 soil application of 25 kg $ZnSO_4.7H_2O$ gave significantly lower AE than 1.0% $ZnSO_4.7H_2O$-coated urea. Since zinc coated urea will be used both for rice and wheat and at N application level of 120 kg ha^{-1} to each crop it will supply 5.2 kg Zn ha^{-1} yr^{-1} that is about the same amount as recommended as soil application per year to RWCS. They claim that the major advantage with the factory-made Zn-coated by the reputed company is that it will assure a quality product and application of Zn will be assured. Therefore application of Zn coated urea is much better than separate soil application of $ZnSO_4.7H_2O$. Shivay et al (2007) further examined the relative efficiency of above materials in the RWCS and showed that the highest grain yield of RWCS was obtained with 2% coating of urea and $ZnSO_4.7H_2O$–coated urea was a better coating material than ZnO. They concluded that $ZnSO_4.7H_2O$ coated urea is better source than ZnO- coated urea and 1% coating may be sufficient for rice and give higher economic return. Nevertheless, it has several draw backs that are being elaborated under the epilogue section.

Efficacy of Straight Sources of Zinc

Out of $ZnSO_4$, Zn-EDTA and dipping of cane sets in 4% ZnO suspension for two hours before planting for sugarcane tested on a Zn-deficient loamy sand soil (DTPA- Zn, 0.43 mg kg^{-1}), $ZnSO_4$ (11.2-kg Zn ha^{-1}) was found to be significantly superior to dipping the cane sets in ZnO suspension in increasing the cane yield (Nayyar et al., 1984). The efficiency of sparingly soluble Zn sources namely, ZnO and Zn-frits was evaluated against the soluble sources $ZnSO_4$ and Multi-micronutrient mixture - MMCM (6.5% Zn, 4.2% Fe,

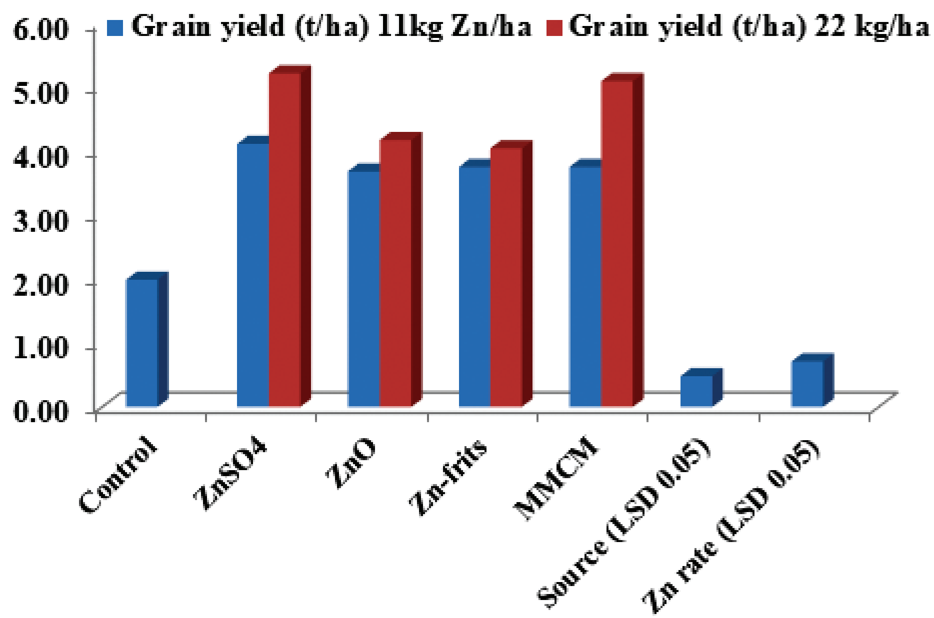


Figure 4. **Comparative efficacy of sparingly soluble and sparingly soluble Zn sources in correcting Zn deficiency in rice on a Zn deficient highly sodic soil (Nayyar and Takkar, 1981)**

0.04% Cu, 10 % Mn) for wetland rice on a highly sodic Zn-deficient soil of Ghabdan series. Rice grain yield in the soluble Zn sources $ZnSO_4$ and MMCM were more than the sparingly soluble sources and also produced significantly higher rice yield at high rate of 22 kg ha^{-1} than at low rate of 11 kg Zn ha^{-1} **(Figure 4)** because of rapid rate of conversion of soluble Zn, at low rate of its application to insoluble forms in wetland rice soil. Also multi-micronutrient mixture (MMCM) produced 120 to 360 kg ha^{-1} less rice grain yield as compared to $ZnSO_4$ applied at equal rates of Zn application. It indicates that presence of micronutrient cations other than the deficient (Zn) decreased its absorption and/or the utilization by rice plant as a result of antagonistic reaction (Nayyar and Takkar, 1980). In field experiments on a zinc-deficient flood plain alluvial soil, Sharma and Katyal (2009) showed that irrespective of the source, grain yield significantly increased up to 10 kg Zn ha^{-1} and broadcasting of $ZnSO_4$ and drilling of ZnO below the seed were equally effective in increasing the grain yield of wheat. However, the efficiency of $ZnSO_4$ at 11 kg Zn ha^{-1} was equal to 22 kg Zn ha^{-1} from sparingly soluble ZnO and Zn-frits sources (**Figure 4**). Nevertheless, $ZnSO_4$ proved to be better than other sources in correcting the Zn deficiency (Takkar et al., 1997; Katyal et al., 2004), but in highly Zn deficient alkali soils the amount of Zn required for efficiently correcting Zn deficiency and for sustainable high productivity of crops its rate was double from the sparingly soluble Zn sources than from the soluble Zn sources.

Bansal and Nayyar (1989) showed that foliar sprays of 0.10% Zn solution from $ZnSO_4$ and Zn-EDTA though produced equal and significantly higher grain yield over control, but these remained significantly inferior to the soil application of 11.2 kg Zn ha^{-1}. Nevertheless, Zn-EDTA proved superior to $ZnSO_4$ as it produced 500 kg ha^{-1} more rice yield than the $ZnSO_4$ source at their equivalent rate of 11.2 kg Zn ha^{-1} soil application. But Zn-EDTA was found at par with $ZnSO_4$ in calcareous soils of Pusa and sierozem soil of Hisar (Singh, 1998). Nonetheless, because of higher price of Zn-EDTA it is uneconomical than the $ZnSO_4$ therefore is not a favorite choice with the farmers. Two decades (1967-1987) of researches reveal that application of Zn through $ZnSO_4$ and ZnO significantly increased the grain yield of wheat, rice, maize, soybean, sorghum and Bengal gram over control and efficacy of both the sources were almost at par in all the six states except of ZnO for wheat and rice in Haryana and Punjab where it was significantly inferior to $ZnSO_4$ **(Table 2)**.

Organic Manures as a Source of Zinc Supply

Organic manures, besides supplying micronutrients in the form slowly available to plants, synchronizing with its mineralization rate in soil-environment conditions, also mobilize the native micronutrients by the organic acids and or chelating agents liberated during the mineralization process of added organic manures and biomass.

In a six year field experiment, comparative efficiency of organic manures verses fertilizer $ZnSO_4$ was

Table 2. Effect of zinc carrier (applied @ 10-11 kg Zn ha^{-1}) on grain yield of crops on Zn- deficient soils of India (Takkar et al., 1989)

Zn carrier	Grain yield of crops (t ha^{-1})											
	Wheat	Rice	Bengal gram	Soybean-bean	Sorghum	Maize	Wheat	Rice	Rice	Wheat	Rice	Barley
Control	3.4	2.8	1.6	1.1	2.1	2.3	4.0	6.4	7.2	3.3	4.9	4.2
$ZnSO_4.7H_2O$	3.9	4.0	2.2	1.4	3.0	3.2	5.6	7.6	8.4	4.5	5.7	4.8
ZnO	4.0	3.9	2.1	1.3	2.9	3.3	4.8	6.8	7.5	3.8	5.4	4.8
$Zn_3(PO_4)_2/ZnCl_2$	3.5	-	2.1	1.4	-	-	5.1#	7.2	-	-	-	-
Zn-frits/$ZnCO_3$	-	3.7*	-	1.6	-	3.4		-	8.2	4.0	5.7/5.5*	4.4
Zn-SSP	-	-	-	-	-	-	4.9	-	-	-	-	-
CD (P = 0.05)	0.2	0.4	0.2	0.2	-	-	0.2	0.4	0.2	0.2	0.5	0.5
Soil type	Medium black	Medium black	Medium black	Deep black	Black	Red sandy	Alluvial	Alluvial	Alluvial	Alluvial	-	Alluvial
States*	1	1	1	1	2	2	3	3	4	4	5	6
Texture#	C	C	C	C	C	S	SL	L	L	LS	CL	Sil-L
DTPA-Zn (mg kg^{-1})	<0.6	<0.6	0.42	0.23	0.83	0.80	<0.6	<0.6	<0.6	<0.6	<0.6	0.58

* 1 = Madhya Pradesh; 2 = Tamil Nadu; 3 = Haryana; 4 = Punjab; 5 = AP; 6 = Bihar
# S - Sandy; LS - Loamy sand, C - Clay; L - loam; Sil-L - Silty loam

evaluated for mitigating Zn deficiency in maize-wheat cropping system. The manures were applied only to every maize crop and Zn to the first maize crop. The mean gain yield in **Table 3** indicates that 12, 5 and 2.5 t ha^{-1} FYM, poultry manure (Pt-M) and piggery manure (Pig-M) were equally efficient as 11.2 kg Zn ha^{-1} from $ZnSO_4$ at normal fertility level for the production of sustainable high productivity of maize in a maize wheat rotation. The residual effect of manures on wheat indicates that 12 t ha^{-1} FYM, 5 t ha^{-1} Pt-M and 2.5 t ha^{-1} Pig-M were as effective as $ZnSO_4$ at the normal and the medium fertility levels (Nayyar et al., 1990; Takkar, 1991; Singh et al., 1992).

Integrated Zinc Management and Supply

Generally organic manures are not available in sufficient quantities to meet fully the nutrient requirements of crops of all the deficient soils. In view of this, the possibility of low to moderate rates of manures in conjunction with low to moderate rates of Zn from $ZnSO_4$ was explored for ameliorating the Zn deficiency in crops. In a three-year maize-wheat rotation experiment on a Zn deficient loamy sand soil at Ludhiana, 3 and 6 t ha^{-1} FYM and 1 and 2 t ha^{-1} each of Pt-M and Pig-M were applied alone and after mixing with 2.8 and 5.6 kg Zn ha^{-1} only to maize crop in the rotation. Mixture of 6 t ha^{-1} FYM and 5.6 kg Zn ha^{-1} produced the largest yield and was at par with the yields obtained with a mixture of 5.6 kg Zn with 2 t ha^{-1} of Pt. M or Pig. M ha^{-1} and were significantly better than 5.6 kg Zn ha^{-1} applied alone. Also, the residual effect of Zn with organic manures on wheat crop was clearly discernible over Zn application alone significantly better than Zn.

In a field experiment on Zn deficient soil of Madhya Pradesh, Rathore et al. (1995) showed that enrichment of 5 t FYM ha^{-1} with 5 kg Zn ha^{-1} helped to obtain similar increase in rice and wheat yield as with 10 kg Zn ha^{-1} alone. Thus application of 5 t FYM ha^{-1} contributed 5-kg Zn ha^{-1}. Organic manure, compost and poultry manure (Pt-M) applied in conjunction with $ZnSO_4$ were superior to $ZnSO_4$ in augmenting the yield of rice–winter maize cropping system on a calcareous soil of Bihar (Sakal et al., 1996). The magnitude of increase in rice grain yield due to Pt-M alone was equivalent to that of 25 kg $ZnSO_4$ ha^{-1} alone or 12.5 kg $ZnSO_4$ ha^{-1} mixed with 5 t ha^{-1} compost. Residual effect of these treatments on winter maize yield followed a similar trend. All organic wastes alone and in combination with Zn were superior to $ZnSO_4$. Use of bio-gas slurry (BGS) also helped in

Table 3. Comparative efficacy of $ZnSO_4$ and organic manures in a six-year long-term field experiment on a Zn-deficient loamy sand soil for maize-wheat productivity (Nayyar et al., 1990)

Source	Rates	Mean grain yield (t ha^{-1})	
		Maize	Wheat
Control		2.94	4.26
Zinc sulphate	11.2 kg ha^{-1}	3.35	4.44
Farmyard manure	6 t ha^{-1}	3.00	4.35
	12 t ha^{-1}	3.49	4.46
Poultry manure	2.5 t ha^{-1}	2.97	4.30
	5.0 t ha^{-1}	3.41	4.49
Piggery manure	2.5 t ha^{-1}	3.30	4.48
	5.0 t ha^{-1}	3.09	4.50
CD (P = 0.05)		0.18	0.16

Table 4. Effect of rates of zinc application on increase in crop yields (Singh,1998)

Crop	No. of experiments	Zn rates (kg Zn ha^{-1})				
		0	3	6	11	22
		Response of Crops (kg grain/ cane ha^{-1})				
Rice	93	3,687	-	911	562	745
Wheat	39	3,187	127	276	849	200
Maize	23	-	-	439	217	-
Sorghum	6	1,217	200	250	266	-
Groundnut	2	1,300	300	400	400	-
Raya	1	1,800	300	300	0	0
Soybean	2	400	300	600	600	-
Ragi	1	3,500	400	400	400	-
Sugarcane	9	10,300	-	20000	180000	-

correcting Zn deficiency and sustaining high productivity. The combined application of Zn (5 kg ha^{-1}) and BGS (2.5 t ha^{-1} in rice and 5 t ha^{-1} in wheat) was more effective than their single application in enhancing crop yields (Singh et al., 1998). This beneficial effect is attributed to the presence of complexed Zn in organic manures as well as due to the release of solid phase labile Zn by the complexing agents/organic acids liberated during the break down of the organic manures, which act as a conduit or courier to deliver Zn/micronutrients to the plant roots.

Rates of Zinc Application

The optimum rates of Zn application varied with severity of its deficiency, soil types and nature of crops. Results from large number of field studies indicated that 2.5 to 11 kg Zn ha^{-1} as $ZnSO_4.7H_2O$ proved to be most effective in mitigating its deficiency and in sustaining high soil productivity in most of the crops grown on diverse Zn-deficient soils. Zinc deficiency can best be alleviated with application of 11 kg Zn ha^{-1} to wheat and rice; 5.5 kg Zn ha^{-1} to maize, soybean and sugarcane and 2.5 kg Zn ha^{-1} to groundnut, Indian mustard and red millet (**Table 4**; Takkar et al., 1989; Takkar,1996; Takkar et al., 1997; Singh, 1998; Takkar and Shukla, 2015).

The rates of Zn application for obtaining the optimum yield differ with the texture of the soil. The best rate of Zn application for wheat on relatively coarse texture loamy sand soils was 11 kg Zn ha^{-1} as compared to 5.5 kg Zn ha^{-1} in fine textured loam soils for obtaining optimum rice yields (Takkar et al,, 1989; Nayyar et al., 1990). Also, the rate of Zn application for a crop increased with the severity of Zn deficiency and deterioration of the soil conditions. On moderately alkali soils (pH 9.4 to 9.7), the optimum rate of Zn application for rice was 11 kg Zn ha^{-1} (Takkar and Singh, 1978) and it increased to 22 kg Zn ha^{-1} on highly sodic soils (pH >10) as well as in flood plain soils (**Figure 5:** Takkar and Nayyar, 1981; Takkar and Nayyar, 1986; Takkar et al., 1989; Nayyar et al., 1990) and 2.5 kg ha^{-1} in sandy alkaline soil (Takkar et al., 2004).

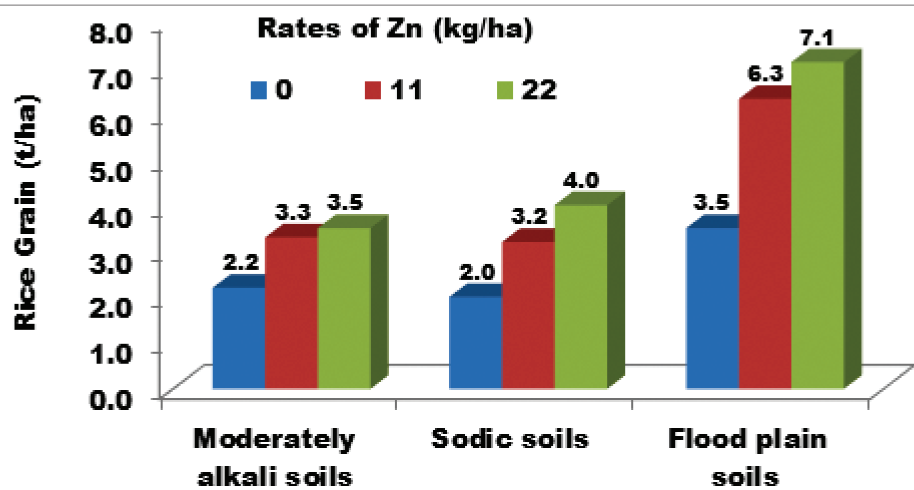


Figure 5. Rates of Zn application for rice grain yield (t ha^{-1}) No. of experiments: 8, 2, 6 respectively on moderately alkali, sodic, and flood plain soils

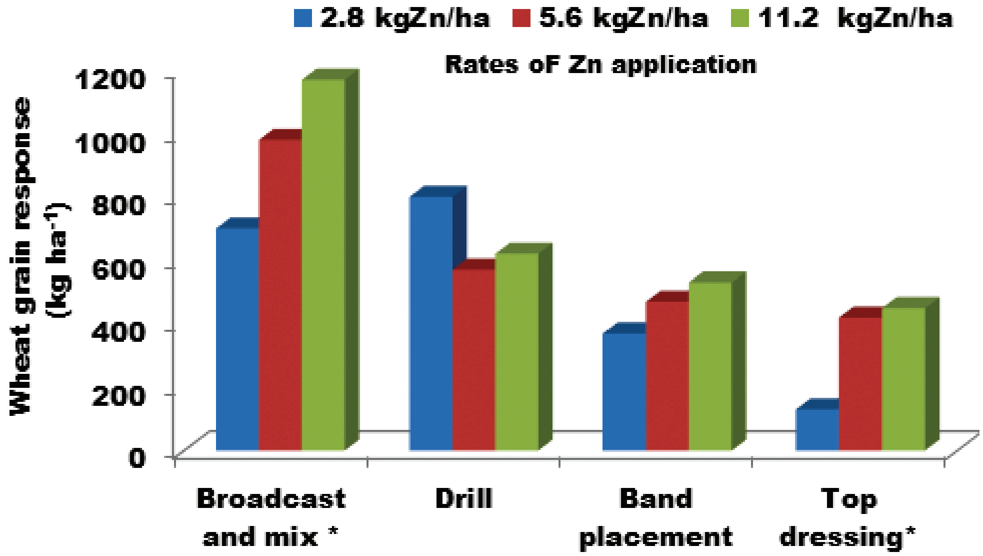


Figure 6. Comparative effectiveness of methods of soil application of Zn for sustainable high productivity of wheat on a Zn deficient loamy sand soil. Control yield = 3960 kg ha^{-1}; LSD (0.05) = 60

Also optimum rates of Zn application for a crop vary with the variety. Out of the four wheat varieties, 11.2 kg Zn ha^{-1} rate of application proved optimum in WG 357 and PV 18 varieties and it was 5.6 kg Zn ha^{-1} in WD 377 and WL 711 varieties. Nevertheless, irrespective of the varieties, the best rate of soil application of Zn was 11.2 kg ha^{-1} (Nayyar et al., 1990). Also 11.2 kg Zn ha^{-1} rate was the optimum in pearl millet varieties namely, PHB 37, 76/2; 5.6 kg Zn ha^{-1} in PHB 12, PHB; and 2.8 kg Zn ha^{-1} in PHB 10 (Takkar et al., 1988).

Methods of Zinc Application

The methods of Zn application that have been evaluated include soil application through broadcast and mixing in soil, drill or band placement, foliar application, coating seed with Zn powders or soaking seeds in Zn salt solutions and dipping the roots in transplanted crops in ZnO suspension. Research work carried out on these aspects is reviewed below.

Soil Application

In a field experiment on a Zn-deficient loamy sand soil comparative efficiency of methods of soil application of Zn was evaluated for high productivity of wheat and rice. The results in **Figure 6** reflect that Zn application at 11.2 kg ha^{-1} rate produced the maximum wheat grain yield. Broadcast and mix mode of Zn application proved more efficient as compared to drill or band-placed Zn (Takkar et al., 1974; Sadana and Takkar, 1982). Top-dressing Zn after 60 days of seeding proved least effective. Takkar and Bansal, (1987) further showed that both the band placement and broadcast and mix modes of Zn application were equally efficient for wheat. Nevertheless, the yield response of wheat to broadcast and mix mode of Zn application was more than its band placement. Sharma and Katyal (2009) also found Similar results in a field experiment.

Foliar versus *Soil Application of Zn*

Comparison of the efficacy of foliar *versus* soil application of Zn to different crops was made in several field experiments on Zn-deficient soils. By and large, soil application of Zn proved markedly superior to foliar sprays of 0.5% $ZnSO_4$ neutralized solution (**Figure 7**; Sharma et al., 1982; Takkar and Bansal, 1987). Sharma and Katyal (2009) also reported that foliar spray of $ZnSO_4$ was an effective emergency method, but in highly Zn-deficient soils it did not compare well with soil application of Zn. The low efficiency of foliar sprays has resulted firstly from the concentration of Zn in the spray solution and its supply at a stage which is not enough to meet the Zn requirement of the crop. Secondly, the crop had already suffered due to Zn deficiency before it received the foliar sprays. Nevertheless, it is understandable that if the crop is fed with the needed amount of Zn through foliar application with higher concentration of $ZnSO_4$ solution it may prove equally efficient to soil application. The results of a field experiment on this aspect proved that soil application of 11.2 kg Zn ha^{-1} and one foliar spray of 2% $ZnSO_4$ solution were equally effective for sustaining high productivity of wheat (**Figure 7**: Takkar and Bansal, 1987). However, for rice grown on a highly Zn-deficient sodic soil (DTPA-Zn 0.31 mg kg^{-1}, pH 9 5), foliar sprays though increased the rice yield significantly over the control,

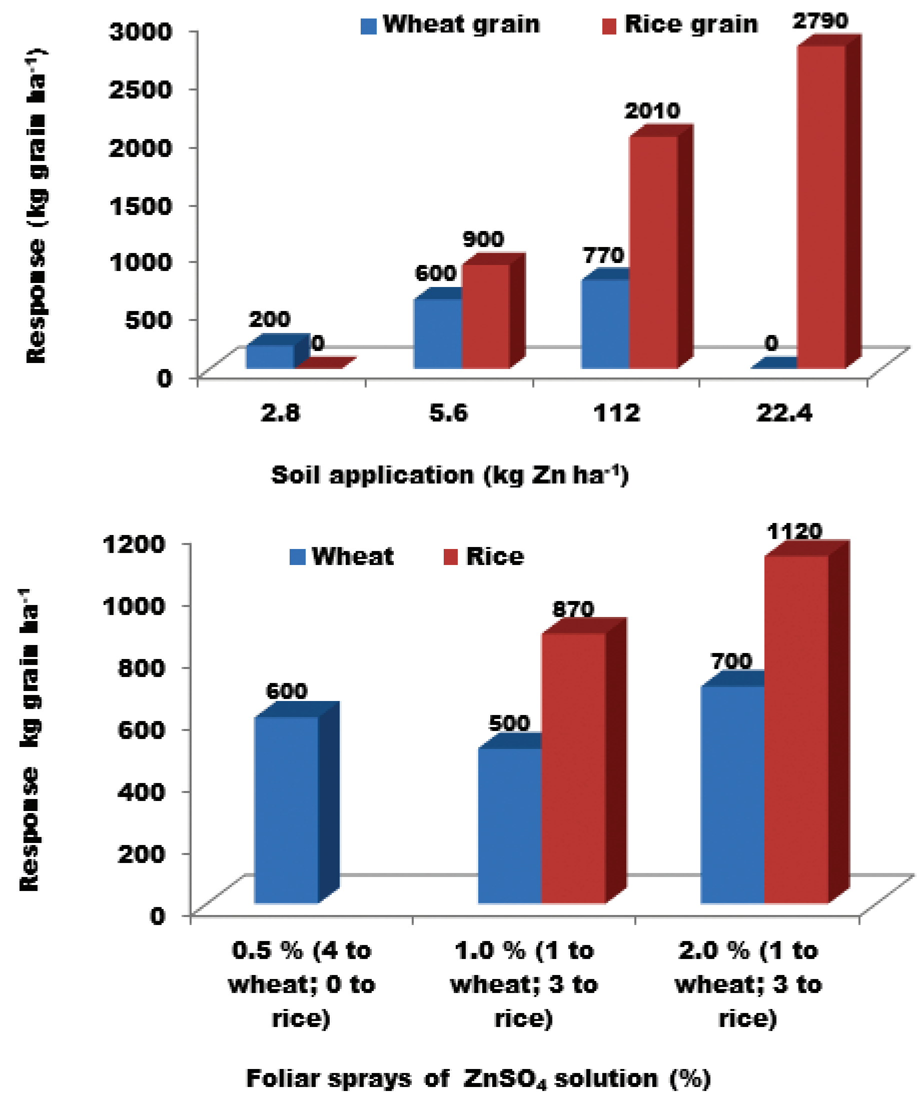


Figure 7. Influence of rates and modes of Zn application on rice and wheat productivity (Source: Sharma et al., 1982 for rice; Takkar and Bansal, 1987 for wheat)

but were far less efficient than the soil mode of Zn application (**Figure 7**: Sharma et al., 1982). It indicates that in severely Zn-deficient soils foliar method is not a substitute to soil mode of Zn application.

Time of Zinc Application

The efficiency of Zn fertilizers for ameliorating Zn deficiency in crops depends not only on the rates and modes of their application but also on the right time and frequency of their application. Results of field experiments have shown that the best and right time of Zn application is just before sowing or transplanting of the crop as reflected by the lower yields of wheat and rice when Zn was top-dressed beyond 30 days as compared to when it was applied just before seeding/transplanting (Takkar et al., 1974b ; Sadana and Takkar, 1983). Thus the right time of Zn applications is just before sowing of crops for attaining sustainable high crop yields.

Other Methods

In view of very low efficiency of soil applied Zn, efforts have been wade to enhance the same by coating or soaking seeds in Zn solution, dipping rice seedling roots in ZnO suspension and transplanting Zn-enriched nursery. The results revealed that soaking of seed for 24 hours in 0.02 *M* $ZnSO_4$ solution or with Sahayield-101 and Booster produced appre-ciably lower yields of maize and wheat as compared to soil application of 11.2 kg Zn ha^{-1} (Takkar et al., 1974; Takkar and Bansal, 1987). The results of dipping roots of rice seedlings in 2 and 4% ZnO suspension in water

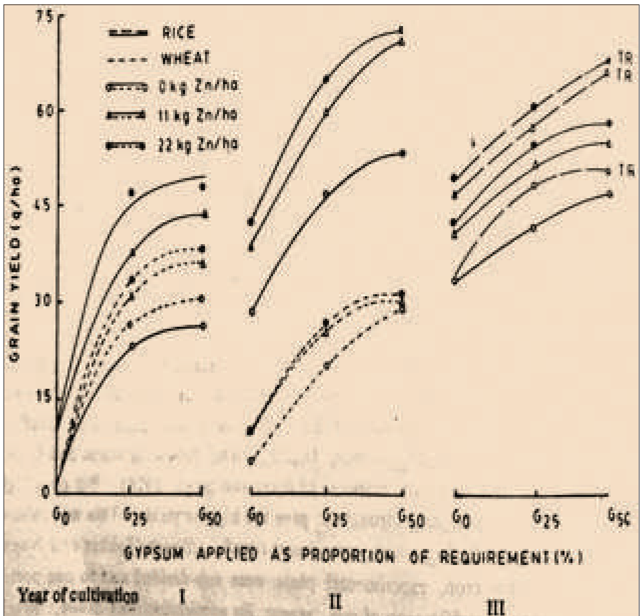


Figure 8. Effects of rates of Zn and gypsum on rice-wheat cropping system on a highly deteriorated alkali soil irrigated with brackish water (Takkar and Nayyar, 1981; Nayyar et al., 1990)

were not conclusive as in one experiment it proved significantly inferior while in other it proved to be as efficient as soil application of 11.2 kg Zn ha^{-1} (Sharma et al., 1982).

Management of Zn Deficiency in Cropping Systems

Most of the studies were though directed to meet the immediate requirements of individual crops, yet some long-term experiments have been conducted on different soils to identify the efficient carriers, their mode, rate and frequency of application in different cropping systems.

Management of Zn at the rates of 2.75, 5.5, and 11.0 kg ha^{-1} as $ZnSO_4$, with repeat application after the fourth crop in a wheat-rice rotation, for 12 crops was investigated. The results indicate that for all the rice crops 5.5 kg Zn ha^{-1} and for wheat half the rate of 2.75 kg Zn ha^{-1} was the optimum. But, for the system of first four crops 5.5 kg Zn ha^{-1} and for the next eight crops, after repeat Zn application, 2.75 kg Zn ha^{-1} and for 12 crops 5.5 kg Zn ha^{-1} produced the sustainable high yields (Nayyar et al., 1990). Thus 5.5 kg Zn ha^{-1} is a better rate for managing Zn deficiency on a sustainable long-term basis in a rice-wheat cropping system on a sandy loam alkaline Zn deficient soil.

Alkali or Sodic Soils

Generally these soils are highly deficient in Zn because of high to very high pH and or sodicity. It has been demonstrated that with increase in one unit of pH the Zn activity in soil solution decreases 100-fold (Lindsay, 1979). Three field experiments were conducted on Zn-deficient moderately deteriorated alkali soils (pH 9.1 to 9.6; **Figure 8**; Takkar and Singh, 1978) and one on highly deteriorated alkali soil (pH 10.4; Takkar and Nayyar, 1981a) to assess the effect of three rates of gypsum (G_0, G_{25}, G_{50} % of the gypsum requirement of soil) and three rates of Zn (Zn_o, Zn_{11}, Zn_{22} kg ha^{-1}) in RWCS. In moderately deteriorate alkali soils application of gypsum did not increase the rice yield but increased that of wheat yield. The beneficial effect of Zn application to rice was far more than that of gypsum. Nevertheless, application of G_0Zn_{22} or $G_{25}Zn_{11}$ to rice, $G_{50}Zn_{11}$ to the following wheat and $G_{50}Zn_{22}$ to the cropping system gave the highest response and productivity (Takkar and Singh, 1978). But on highly deteriorated sodic soil (pH 10.4) irrigated with brackish water, $G_{50}Zn_{22}$ throughout gave the highest yields. This was followed by either $G_{50}Zn_{11}$ or $G_{25}Zn_{22}$ which were almost equally efficient (Takkar and Nayyar, 1981a). Marked and significant response of rice to repeat Zn application, to 5th rice crop over the initial residual one proved that residual availability of Zn lasted up to four crops and the fifth crop needed fresh Zn application to sustain high productivity of RWCS. Whereas, residual effect of 18 kg Zn ha^{-1} applied to rice in rice-wheat system lasted up to 7 crops on an alkali soil (pH 10.45) but irrigated with normal water (Singh and Abrol, 1985). Thus, the use of brackish water on highly sodic soil shortened the residual effectiveness of Zn. These results clearly demonstrate that highly deteriorated alkali soil was highly deficient both in Ca and Zn and that Zn deficiency in RWCS cannot be corrected by its application alone, but only when Ca deficiency or Na toxicity is simultaneously corrected by adding gypsum or other suitable amendments. The treatment of $G_{50}Zn_{22}$ in sodic soils irrigated with brackish water is the best option for attaining sustainable high productivity of RWCS.

In upland cropping systems, the residual effect of 22 kg Zn ha^{-1} lasted for at least 7 crops in a wheat-groundnut rotation on loamy sand soil (Takkar et al., 1975). In a silty loam soil, residual effect of an initial application of 5.9 kg Zn ha^{-1} became negligible in the sixth rice or seventh wheat crop in the RWCS (Bhardwaj and Prasad, 1981).

Studies to evaluate optimum rate and frequency of zinc application to rice-wheat systems revealed that application of 5 kg Zn ha^{-1} to every 3rd crop of rice and 10 kg Zn ha^{-1} to first and 6th crop of rice in Ustochrepts of Karnal in Haryana, 10 kg Zn ha^{-1} to every 5th crop in Calciorthents of Pusa in Bihar, and 11 kg Zn ha^{-1} after 6th crop in Typic Ustrochrepts of Ludhiana in Punjab is sufficient to sustain high productivity of the cropping systems (Gupta *et at*, 1994; Singh, 1998).

Chhibba et al. (1989) demonstrated that 5 kg Zn ha^{-1} rate was though optimum for rice, but for the RWCS 10 kg Zn ha^{-1} gave the highest increase in yield and productivity because of its superior residual effect on the subsequent wheat crop.

Zinc-efficient Cultivars

Identifying and/or breeding high-yielding Zn-efficient cultivars may prove better alternative to reduce and/ or meet fertilizer Zn need of crops. Several studies have examined crop cultivars and identified Zn-efficient cultivars capable of producing higher sustainable yield at low level of native available soil Zn or required less application of micronutrients than others. Wheat cultivars WG 377 and WL 711 had lesser Zn requirement of 5.6 kg ha^{-1} than 11.2 kg ha^{-1} required by other varieties to reach their maximum yield on a Zn-deficient soil (Takkar and Nayyar, 1984). Similarly, Ratna and UPR 238 were relatively more Zn-efficient as these gave optimum yield at 5 kg ha^{-1} as compared to others at 10 kg Zn ha^{-1} (Sakal et al., 1996). Cultivars of several crops have been rated with respect to their Zn-efficiency and inefficiency (Takkar, 1993; 1996). On the basis of micronutrients uptake efficiency and micronutrient yield efficiency indices, Shukla (2014) has identified agronomically and genetically efficient cultivars of wheat, rice, maize, and pigeonpea. However, a distinction should be made between the tolerance of an individual crop and that of a cropping system to Zn deficiency. The latter has been rarely studied but, for example, it has been observed that wheat grown in rotation with rice yielded less than wheat in rotation with maize (Chandi and Takkar, 1982). Wheat in rotation with rice also removed less Zn. Rice itself was observed to take up greater quantities of Zn than eight other species, due in part to higher yields (Takkar and Walker, 1993).

Iron

Iron Status and Extent of Deficiency

In Indian soils total Fe ranged from 0.4 to 27.3% and available Fe content varied from 0.36 to 174 mg kg^{-1}. Iron deficiency in Indian soils generally remained nearly at 12-15%. However, Fe-deficiency has been prevalent in some specific soil-crop conditions *viz*. in rice, sugarcane, chickpea on coarse textured alkaline soils of Punjab low in organic matter (Takkar et al., 1979 Takkar, 1979, a, b); in wheat, groundnut and rice on yellow brown alluvial sandy loam soils of Gujarat; in groundnut and sorghum on Alfisols and Vertisols of Andhra Pradesh and Tamil Nadu; in sorghum on calcareous soils of Bihar; in wheat on black clay soils of Madhya Pradesh; in sugarcane in black clay soils of Maharashtra; and in clay soils of Rajasthan (Takkar, 1966), and thus threatened the sustainable productivity of these crops. Thus average number of Fe deficient samples may not reveal the real picture of its deficiency in certain specific soils, crops, areas or regions (Takkar and Shukla, 2015). Iron deficiency in crops is most difficult to correct in the field. The addition of iron fertilizer will correct the deficiency, provided it is not being rendered unavailable in the soil or at roots or in the plant after absorption (Takkar and Randhawa, 1978). This happens due to rapid conversion of added Fc^{2+} iron salt like ferrous sulphate ($FeSO_4$) in soils to unavailable Fe^{3+} iron form to plants.

Crop Responses to Iron Application

On an average, crop responses to soil and foliar application of Fe range from 0.45 to 0.89 t ha^{-1} for cereals, 0.3 to 0.68 t ha^{-1} for millet, 0.34 to 0.58 t ha^{-1} for pulses, 0.16 to 0.55 t ha^{-1} for oilseeds, 0.20 to 1.53 t ha^{-1} for vegetables, and 0.39 to 9.68 t ha^{-1} for cash and other crops (Takkar et al., 1989, 1997; Shukla et al., 2014).

Correction of Iron Deficiency

In Punjab extensive Fe-deficiency in rice has been recorded because its cultivation has been extended to permeable coarse textured soils low in Fe and organic matter and alkaline and or calcareous in nature. Therefore, researches on the mitigation of Fe deficiency have been focused on rice besides other crops like sugarcane and sorghum. Very few studies have been reported from other regions and states. Nevertheless, right Fe sources, rates, methods, time and frequency of application for the correction of Fe deficiency are presented below.

Sources of Iron and their Relative Efficacy

Several inorganic sources: ferrous sulphate ($FeSO_4.7H_2O$:19-20.5% Fe), Fe-EDTA (9-12% Fe), Fe-EDDHA (10.0% Fe), pyrite, biotite and organic carriers: organic manures (FYM 0.15% Fe), poultry and piggery manure (0.16% Fe), sewage sludge are being used as sources of Fe to alleviate its deficiency in crops. Among various sources, ferrous sulphate proved superior to pyrite and biotite in increasing the rice yield and Fe uptake in Vertisols (Deore et al., 1994). Coating of rice seeds with 2% slurry/solution of Fe-EDTA or $FeSO_4$ proved equally effective in increasing rice yield (Ingle and Sonar, 1982). Singh and Dayal (1992) showed higher efficiency of $FeSO_4$ + citric acid in increasing the groundnut yield by 16-24% than $FeSO_4$, Fe-citrate and Fe-EDTA. Foliar sprays of $FeSO_4$ solution proved more effective than soil application in correcting Fe-chlorosis in groundnut (Potdar, 1994) and sugarcane (Mathur *et at.*, 1987). Sakal (2001) showed that application of 50 kg $FeSO_4$ ha^{-1} significantly increased the grain yield of rice by 0.87 t ha^{-1} over control in calcareous soils of Bihar. In terms of effectiveness, 10 t ha^{-1} compost alone was at par with 50 or 100 kg $FeSO_4$

ha^{-1}. Response of rice to $FeSO_4$ or pyrite increased when applied in combination with compost. The residual effect of pyrite was about 4-times greater than $FeSO_4$ and further increased when these were applied together with compost.

Rates of Iron Application

By and large, foliar application of 10-15 kg $FeSO_4$ ha^{-1} or soil application of 50-200 kg $FeSO_4$ ha^{-1} alleviated Fe deficiency in most of the soil-crop conditions depending upon the crop, type of soil, deficiency status, and cultural practices. But the rates of soil application of Fe are very high and uneconomical as compared to foliar application.

Cultural Practices for Enhancing Iron Availability

Iron deficiency in rice grown on permeable sandy soils results not only because of the inherent low Fe content of soils but more so due to unfavorable conditions for reduction of Fe^{3+} to Fe^{2+} as a result of non-ponding of irrigation water for longer periods. Therefore, only puddling of the soil before transplanting rice helped in increasing markedly the rice yield and the increase was almost equal to the best yield obtained with foliar applications of Fe under un-puddled soil conditions (Takkar, 1979a,b; Takkar and Nayyar, 1979; Takkar et al., 1979; Nayyar and Takkar, 1989 **(Table 5)**.

Soil versus *Foliar Application*

Foliar sprays of $FeSO_4$ solutions proved significantly and remarkably better than its application to soil. Also, increasing the concentration of Fe in the spray solution from 0.5% to 3% significantly increased the grain yield of rice and the best yields were obtained with 3% $FeSO_4$ solution (**Table 5**). But foliar sprays of un-neutralized $FeSO_4$ solution were more effective than the neutralized with lime mainly because of rapid conversion of soluble form of Fe^{2+} to insoluble hydroxides and carbonates besides the photochemical oxidation of Fe^{2+} to Fe^{3+} iron form in alkaline environment (Takkar and Nayyar, 1979; Nayyar and Takkar, 1989). In a field experiment, on a loamy sand soil with pH 8.3, 5-foliar sprays of 1.0% $FeSO_4$ solution on the foliage of a month-old transplanted rice crop suffering from severe Fe-chlorosis were made at an interval of 5 to 7 days. The acidity of the spray solution markedly influenced the response of rice to Fe. Grain response markedly decreased from 2.96 to 2.19 and 1.33 t ha^{-1} with decrease in acidity of $FeSO_4$ solution from pH 2.30 to 2.60 and 3.I5, respectively (Singh et al., 1988b).

Integrated Iron Management and Supply

Mixing of $FeSO_4$ with FYM has been found to increase the rice yield over $FeSO_4$ alone and the effect was more pronounced under puddled soil conditions. However, the yield remained significantly below the yields obtained with foliar application of $FeSO_4$ (**Table 5**). That is why foliar spray of Fe has been more successful than Fe application to soil or Soil + FYM in correcting Fe-chlorosis. The efficiency of green manure (GM) crop *(Sesbania aculeata)* in comparison with soil and foliar application of $FeSO_4$ to rice was evaluated in a three years field experiment on loamy sand alkaline soils (Nayyar and Takkar, 1989). Incorporation of only GM markedly and signi-ficantly increased the grain yield of rice (**Figure 9**). Nevertheless, combination of GM

Table 5. Rice grain yield and Fe uptake as influenced by the soil and foliar application of Fe under puddled (P) and un-puddled (UP) soil conditions (Takkar and Nayyar, 1979; Nayyar and Takkar, 1989)

Treatments Foliar application	No. of sprays	Grain yield (t ha^{-1})		Fe uptake (kg ha^{-1})	
		UP	P	UP	P
$FeSO_4.7H_2O$ solution (%)					
0.5	6	3.78	—	1.76	—
1.0	3	3.85	—	1.83	—
2.0	3	4.47	8.41	2.22	3.98
3.0	3	5.51	8.70	2.50	3.43
Soil application					
$FeSO_4.7H_20$ (kg ha^{-1})					
100		1.57	6.54	1.18	2.04
200		2.60	—	1.33	—
100 + 10 t FYM ha^{-1}		2.78	8.14	1.28	2.91
Control		1.50	5.63	1.01	1.87
CD (P = 0 05)		0.33	0.60	0.84	0.73

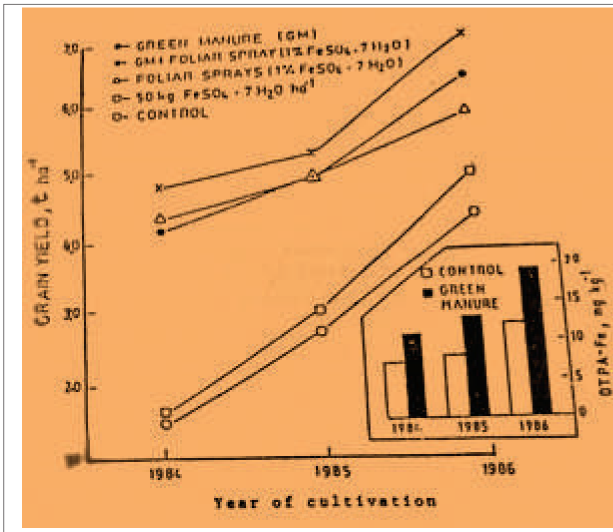


Figure 9. Rice yield and iron availability as influenced by green manuring and iron application

and foliar spray of 1% $FeSO_4$ solution gave the sustainable high productivity of rice grain yield, followed by GM or foliar sprays. Incorporation of green manure helped in enhancing the reduced condition and in mobilization of internal soil Fe resource during its decomposition process. This was also revealed by the higher active Fe (49-56 %) in the leaves of 45 –day old plants, that was significantly correlated with rice grain yield (r = 0.77), as well as significant increase in DTPA-Fe in GM as compared to the control plot (Nayyar et al., 1990).

Both soil applied 12 kg Fe ha^{-1} and foliar application of 1 % $FeSO_4$ solution proved equally effective in increasing grain yield of sorghum. Iron-enriched FYM was the best followed by 4-sprays of 1% $FeSO_4$ solution and soil application (Singh et al., 1983; **Figure 10**). The rates of soil application of $FeSO_4$ were very high 100-200 kg ha^{-1}, compared to foliar application and as such were uneconomical. Similarly high cost of Fe-chelates discourages farmers to use these. Even foliar sprays of $FeSO_4$ solution were more effective and efficient than soil application in correcting Fe-chlorosis in tomato, chilli, groundnut, sorghum and sugarcane (Singh et al., 1983, Singh, and Chaudhari., 1991).

Pal et al. (2008) studied the comparative effect of sources and methods of Fe application on grain yield of different varieties of rice under aerobic conditions at IARI, New Delhi farm. The mean grain yield response of rice was 67, 37 and 85% under 30 kg Fe ha^{-1} + 10 t FYM ha^{-1}, 50.95 kg Fe ha^{-1}, and 3-foliar sprays of $FeSO_4$ (3%), respectively, over the control (**Table 6**). Soil application of as high as 50.9 kg Fe ha^{-1} (305 kg $FeSO_4$ $7H_2O$) was found to be less efficient than 3-foliar sprays of 3% $FeSO_4.7H_2O$ (45 kg $FeSO_4.7H_2O$ ha^{-1}) in increasing the grain yield of rice. Mixing of 30 kg Fe ha^{-1} (150 kg $FeSO_4.7H_2O$) with 10 t FYM ha^{-1} also remained significantly lower than the foliar application. Superiority of foliar application of Fe over soil application has also been reported by Nayyar and Takkar (1989) and Sakal et

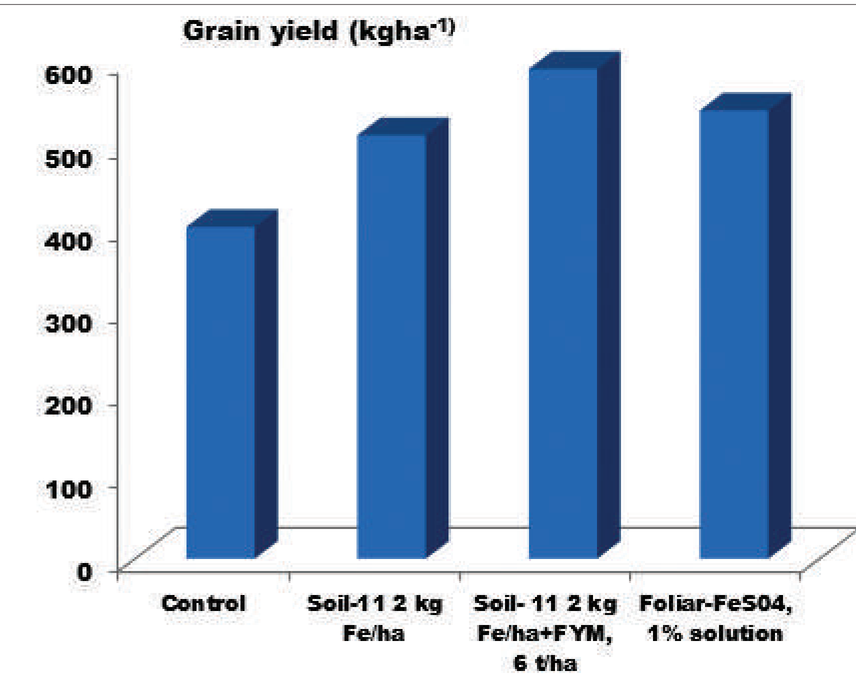


Figure 10. Effect of source and mode of Fe application on sorghum grain yield (kg ha^{-1})

Table 6. Effect of sources and methods of Fe application on the grain yield of rice cultivars (Pal et al., 2008)

Applied Fe	Cultivars				Mean
	IR 36	IR 64	1R 71525-19-1-1	CT	
Grain yield (t ha^{-1})					
Control	1.10	0.73	2.28	2.25	1.59
30 kg Fe ha^{-1} as $FeSO_4$ $7H_2O$ + 10 t FYM ha^{-1}	2.39	1.82	3.13	3.25	2.65
50.95 kg Fe ha^{-1} as $FeSO_4$ $7H_2O$	1.98	1.53	2.48	2.75	2.18
3-foliar sprays of $FeSO_4$ $7H_2O$ (3%)	2.81	1.82	3.43	3.76	2.95
Mean	2.07	1.48	2.83	3.00	
CD (P = 0.05)	*Fe*	*Cultivar*	*Fe x Cultivar*		
	0.26	0.26	NS		

al. (1996).

Iron-efficient Cultivars

For effective control of Fe deficiency, solution lies more with development of Fe-efficient cultivars of Fe-sensitive crops than with Fe fertilizers and methods of application. Several cultivars of groundnut (Singh and Choudhari, 1991), chickpea, lentil, and sorghum (Singh et al., 1985b) tolerant to Fe-deficiency have been identified. Also genetically and agronomically Fe-efficient and inefficient cultivars of pigeonpea, chickpea, rice and maize have been identified and these can be cultivated on Fe-deficient soils for achieving sustainable high grain yield as well as high density Fe seeds to help mitigate Fe-malnutrition in human (Takkar, 1993; Shukla 2014). Pal et al., (2008) further showed significant varietal difference to Fe-deficiency in respect of grain yield (**Table 6**). On an average, highest grain yield was obtained with cultivar CT (3.0 t ha^{-1}), followed by 1R 71525-19-1-1 (2.83 t ha^{-1}), IR 36 (2.07 t ha^{-1}), and IR 64 V_2 (1.48 t ha^{-1}).

Manganese

Manganese Status and Extent of Deficiencies

Total Mn content in Indian soils varied from 37 to 11,500 mg kg^{-1} and available content ranged from 0.01 to 445 mg kg^{-1}, with a mean value of 21.8 mg kg^{-1}. Nearly 7.1% soils of the county are deficient in Mn. Although Mn deficiency is not a major problem in India soils as revealed by soil analysis, but its field scale deficiency in wheat was first discovered in 1979 under RWCS adopted for 7-8 years or more in place of maize-wheat or groundnut-wheat system on highly permeable coarse textured alkaline soils of Punjab. The DTPA available Mn in these soils/sites ranged between 0.5 and 2.8 mg kg^{-1} and was below the critical value of its deficiency. Spectacular response of 200 to1500 kg ha^{-1} of wheat grain to foliar application of un-neutralized 0.5-1.0 % $MnSO_4$ solution was recorded at these sites (Takkar and Nayyar, 1981c; Bansal et al., 1987). Manganese deficiency has become a perpetual problem in wheat and other crops grown after rice under RWCS on highly coarse textured soils. *Thus, the sustainability of the RWCS on such soils is short lived.*

Also, Mn deficiency has now engulfed the similar soil-cropping system in the states of Haryana, western Uttar Pradesh, Tamil Nadu and Himachal Pradesh. During rice cultivation solubility of Mn increases and it causes leaching of Mn to lower soil layers with period of rice cultivation. As a result available Mn content declined below the critical level of 3.5 mg kg^{-1} for wheat and other crops (Bansal et al., 1987). Overall Mn deficiency has increased nearly 8-fold from 2 to 16% over the years in Punjab (Sadana et al., 2010) and has become a perpetual chronic problem. Responses of wheat, rice, soybean, sunflower, onion, and tomato to Mn ranged from traces to 3.78, 1.78, 1.02, 0.70, 4.30, and 0.80 t ha^{-1}, respectively (Nayyar et al. 1990; Takkar et al. 2004).

Sources of Manganese and their Relative Efficacy

Manganese sulphate ($MnSO_4.H_2O$; 32% *Mn*), MnO_2, Mn-frits, EDTA-Mn, Tracel-I, Tracel-II, Devi microshakti are some the chemical sources for Mn supply. Organic manures: FYM, green manures are also used for mending the Mn-deficiency. So far, $MnSO_4.H_2O$ is the main Mn-fertilizer source used to correct its deficiency. Kang (1985) showed that $MnSO_4$ proved 1.5 and 10 times more effective than the Mn-frits and MnO_2, respectively, in increasing the the wheat grain yield. Foliar sprays of 1.0% $MnSO_4$ solution produced the highest grain yield which was about 1.2 times greater than that obtained with the foliar sprays of Tracel-I, Tracel-II or Devi microshakti (Sadana et al., 1989).

Methods, Rates and Time of Mn Application

Severe Mn-deficiency is difficult to manage with soil application due to oxidation of soil-applied Mn, especially in high pH soils. Foliar application of $MnSO_4$ is an immediate effective measure to combat Mn-deficiency in wheat and *berseem* (Takkar and Nayyar, 1981c; Sadana et al., 1991), though repeated foliar application has to be applied every year. Economic benefit of foliar application of Mn to wheat was more than 2-fold (B:C ratio 4.5) as compared to its soil application (B:C ratio 2.1) (Takkar and Shukla, 2015). Manganese applied to the soil at the rate of 30-40 kg ha^{-1} though produced yield equivalent to that of 3-foliar sprays of 1% $MnSO_4$ solution (5 kg ha^{-1}), yet it was uneconomical (Nayyar et al. (1985). The reversion of soil applied Mn to the higher oxides in a form unavailable to plants in alkaline soils is the cause for its low availability and efficiency. Takkar et al., (1986b) further demonstrated that yield and Mn concentration of wheat grain significantly and spectacularly increased with Mn application irrespective of the mode of application. However, Mn application through foliar sprays as compared to soil application proved significantly superior to soil mode of Mn application. Also 3-sprays of 0.5 % $MnSO_4$ solution produced sustainable high grain yield followed by 2-sprays of 1.0%, and 2 sprays of 2% $2MnSO_4$ solution (**Table 7**),

Time and Frequency of Manganese Application

Time of Mn application is very crucial to feed Mn-hungry crop at the earliest stage, before the onset of visual Mn deficiency symptoms, that usually manifest after the first irrigation in wheat, to effectively correct its deficiency than its mitigation at a later stage when a substantial damage to the crop may have already occurred. Therefore, efficacy of foliar feeding of wheat with Mn through $MnSO_4$ solution, starting before the application of first irrigation against its application after the first irrigation, was evaluated in a series of experiments on Mn-deficient soils Results in **Table 8** clearly reveal that at equal number of sprays of 0.5% or 1.0% of $MnSO_4$ solution initiated before the first irrigation produced significantly more grain yield than when these were started after the first irrigation and were also superior to that of soil application of 50 kg Mn ha^{-1} (Takkar et al., 1986b; Sadana et al., 1991). It suggests that time of application of Mn is very crucial for efficiently mitigating its deficiency. Appreciably higher grain yield with 3-sprays of 1.0% as compared to 0.5% $MnSO_4$ solution at site I and II showed that 3-sprays of 0.5% $MnSO_4$ solution are not sufficient to completely correct the Mn-deficiency in wheat. Four sprays of 0.5% $MnSO_4$ solution (7.5 kg $MnSO_4$ ha^{-1}) produced the largest grain yield response of 2.5 t ha^{-1} followed by that of 1.5 to 2.2 t ha^{-1} by 3 sprays of 1.0% solution (15 kg $MnSO_4$ ha^{-1}). Hence four sprays of 0.5% $MnSO_4$ solution, one before and three after the first irrigation at 7-10 days' interval, help to effectively correct the Mn deficiency. Alternatively, 3 sprays of 1% $MnSO_4$ solution are almost equally effective; the choice, however, depends upon the cost and availability of labour resources with the farmers.

Soaking of potato tubers in 0.05% $MnSO_4$ solution for three hours proved 2.7 times more effective than soil application of 20 kg $MnSO_4$ ha^{-1} and 11% more effective than 2 foliar sprays of 0.2% $MnSO_4$ solution in increasing the tuber yield (Sharma and Grewal, 1988).

Table 7. Yield and Mn content in wheat as influenced by the method of $MnSO_4$ application (Takkar et al., 1986b)

Treatments	No. of sprays	Yield (t ha^{-1})		Mn concentration {mg kg^{-1})	
		Grain	Straw	Grain	Straw
Foliar spray (% $MnSO_4$ solution)					
0.5	2	3.23	4.89	18.9	13.2
0.5	3	3.78	5.83	20.0	15.9
1.0	1	2.95	5.22	18.9	14.5
1.0	2	3.67	5.89	21.6	15.1
2.0	1	3.00	5.19	19.5	16.3
2.0	2	3.45	5.55	20.0	17.4
Soil (kg Mn ha^{-1})					
5		2.17	3.78	18.9	12.9
10		2.44	3.79	20.0	14.2
20		2.50	4.44	19.5	14.2
Control		1.31	2.85	13.5	11.4
CD (P = 0.05)		0.75	0.45	1.9	1.7

Table 8. Grain yield of wheat as influenced by the time and method of manganese application (Takkar et al., 1989; Nayyar et al., 1990)

Treatments	No. of sprays		Grain yield (t ha^{-1})			
Foliar application			Experiment no.			
	Before 1st irrigation	After 1st irrigation	I	II	III	IV
0 5% $MnSO_4$ H_2O	1	2	4.6	4.8	4.7	—
"	0	3	4.3	4.4	4.0	—
"	1	3	5.2	—	—	—
"	0	4	—	4.2	—	—
1.0% $MnS0_4.H_2O$	1	2	4.9	5.1	4.9	5.1
"	0	3	4.5	4.5	4.2	4.7
"	1	3	—	—	—	5.2
"	0	4	—	—	—	4.8
Soil application - 50 kg Mn ha^{-1}			4.7	4.3	—	4.8
Control			2.7	3.0	2.7	3.4
CD (P = 0.05)			0.3	0.3	0.3	0.3

Manganese-efficient Cultivars

Manganese-efficient wheat cultivars were found to have higher harvest index as well as grain yield than the Mn-inefficient cultivars (Jhanzi et al., 2013). The magnitude of response of 53 cultivars to Mn application on coarse-textured Mn-deficient field decreased successively as the rating of the tolerance increased and there were no significant responses in the most tolerant categories (Takkar, 1993). Recently, genetically and/ or agronomically Mn-efficient cultivars of wheat and rice have been identified (Shukla, 2014). Among the crops, Indian mustard is more Mn-efficient than wheat on Mn-deficient soils (Sadana et al., 2003).

Boron

Status and Extent of Boron Deficiency

Total and available B content in Indian soils ranges from 2.6 to 630 mg kg^{-1} and trace to 3.0 mg kg^{-1}, respectively (Takkar, 2011). Analysis of available B in few states revealed that 31% soil samples of Haryana and 22-24% of Uttar Pradesh and Madhya Pradesh were deficient in B (Takkar et al., 1997). However, recent analysis of 88030 soil samples from 18 states shows that B deficiency was much higher 46.9-56.0 % in the states of Jharkhand, Maharashtra, Orissa and West Bengal, moderate 20 – 36 % in Bihar, Himachal Pradesh, Kerala and Tamil Nadu; and less than 20 % in other states. Out of 193 districts, 84 indicated less than 10% B deficiency (Singh et al., 2006; Shukla and Behra, 2011).

However, B deficiency in some regions is becoming a serious constraint, next to Zn deficiency. In general, B deficiency was higher in eastern region and has arisen from its excess leaching in sandy loam soils, alluvial and loess deposits. By and large, B-deficiency is more critical to sustainable productivity in highly calcareous soils, sandy, leached soils, acid apple orchard soils, limed acid soils or reclaimed lateritic soils (Sharma and Bhandari, 1995; Sakal and Singh, 1995; Takkar, 1996; Takkar and Jalali, 2005; Takkar 2011; Takkar and Shukla, 2015)

Sources of Boron and their Relative Efficacy

Soil application of borax or sodium tetra-borate ($Na_2B_4O7.10H_2O$, fertilizer grade, 10.5% B), granubor (15% B) is commonly used to correct its deficiency. Deficiency of B is invariably corrected by its soil application. Both granubor and borax proved equally effective in mitigating B deficiency. However, sources of B are available in various categories or forms like straight micronutrient, fortified, multi-micronutrient mixtures, customized and water soluble mixture of fertilizers. There has been rapid growth in B fortified fertilizers during last 10 years and these include boronated NPK complex; boronated DAP; NPK 14:35:14 fortified with Zn and B; SSP fortified with Zn and B and boronated sulphur. All these fortified fertilizers contain 0.2-0.3% B except boronated sulphur which has 1.2% B. About 84 state-specific multi-micronutrient mixture formulations notified by State Governments contain 0.05 to 5.0% B. Out of the total 26 approved grades of customized fertilizers (CF) for basal application, 11 grades contained B and its content varied between 0.05% and 0.3% (Tewatia et al., 2018a). Recently data on B-containing CFs has been reported for apple in J&K and Himachal Pradesh (Bhadraray et al., 2017) and elephant foot yam (EFY) in Kerala have been published (Anju et al., 2018). Government has allowed the fortification of fertilizers specified in the FCO and manufacturers are allowed to recover additional cost in fortification by charging

10% over MRP on B-fortified fertilizers. A variety of B containing fertilizers have been evaluated for their efficiency and effectiveness under field and horticultural crops. On an acidic B-deficient soil of Ranchi, borax and boric acid were found to be equally effective (Tewatia et al., 2018b)

Crop Responses to Boron Application

In B-deficient soils of Bihar, Odisha, West Bengal, Assam and Punjab, soil application of 0.5 to 2.5 kg B ha^{-1} to cereals, pulses, oilseeds and cash crops gave a response of 108 to 684 kg grain kg^{-1} of B and helped in sustaining their high productivity (Sakal et al., 1996, 2002; Takkar, 1996). The on-farm trials conducted in states of eastern India indicated that rainy season rice, wheat and mustard responded positively (response >200 kg ha^{-1}) to applied B in 69, 70, 79 and 71% of the experiments. Calcareous soils of North Bihar and acid red soils of Bihar plateau, now Jharkhand, showed spectacular responses to B application (Sakal et al., 1996).

Methods and Rates of Boron Application

Application of 0.75–1.25 kg B ha^{-1} to soil markedly increased the grain yield of pigeonpea and cauliflower curd (Singh, 2008). While groundnut grown in the coarse textured alkaline soils of Punjab yielded maximum with 0.5 kg B ha^{-1} (Arora et al., 1985), in the calcareous soils of Bihar, this dose was 2 kg ha^{-1} (Sakal and Singh, 1995). Similarly, the optimum rate of B was 1.0 kg ha^{-1} for wheat grain yield both in the calcareous soils of Bihar (Sakal et al., 1996) and in the acid soils of West Bengal (Ali and Monoranjan, 1989). In studies on the calcareous soils of Bihar (Sakal and Singh, 1995; Sakal et al.; 1988), optimum rate varied between 2 and 2.5 kg B ha^{-1} for different crops.

Rate of B application varied with crop, season and type of soil. In the B-deficient sandy loam calcareous soils of Bihar, it was 2.08 kg B ha^{-1} for chickpea and 1.68 kg B ha^{-1} for winter maize. For summer crops namely groundnut, maize, bean, onion, yam, and black gram it was higher 2.0-2.5 kg B ha^{-1} as compared to 1.5 kg B ha^{-1} for winter crops *viz*., mustard, maize, sunflower, onion and lentil (Sakal and Singh 1995, Takkar, 1996). By and large, soil application of B is a better method of its management than the foliar and seed soaking. Foliar application of B has, however, been observed to be useful in fruit trees. For instance, Rajput et al. (1976) reported the optimum improvement in growth, flowering, fruiting and fruit quality of mango with the spray of 0.8% boric acid solution. Response to boron application is quite high in horticultural corps. Under a large number of demonstrations conducted at farmers' fields and at the IIHR campus, increase in yield varied from 39% in cucumber to as high as 84 % in ash gourd (Tewatia et al., 2018a).

Management of Boron in Cropping Systems

In B-deficient coarse textured soils of Tamil Nadu, initial application of 2 kg B ha^{-1} followed by application of 0.5 kg B ha^{-1} to alternate crops of groundnut-maize cropping system sustained highest system's productivity and total B uptake (Singh, 2007; Tewatia et al., 2018a). On calcareous soils of Pusa, Bihar, application of 16 kg borax ha^{-1} to alternate crop in rice-wheat and maize-mustard cropping systems maximized the system productivity (**Table 9**). Dwivedi et al. (1990) showed that both the soil

Table 9. Effect of rate and frequency of B application on cumulative grain yield response (t ha^{-1}) and total B uptake (g ha^{-1}) in calcareous soils (Sakal et al., 2002)

Treatment (kg borax ha^{-1})	Rice-Wheat		Maize-Mustard	
	Grain yield (t ha^{-1})	B uptake (g ha^{-1})	Grain yield (t ha^{-1})	B uptake (g ha^{-1})
8 kg to 1st crop only	2.34	261	0.82	127
8 kg to alternate crop	5.26	722	2.24	466
8 kg to each crop	**6.80**	**1311**	**3.85**	**954**
16 kg to 1st crop only	4.19	584	1.44	391
16 kg at two crops interval	6.85	1288	3.61	973
16 kg to alternate crop	**9.28**	**1696**	**4.61**	**1099**
16 kg to each crop	5.45	2622	3.49	2063
32 kg to 1st crop only	3.95	925	2.21	880
16 kg at two crops interval	6.82	2709	3.60	1657
0.25% boric acid solution spray thrice to each crop	2.81	891	2.03	694

application of B @ 20 kg sodium tetraborate ha^{-1} and two foliar sprays with 0.2% solution of this salt proved equally effective in increasing soybean grain yield and the residual effect of soil applied B on wheat was significantly more than that of the foliage sprays. In calcareous soil, residual effect of 1.76 kg B ha^{-1} applied to every third crop in a sesame-chickpea cropping system sustained the best yields (Sakal et al., 1996). Application of 1.0 kg B ha^{-1} to each rice crop or 0.5 kg B ha^{-1} to both rice and wheat for five years met the B requirement of hybrid rice-wheat cropping system in Mollisols of Pantnagar (Shukla and Behera, 2012). In view of very sharp and narrow difference between optimum and the toxic levels of B, great precaution is required in its repeat application, particularly in medium to heavy textured soils.

Copper

Total Cu content in Indian soils ranged from 1.80 to 960 mg kg^{-1} and available Cu varied from 0.02 to 379 mg kg^{-1}. Very few 1-13 % soil samples were found to be deficient in Cu with the exception of 35.5% in Rajasthan. In general, crop responses to Cu application ranged from traces to 1.78 t ha^{-1} of cereals, 0.20 to 0.30 t ha^{-1} of millets, trace to 0.80 t ha^{-1} of oilseeds, 4.43 to 6.18 t ha^{-1} of onion and 0.30 to 0.50 t ha^{-1} of sugarcane (Takkar et al., 1997). Both soil and foliar application of Cu to soybean-wheat cropping system proved equally effective in correcting its deficiency in Typic Ustipsamments of Ludhiana. Soil application of 5.0 kg Cu ha^{-1} to the first crop gave significant response of 0.2 t ha^{-1}. Foliar spray of 0.2% $CuSO_4$ solution increased soybean grain yield from 2.18 to 2.35 t ha^{-1} (Lal, et al.,1971; Dwivedi et al.,1990). Although soil test revealed higher Cu deficiency in some areas/ districts, but no matching response of crops to Cu application could be observed. It implies that there is a need to develop reliable soil test methods for Cu to establish its deficiency/adequacy in different soil-crop conditions (Takkar and Shukla, 2015)

Molybdenum

Since the availability of Mo increases with a rise in pH, its deficiency is invariably a problem on acid soils. Among crops, however, legumes are known to be benefited more from its application because of their high Mo requirement.

Sources of Molybdenum

Sodium molybdate ($Na_2MoO_4H_2O$: 39% Mo), ammonium molybdate $(NH_4)_6$ $MO_7O_{24}.4H_2O$: 54% Mo) and molybdenum trioxide (MoO_3: 66% Mo) are the most common sources of Mo. Sodium molybdate is more popular and commonly used to correct Mo deficiency.

Status of Molybdenum

Total Mo in Indian soils ranged between 0.1 and 12 mg kg^{-1} and available Mo varied from trace to 2.8 mg kg^{-1}. Molybdenum deficiency is very meagre in Indian soils and is highly localized in some parts of Madhya Pradesh, Maharashtra and acidic soils of Odisha and West Bengal, particularly in the pulse-growing areas. Nevertheless, its deficiency is noticed in some acidic, sandy and leached soils. Deficiency of Mo is also reported in the high-rainfall area of eastern India.

Crop Responses to Molybdenum Application

Response of crops to applied Mo ranged from 0.24 to 1.01 t ha^{-1} for rice, 0 to 0.47 t ha^{-1} for wheat, 0.08 to 0.19 t ha^{-1} for soybean, and 0.10 to 0.40 t ha^{-1} for green gram.

Methods and Rates of Molybdenum Application

Soaking potato tuber in 0.01% ammonium molybdate solution for 24 hours before sowing increased the tuber yield by 1.3 to 2.9 t ha^{-1} in different soils (Grewal and Trehan, 1990). In acid soils of Himachal Pradesh, seed treatment of soybean with Mo proved to be more promising than its soil application in increasing its grain yield (Sharma and Minhas, 1986). Soil application of 1.0 kg sodium molybdate ha^{-1} was inferior to its 0.1% foliar spray solution in correcting Mo deficiency in black gram and green gram. In West Bengal, Samui and Bhattacharya (1980) reported that the soil applied sodium molybdate @ 2 kg ha^{-1} was significantly superior to the same amount applied through 3-foliar sprays in increasing the sunflower oil yield. Liming acid soils helps in better utilization of soil applied Mo. Grain yield of soybean with 2 kg sodium molybdate ha^{-1} far-exceeded when Mo was applied to a limed than that to an un-limed acid soil receiving the same rate of Mo (Dwivedi et al., 1990)

Multi-micronutrient Deficiencies

Singh (1992, 2008) reported multiple micronutrient deficiencies, but of very small magnitude. During 2009-14 deficiencies common for Zn+Fe (6.3%), Zn+Cu (4%), Zn+Mn (3%) and Zn+B (8.6%) were observed. Among these, simultaneous deficiency of Zn+B was highest and occurred mostly in acid leached Alfisols, and red and lateritic soils. Also, the deficiency of Zn+B was much higher in Maharashtra (30.5%), Bihar (16.5%), Tamil Nadu (13.5%), Odisha (12.2%) and Jharkhand (11.7%) states. Deficiency of Zn+Fe was less than 10% except in Maharashtra (12.3%). Deficiency of Zn+Mn was widespread in coarse textured soils of Punjab under rice-wheat rotation. On the whole, simultaneous deficiency for three nutrients namely, Zn+Fe+Mn; Zn+Cu+Mn and Zn+Fe+B is less than 2% (Shukla et al., 2014).

As a corollary, deficiency of single micronutrients is most predominant as compared to the combined deficiency of two or three micronutrients. The results of field experiments reported in the above sections clearly demonstrate that multi-micronutrient mixtures are either inferior or in some cases equally efficient only when their applications are made on equivalent rates basis *vis-a-vis* the standard sources. In view of this, use of multi-micronutrient mixtures should be made only on the basis of their established deficiency based on the soil test of individual fields otherwise their general broad regional or area wise use or recommendation would be uneconomical and a wasteful expenditure to the farmers and the nation.

Epilogue

Widespread micronutrient deficiencies have emerged and are increasing alarmingly in Indian soils and crops after mid-sixties as a consequence of depleting their resource in soil with the change of environment towards intensive cropping with "Green Revolution" high yielding varieties of wheat, rice etc., use of high analysis NPK fertilizers, and little use of organic manures. Their deficiency status is changing due intensification of agriculture and adoption of developed management practices to correct these for getting sustainable high productivity and stability. For example, deficiency of Zn decreased from 48 and 59.5% during 1967-2011 to 36 and 18.5% during 2009-2015 in Punjab and northern zone, respectively due to regular use of $ZnSO_4$ fertilizer in these areas but it increased in southern region from 43 to 53% probably due to intensive cropping with NPK only. The severity of Zn-deficiency has increased from normal soil to alkaline, moderately alkali and highly alkali/sodic soils largely due to increase in soil pH (as one unit increase in pH causes 100-fold decrease in Zn activity in soil solution) and decrease in SOC content. Consequently, the rates of Zn application to these soils have increased from 5.5 to 11 and 22 kg ha^{-1} respectively to get sustainable high production and productivity of RWCS; and are also the cause for shortening the period of residual effect of Zn. It is not possible to correct the deficiency of Zn in the highly alkali soil unless the deficiency of Ca (being most limiting nutrient after NPK) and/or toxicity of Na is simultaneously corrected with the addition gypsum or other suitable amendment. By and large, soil application of Zn, B, and Cu is more effective method to correct their deficiency than their foliar application because of their immediate supply from the soil to the plant right from the germinating stage as compared to their delayed supply through foliar feeding on moderate to highly deficient soils. But soil application of Fe is ineffective method than the foliar feeding of crops because these elements get readily oxidized at a faster rate under aerobic soil conditions from soluble ferrous Fe^{2+} iron forms (ferrous sulphate) to insoluble ferric F^{3+} iron forms, and thus less available to plants than their direct feeding 3-4 times through the foliage. But foliar applications have to be repeated as these leave no residual availability. As the acidity of their spray solution is generally neutralize with lime addition it also result in their oxidation, therefore the un-neutralized solutions are more effective to mitigate their deficiency. Soluble sources of micronutrients proved more effective than sparingly soluble sources because of their immediate supply to plants in adequate amounts as per the requirement of crops than from the sparingly soluble sources like ZnO, MnO, $Fe_2(SO_4)_3$ etc. Poor or equal performance of multi-micronutrient mixtures than their direct source of micronutrients, when applied in equivalent amount of the individual deficient micronutrient (e.g., Zn), resulted from the existence of the deficiency of only that micronutrient (Zn) and inadvertent application of other micronutrients from the mixture play no role other than to increase their cost to the farmers. The equal performance of 1.5-2.0 % $ZnSO_4$ or ZnO coated urea as that of 5.5 kg Zn ha^{-1} from $ZnSO_4$ may be good source to apply both Zn and N in one go for mild to moderately Zn-deficient soils for rice or wheat crop as it saves on labour cost to make separate application of $ZnSO_4$ and of urea while ensuring their uniform application than that of a physical mixture of these sources. Nevertheless, it has many drawbacks: (1) the residual effects of 5.5 kg Zn ha^{-1} generally last for 2-3 crops in RWCS on mild to moderate Zn-deficient soils so its repeat application to wheat after rice is a wasteful expenditure to the farmers and to the nation, (2) the rates of Zn application are 11 to 22 kg ha^{-1} for RWCS on moderately and highly alkali soils so it will not be suitable for these soil-cropping systems, (3) as it may find inadvertently its application to soils not deficient in Zn, because all the farmers are not so well educated to distinguish between the normal urea and the zincated urea sources, so it will be a wasteful expenditure and (4) it may be a mismatch for many crops that have low requirement for N but cultivated on Zn-deficient soils, so a mismatch with the Zn requirement of such soil-crop conditions. Similarly for multi-micronutrient deficient areas, especially in two elements, Zn+Mn in coarse textured soil under RWCS in Punjab, Zn has to be supplied through the soil to rice crop and Mn to wheat through the foliage, so a multi-micronutrient product of these two elements will not work for such soil-cropping systems. But for Zn+B deficient area both the elements can be supplied through soil therefore specific customized/tailor-made multi-micronutrient product matching the specific requirements of the soil-cropping system has to be developed/manufactured and its superiority over their separate application needs to be demonstrated through meticulous field experiments right on such deficient soils for major soil-cropping systems, that are lacking in both. Application of different organic manures at right rates corrected fully or partially the micronutrient deficiency because of their supply from the manure itself as well as mobilization of native soil micronutrient resource by chelating agents or organic acids liberated during the processes of mineralization of manures. Chelates form stable complexes with micronutrients that act as a courier or conduits to supply micronutrients to the plant roots in available forms without these being subjected to fixation and transformation reactions to unavailable forms. The integrated use of organic manures and inorganic micronutrient fertilizers, in different permutation and combinations depending upon the availability organic manure resources with the farmers, helped in correcting the deficiency and saving on micronutrient fertilizer by 25 to 100% under various soil-cropping conditions. Puddling of sandy soil for rice cultivation helps in ponding of water and consequently creating reduced soil conditions that help in mobilizing unavailable Fe^{3+} iron to available Fe^{2+} iron forms and thereby help in correcting the Fe-deficiency generally encountered on such sandy soils. Micronutrient-efficient genotypes of important crops tolerant to specific micronutrient deficiency and high efficiency of their utilization have been identified and their adoption will help to minimize soil depletion and the use of micronutrient fertilizers. But so far we are not very successful in breeding such micronutrient-efficient cultivars.

Future Projections

1. The deficiency status of micronutrients in Indian soils though has been based on well representative soil samples, yet their numbers are very meagre, particularly of GPS referred samples, to really represent the vast agricultural area of the country. There is a need to further collect large number of soil samples with GPS reference representing major soil-cropping systems of the agro-ecological zones for mapping micronutrient deficiencies. The soil health card (SHC) data pertaining to the micronutrient status may be used if it is GPS-based, if not then efforts may be made to get it included in the SHC in a mission mode. Alternatively, the collection of GPS-referred soil samples may be made as a farmers-public-participatory programme (FPPP) wherein mobile phones can be used for this purpose.

2. The existing soil testing laboratories should be strengthened with modern equipment, technical and soil scientists for precise and quality analysis of micronutrients for large number of soil samples. For quality control of soil testing service a regulatory authority may be created.

3. Predictability of the current critical values of micronutrients range between 60-80% with the exception of few soil-cropping systems. Therefore, these need to be redone to forecast 90-95% predictability of deficiency for the specific soil-cropping systems.

4. Evaluation of right sources of micronutrients, including multi-micronutrients, customized micronutrients etc., their right rates, mode, time and frequency of application to combat micronutrient deficiency in representing major soil cropping practices needs to be examined in the light of modern developments in agricultural systems: practices, management, emerging micronutrient deficiencies in some regions and decline in the others, imbalanced use of nutrients, use and recycling of organic waste etc. This will help in developing strategies / technologies to take timely measures to tackle the emerging from them to sustainable high food gain production and nutritional security.

5. As very meagre researches have been carried out on multi-micronutrients and customized fertilizers right in problem areas/soils, there is an urgent need to take up meticulous studies on these aspects, with all pros and cons, right in the farmers' fields/soils having established deficiencies of multi-micronutrients.

6. Researches on integrated management of all kinds of organic wastes, available on farm in different amounts with the farmers, as a potential source of micronutrient supply with inorganic micronutrient sources need to be taken up for their supply and enhancing the use efficiency of micronutrients as well as for sustaining higher crop production and productivity.

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Global Micronutrient Summit
5-6 September, 2019, New Delhi

The Fertiliser Association of India (FAI) and International Zinc Association (IZA) jointly organised two-days Global Micronutrient Summit during 5-6 September 2019 at The Hotel Leela Palace, Chanakyapuri, New Delhi. It was inaugurated by Shri Narendra Singh Tomar, Hon'ble Union Minister of Agriculture and Farmers Welfare, Government of India. Dr. Ashok Dalwai, Chief Executive Officer, National Rainfed Area Authority, Ministry of Agriculture & Farmers Welfare was the Guest of Honour at inaugural function. Over 175 delegates including scientists, policy makers, government officials and industry experts from India and abroad attended the programme. Message of Prof. M.S. Swaminathan to the Summit was played during the inaugural session.

Hon'ble Minister for Agriculture and Farmers Welfare, Shri Narendra Singh Tomar lighting the lamp at the inaugural function

Inaugural ceremony started with introductory remarks by Dr. Andrew Green, Executive Director, International Zinc Association (IZA), USA. Dr. Green stated that there has been recognition around the world about the need to focus not only on macro nutrients but micronutrients also. He added that although the mandate of IZA was to promote zinc, conscious decision was taken to broaden the focus to cover all the micro-nutrients for arriving at the balanced use of nutrients, maximization of income and productivity of crops, and ensuring food and nutritional security. Dr. Green acknowledged and complimented the ICAR for developing valuable information on micronutrient deficiencies in the Indian soils. He said that deficiencies of zinc and boron have been identified as the most critical ones which not only affect crop production but also human health. He stressed on the need to improve farmers' awareness on the role and importance of micronutrients and suggested that the government, researchers and fertilizer industry should make joint efforts/campaigns. He also underlined on the need of rationalization of GST rates for micronutrients on the pattern of major nutrients, correction in zincated urea pricing, and addressing the nutrient based subsidy (NBS)- related issues to promote the use of micronutrients.

Shri Satish Chander, Director General, Fertiliser Association of India (FAI) made a formal welcome to the Chief Guest, Guest of Honour, special dignitaries, delegates and invitees to the Summit. Shri Chander stated that the micronutrients play an important role in sustenance of crop production. Quoting from the FAO study, he said that the problems of micronutrient deficiencies in soils and crops have been on the rise and the deficiencies of zinc and boron are suspected in almost every country. He pointed out that micronutrient deficiencies in soil are intricately linked to their deficiencies in animals and human beings. For example, nearly 25% of population in India suffers from zinc deficiency and more than 80% of pregnant women suffer from iron deficiency.

Shri Chander informed the audience that abysmally low use efficiency of micronutrients continues to be a cause of concern and enhancing it should be the top priority area of research. Uniform application of micronutrient fertilizers in field is a major problem as these are applied in small quantities. He mentioned that the Government has been aware of the importance of micronutrients in balanced fertilization and has taken number of initiatives to promote the use of micronutrients. These include a provision of subsidy of Rs. 500/- per hectare for application of micronutrient fertilizers under National Food Security Mission (NFSM) and subsidy of Rs. 500 and Rs. 300 per tonne for production of fertilizers fortified with zinc and boron, respectively, under the nutrient based subsidy (NBS) scheme.

Shri Chander stated that the rate of customs duty and GST on micronutrients is higher *vis-à-vis* conventional fertilizers. For instance, micronutrient

Release of Knowledge Book at the inaugural function. Seen in the picture (L-R) are Dr. Andrew Green, Shri Satish Chander, Shri Narendra Singh Tomar (Chief Guest) and Dr. Ashok Dalwai

fertilizers attract 12% GST against 5% for the conventional fertilizers. He stressed that all the fertilizers listed in Fertiliser (Control) Order 1985 should be treated at par in terms of customs duty and GST. DG informed the delegates that the FAI has been requesting the Government of India to provide subsidy directly to the farmers as it will give choice to farmers to use most efficient fertilizer products including micronutrients; it will encourage the micronutrient manufacturers to develop innovative products.

Briefing about the FAI initiatives to highlight the importance of micronutrients in Indian agriculture, Shri Chander informed the audience that some of the international agencies particularly, IZA, IFA and Rio Tinto have joined hands in addressing the problems of micronutrients. The Global Micronutrient Summit is also an effort in this direction. He hoped that the programme would provide good opportunity to share latest developments in micronutrient research and discuss strategies to promote the use of micronutrients.

In his inaugural address, Shri Narendra Singh Tomar, Hon'ble Minister of Agriculture and Farmers Welfare stated that agriculture occupies a special place for sustenance of life on earth as it is the single most important employer and constitutes the backbone of rural economy. He was emphatic in his pronouncement that the progress in agriculture acts as a catalyst in taking the nation forward. Shri Tomar complimented the successive governments for taking necessary steps in making the country agriculturally strong and stated that it is only the result of their sustained efforts that the country could become self-sufficient in food grains production. He added a word of caution that while self-sufficiency in food production provided us a reason to rejoice, it gave rise to another set of problems like soil health degradation, expanding multinutrient deficiencies, stagnation in crop productivity, and reduction in farmers' income. He said that our primary aims namely, i) production and productivity of farm and farmers' income should witness quantum jump, ii) latest improved technologies should be used, iii) production-oriented agricultural research should get priority, and iv) nutrient balances should be sustained should not be compromised while working out sustainable solutions to these problems.

Hon'ble Agriculture Minister informed the audience that Government of India under the leadership of Honourable Prime Minister, Shri Narendra Modi ji, has been consistently making sustained efforts in this direction. The recommendation of Committee headed by Dr. M.S. Swaminathan for providing minimum support price (MSP) of 150% of the production cost has been accepted and implemented to make farming a profitable proposition. He said that for enhancing the farmers' income, the PM Kisan Samman Nidhi Yojana has been started under which each farmer gets Rs.6000 annually and efforts are being made to provide social security to the farmers under PM Farmers Pension Yojana.

Hon'ble Minister shared with audience that 12 crore farmers have been reached through the Soil Health Card scheme so far. But it has remained only one-way effort so far. He stated that Government is making concerted efforts in making farmers realize the benefits accruing from organic farming as there is niche market for organic products globally and efforts should be made to grab this opportunity as it has potential to bring prosperity in the farm sector. Efforts are being made to educate the farmers on saving water so that he gets more crop per drop of water. Awareness schemes are being implemented across the length and breadth of the country to educate the farmers on the right and balanced use of fertilizers. He said that the Governments, central and states, are working tirelessly and called upon the FAI and associated companies to join this mission.

Hon'ble Minister expressed that discussions in the Conference would greatly help in making farming more sustainable. He assured the delegates that the outcomes/recommendations emanating from the summit would receive adequate support from Government of India.

Publication entitled, "Knowledge Book on Micronutrients" was released by the Chief Guest on the occasion.

Dr. J.C. Katyal, Chairman and Panelists at the Panel discussion

Shri Vikram Merchant, Country Head, Rio Tinto India, Gurgaon proposed a vote of thanks at the end of inaugural session.

Transactions of the Global Micronutrient Summit were spread over five technical sessions. **Technical Session - I** was chaired by Dr. Ashok Dalwai, CEO, National Rainfed Area Authority, Ministry of Agriculture & Farmers Welfare, Government of India. Three papers presented in the session included: i) Zinc in Food and Nutrition Security by Dr. Andrew Green, Executive Director, IZA, USA; ii) Boron in Crop Yield and Quality by Dr. Cleiton de Sequeira, Global Market Development Manager – Agriculture Rio Tinto, Borates, USA; and iii) Micronutrients in Human Health by Dr. Aakriti Gupta, All India Institute of Medical Sciences, New Delhi.

Technical Session - II was chaired by Dr. S.K. Malhotra, Agriculture Commissioner, Ministry of Agriculture & Farmers Welfare, Government of India. Three papers presented in the session included: i) Micronutrients in Soils and Crops by Dr. A.K. Shukla, Project Coordinator (Micronutrient), ICAR-IISS, Bhopal; ii) Agronomic Biofortification for Combating Micronutrient Malnutrition by Dr. Y.S. Shivay, Principal Scientist, Division of Agronomy, ICAR-IARI, New Delhi; and iii) Industry Initiatives on Micronutrient Fertilizers by Mr. Madhab Adhikari, Associate Vice President – Sales & Mktg. (SND), Coromandel International Ltd., Secunderabad.

Technical session – III comprising of a Panel Discussion on "Policy Initiatives in Value Addition of Bulk Fertilizers with Micronutrients – Prospects & Challenges" was chaired by Dr. J.C. Katyal, Former Vice Chancellor, CCS HAU, Hisar. Brief presentations were made by the seven panelists namely, i) Dr. S.K. Malhotra, Agriculture Commissioner, Ministry of Agriculture & Farmers Welfare; ii) Dr. B.S. Dwivedi, Head, Division of Soil Science and Agricultural Chemistry, ICAR-IARI, New Delhi; iii) Dr. A.K. Shukla, Project Coordinator (Micro), ICAR-IISS, Bhopal; iv) Dr. P.P. Biswas, Sr. Consultant (NRM Division), ICAR, New Delhi; v) Dr. Amit Rastogi, Sr. Vice President (Tech), Coromandel International Secunderabad, Telangana; vi) Mr. Naresh Deshmukh, Executive Vice President, Smartchem, Pune; and vii) Dr. Tarunendu Singh, Manager & Head (AS), IFFCO, New Delhi.

Technical Session - IV was chaired by Dr. P.N. Takkar, INSA Emeritus Scientist and Ex-Director ICAR-IISS, Bhopal. Three papers presented in the session included: i) Innovative Technology in Fortified / Customized Fertilizers by Mr. B.B. Singh, Vice President - SCM & Corporate Affairs, IRC Agrochemicals, Kolkata; ii) New and Innovative Product and Technology in Micronutrient Fertilizers by Mr. Dale Edgington, Purchasing & Production Manager, Advanced Micronutrient Products, Michigan, USA; and iii) IZA-BARI Zinc Fertilizer Project – Highlights by Dr. Sohela Akhter, CSO & Head, Soil Science Division BARI, Ministry of Agriculture, Government of the People's Republic of Bangladesh.

Technical Session – V comprising of a Panel Discussion on 'Innovations in Agriculture by Start-Ups and How Micronutrients will Impact the Future' was chaired by Dr. Rahul Mirchandani, CMD, Aries Agro Ltd., Mumbai. Brief presentations were made by the four panelists namely, i) Mr. V.R. Rajesh, Head Sales, North India, Cropin; ii) Mr. R.S. Rajan, Managing Director, Privi Life Sciences; iii) Dr. Namita Singh, Lead

Shri Kailash Chaudhary, Hon'ble Minister of State for Agriculture and Farmers Welfare delivering the valedictory address

Asia Programme, Digital Green, New Delhi; and iv) Mr. Mahesh G. Shetty, President, Indian Micro Fertilizers Manufacturers Association, Pune. An interactive discussion was held after the brief presentations.

At the Concluding Session, Shri Kailash Chaudhary, Minister of State for Agriculture and Farmers Welfare was the Chief Guest. Shri Satish Chander, DG, FAI welcomed the Chief Guest. With a formal welcome, DG gave the gave the brief resume of the deliberations transacted during the 2-days Global Micronutrient Summit. DG stated that the conference was inaugurated by Hon'ble Minister of Agriculture & Farmers Welfare, Shri Narendra Singh Tomarji. DG said that in his inaugural address, Shri Tomar ji had dwelt at length on the policies and initiatives of the government for well-being of Indian farmers.

Giving a brief of the deliberations, Shri Chander mentioned that different speakers highlighted the usefulness of soil health card scheme as the soil testing is the first step for generation of database on 12 chemical parameters including micronutrients and subsequent recommendations for farm-specific balanced plant nutrition. However, the speakers were little sceptical of the quality data, particularly of micronutrients coming out of the soil testing laboratories. Abysmally low use efficiency of micronutrients (only 2 to 5%) continued to be a cause of concern and need for more intensive work for improving micronutrient use efficiency was reiterated. Farmers' awareness about the 4Rs stewardship still continues to be poor and a lot of extension efforts involving all the stakeholders are needed for disseminating the right information to farmers.

Shri Chander stated that the presenters also highlighted that the rate of GST on micronutrients is 12% whereas it is 5% on major fertilizers. The delay in product approval under FCO is an area of concern. Audience was informed that the FAI has been requesting the Ministry to switch over to the label-based regime.

Shri Chander said that important point was made on pricing policy of zincated urea. DG informed that the MRP of zincated urea is fixed by the government but the cost which has been allowed for coating urea with zinc does not meet even 25% of total cost. Need for bringing out a policy paper on micronutrients was also emphasized.

In his valedictory address, Shri Kailash Chaudhary, Minister of State for Agriculture and Farmers Welfare congratulated the organizers for deliberating on the very important issue of micronutrients which has attracted the attention of the whole world. Intense interactions held in last 2-days programme involving all stakeholders speak of seriousness accorded to the vital issue.

Shri Chaudhary stated that India is an agriculture-dominated country and everyone is concerned about what can be done to make farmers future secure. Biggest problem faced by the farmers is they have little or scant information regarding the right source, right rate, right time and method of fertilizer application. Consequently, farmers either make over-use or underuse or imbalanced use of fertilizer. Under such a situation, not only crop production/ productivity suffers but lead to undesirable side-effects like poor crop quality and deterioration of soil, water and environmental quality.

Shri Chaudhary stated that 70% of the population depended on agriculture at the time of independence. Concerned efforts were made and continue to be made to increase the food production to meet food demands of burgeoning population. All five year plans gave stress on increasing the food production but did not visualize or forecast the likely effects on soil health. At that time, it was not realized that zinc was going to be deficient in soils and the grains produced on zinc-deficient soils would produce the low Zn grains which when included in staple food would cause zinc deficiency in the human beings. He mentioned that more than 30% of the Indian soils are deficient in zinc and if zinc is not added as a nutrient in zinc deficient soils, its consequences would be faced by the humans feeding on low-zinc diets. He hoped that all aspects of micronutrient nutrition must have been deliberated in the programme in a holistic manner.

Shri Chaudhary ji informed the audience that the Union Government is trying to address the core issues of soil health degradation, food and nutritional security, lowering farmers' income. A sum of Rs. 80,000 crores is shelled out annually as fertilizer subsidy so that the farmers get fertilizers at affordable prices. Hon'ble Prime Minister, Shri Narendra Modi ji has set a target of doubling farmers' income by 2022; besides doubling the income, their life quality has also to be improved. He stated that the Union Government is promoting zero budget farming to achieve the twin objective of sustaining soil health and improving farmers' income. Shri Chaudhary stated that while during the last 70 years, focus was only on enhancing food production, scant attention was paid to maintenance of soil health. Farmers in states like Punjab and Haryana make excessive use of urea of which only 30% is used by the crops and rest leaks to either groundwater or is lost to atmosphere causing degradation of environment.

Shri Chaudhary called upon all the stakeholders to work for doubling the farmers' income and improving the nutritional security. He stated that the Honourable Prime Minister has started the mid-day meal scheme in the Government schools to make available nutritious food to the children and all the citizens have a duty to supplement the initiative being taken by the Government. He reminded the delegates that all of us have a duty to make farmers aware on how they can maximize their production and productivity. Government has been making efforts to develop soil testing laboratories in the Krishi Vigyan Kendras in each district. With the awareness of usefulness on soil testing, farmer will go to the soil testing laboratory to know which nutrients(s) is deficient in his field. He hoped that on the pattern of this programme, more programmes and trainings would be conducted at the state and district levels with the participation of farmers as the key stakeholders and will go a long way in improving awareness on micronutrients in the farming community.

The 2-day summit concluded with a vote of thanks by Dr. Andrew Green, Executive Director, International Zinc Association.

Recommendations

The important recommendations emerged from the programme are:

1. Zinc and boron are deficient in 36 and 23% in Indian soils, as per ICAR report, which is impacting the crop yield and quality adversely. Concerted efforts by all concerned are needed to address the widespread micronutrient deficiencies in Indian soils.

2. Zinc and iron deficiencies in soils are intricately linked directly to their respective deficiencies in humans. Systematic studies need to be conducted to find out the causes and effects of micronutrient deficiencies in soils on plant, animal and human health.

3. Abysmally low use efficiency of micronutrients at 2 to 5% even under the best management practices continues to be a major cause of concern. Enhancing the use efficiencies through location-specific 4R principles and development of novel specialty fertilizers/ products should constitute a priority area of research.

4. Micronutrients are as important as macronutrients in plant nutrition. However, the terminology 'micronutrients' either undermines or does not truly reflect on their importance and need in terms of meeting nutritional requirements of crops. It is high time to deliberate on the issue of whether a better terminology could be evolved.

5. The rate of customs duty and GST on micronutrients is higher *vis-à-vis* conventional fertilizers. All fertilizers listed in Fertilizer (Control) Order 1985 should be treated at par in terms of customs duty and GST.

6. Fertilizer subsidy should be paid directly to the farmers. It would give choice to the farmers to use more efficient fertilizer products including micronutrients.

7. The MRP of zincated urea (2% Zn) is fixed by the government; however, the cost which is included for coating the urea with zinc does not meet even 25% of total cost of coating. Government of India should have a re-look at the zincated urea pricing policy to encourage its production and use by farmers.

8. The procedure of inclusion of new products in FCO has been simplified but still it takes long time. It is high time to switch over to the label-based product.

9. Awareness campaign involving all stakeholders should be launched to convince the farmers on the importance and increasing need of balanced fertilization including micronutrients to improve soil health, crop production and farm income.

10. Policy paper should be brought out on micro-nutrient fortifications and their use in India.■

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FAI Activities

Workshop on Fertilizer Policy for Encouraging INM and for Smooth Implementation DBT

Fertiliser Association of India – Southern Region (FAI-SR) organized a **Workshop on Fertilizer Policy for Encouraging Integrated Nutrient Management (INM) and for Smooth Implementation of Direct Benefit Transfer (DBT)** at Hyderabad on 16th October 2019. Dr. S.R. Voleti, Director, ICAR - Indian Institute of Rice Research, Rajendranagar inaugurated the workshop. Sixty nine participants comprising of scientists from Agricultural University, ICAR research institutes, officials from the state department of agriculture, Government of Telangana and fertilizer industry participated in the workshop.

Dr. G.V. Subba Reddy addressing the participants. Others seen in the picture (L-R) are Mr. Y.V.N. Murthy, Dr. S.R. Voleti, and Dr. G. Suresh

In his inaugural address, Dr. Voleti stated that maintenance of soil fertility and plant nutrient supply at an optimum level for sustaining the desired productivity through optimization of the benefits from all possible sources of organic, inorganic and biological components in an integrated manner is highly essential under current scenario in view of the decline in organic carbon content of the soil and cropping up of multi-nutrient deficiencies in the soil and plant bio-mass. He stressed on the need of promoting the integrated plant nutrient management (IPNM) which aims to optimize the condition of the soil, with regard to its physical, chemical, biological and hydrological properties, for the purpose of enhancing farm productivity, whilst minimizing land degradation.

He informed that there is now greater awareness that IPNM can not only provide tangible benefits in terms of higher yields but simultaneously and almost imperceptibly conserve the soil resource itself. The field level management practices considered under the heading of IPNM would include the use of farmyard manures, natural and mineral fertilizers, soil amendments, crop residues and farm wastes, agro-forestry and tillage practices, green manures, cover crops, legumes, intercropping, crop rotations, fallows, irrigation, drainage, plus a variety of other agronomic, vegetative and structural measures designed to conserve both water and soil. He mentioned that the underlying principles on how best to manage soils, nutrients, water, crops and vegetation to improve and sustain soil fertility and land productivity and their processes are derived from the essential soil functions necessary for plant growth. He congratulated FAI for organizing the workshop at an appropriate time.

In his presidential address, Mr. G.V. Subba Reddy, Vice President (Marketing), Coromandel International Limited, Secunderabad said that loss of soil productivity is much more important than the loss of soil itself, thus land degradation should be prevented before it arises, instead of attempting to cure it afterwards *i.e.* the focus for IPNM should be on sustaining the productive potential of the soil resource. Soil and plant nutrient management cannot be dealt in isolation but should be promoted as an integral part of a productive farming system. Under rainfed dry land farming conditions, soil moisture availability is the primary limiting factor on crop yields, not soil nutrients as such, hence IPNM requires the adoption of improved rainwater management practices (conservation tillage, tied ridging etc.), so as to increase the effectiveness of the seasonal rainfall. With declining soil organic matter levels following cultivation, the adoption of improved organic matter management practices are prerequisite for restoring and maintaining soil productivity (improved soil nutrient levels, soil moisture retention, soil structure and resistance to erosion). He added that once the improvements in the biological, physical, chemical and hydrological properties are made, the farmers will get the full benefits from the supply of additional plant nutrients, in the form of mineral fertilizers. He concluded that organic and mineral fertilizers are complimentary to each other in improving the quality and productivity of the crops.

Earlier Mr. Y.V.N.Murthy, Regional Head, FAI–Southern Region, Chennai welcomed the dignitaries and delegates and explained about the objectives of the workshop. He informed that in spite of having good arable land and water resources, average yields of major crops in India are much lower and in some cases even half compared to those in many developed and developing countries. Application of farm nutrients through mineral fertilizers plays a major role in enhancing crop productivity. But prudent and scientific use of mineral fertilizers is essential to obtain more crop yields per unit of nutrients applied and to maximize economic return to farmers. Successive governments have very consciously ensured that the prices of mineral fertilizers remain affordable to the farmers. This has been made possible through subsidization of the cost of these fertilizers. The subsidy has all along been routed through fertilizer manufacturers and importers and it continues to be same even after forty years of implementation of fertilizer pricing and subsidy policy in mid 1970s.

Gradually, fertilizer pricing policies shifted focus with decontrol of prices of phosphatic and potassic fertilizers in 1992. Since then, any changes in fertilizer policy have encouraged use of nitrogenous fertilizers. Intensive cultivation led to deficiency of secondary nutrient like sulphur and micronutrients such as zinc, boron and iron. Focus on excessive support to nitrogen deprived the soils of proportionate use of other nutrients. This coupled with other farm practices like mono-cropping and lack of use of organic manures resulted in ever-declining crop response to application of nutrients. He concluded that there is an urgent need for reforms in fertilizer policy which can encourage balanced use of all nutrients through IPNM as per the soil test based results. He also suggested implementation of DBT of fertilizer subsidy in true spirit, so that the industry can focus on developing new fertilizer products required for various stages of crop growth and as per the soil fertility status.

The topics covered during the workshop included i) Balanced Use of Nutrients for Food Security – Rice as a Case Study by Dr. S.R. Voleti; ii) Soil Health Management through INM Approach by Mr. G.V. Subba Reddy; iii) Impact of Fertilizer Policy on Soil Health and Balanced Use of Nutrients by Mr. Y.V.N. Murthy ; iv) Fertigation as a Tool in Promoting INM by Dr. A.S. Subba Rao, Deputy General Manager (Agronomy), Netafim India Limited, Hyderabad; v) INM under Rainfed Production Systems by Dr. Gopinath K.A., Principal Scientist, ICAR-Central Research Institute for Dry Land Agriculture (CRIDA), Hyderabad; vi) Enhancing Fertilizer Use Efficiency under Moisture Stress Conditions by Dr. K. Sammi Reddy, Principal Scientist, ICAR-CRIDA, Hyderabad; and vii) Best Management Practices for Enhancing Resource Use Efficiency in Oilseed Crops by Dr. G. Suresh, Principal Scientist, ICAR-Indian Institute of Oilseeds Research, Rajendranagar. Group discussion was organized on Emerging Issues in Implementation of DBT - Government and Industry perspective. At the end of the workshop, Mr. Y.V.N. Murthy thanked all the faculties for making excellent presentations. He also thanked all the member companies for their support in organizing the workshop. ■

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FAI AWARDS 2019

I. FAI GOLDEN JUBILEE AWARDS

1. *BEST PRODUCTION PERFORMANCE AWARDS*

A. Nitrogenous (Ammonia & Urea) Production Performance Fertilizer Plants

Winner

Indian Farmers Fertiliser Cooperative Limited, Aonla-II

Runner-Up

Indian Farmers Fertiliser Cooperative Limited, Aonla-I

B. Phosphoric Acid Plants

Winner

Paradeep Phosphates Limited, Paradeep

C. Complex (P_2O_5) Fertilizer Plants

Winner

Rashtriya Chemicals & Fertilizers Limited, Trombay

D. Single Super Phosphate Plants

Winner

Rama Krishi Rasayan, Pune

(A Division of Rama Phosphates Ltd.)

E. Improvement in Overall Performance of a Company

Joint Winners

National Fertilizers Limited, Bathinda

and

National Fertilizers Limited, Panipat

2. *BEST TECHNICAL INNOVATION AWARD*

Winner

Krishak Bharati Cooperative Ltd., Surat for their innovation "In-house Development of Electronic Governor of Ammonia Refrigeration Compressor Turbine (105-JT)".

Runner-Up

National Fertilizers Limited, Nangal for their innovation "In-house Modification in Nitric Acid Plant at National Fertilizers Limited, Nangal to reduce NOx Emission".

II. AWARD FOR EXCELLENCE IN SAFETY

Joint Winners

Rashtriya Chemicals & Fertilizers Limited, Thal

and

National Fertilizers Limited, Vijaipur

III. ENVIRONMENT PROTECTION AWARDS

A. Nitrogenous Fertilizer Plants (including ammonia, urea and other straight nitrogenous fertilizer units)

Winner

Indian Farmers Fertiliser Cooperative Limited, Aonla

Runner-Up

Indian Farmers Fertiliser Cooperative Limited, Kalol

B. NP/NPK Complex Fertilizer Plants with Captive Acids

Joint Winners

Paradeep Phosphates Limited, Paradeep

and

Indian Farmers Fertiliser Cooperative Limited, Paradeep

C. NP/NPK Complex Fertilizer Plants without Captive Acids

Winner

IRC Agrochemicals Private Limited, Haldia

D. Single Super Phosphate Plants

Joint Winners

Khaitan Chemicals & Fertilizers Limited, Nimrani

and

IRC Agrochemicals Private Limited, Haldia

IV. VIDEO FILM COMPETITION AWARDS

Winner

Krishak Bharati Cooperative Limited, Noida for their film "बून्द बून्द से खुशहाली"

Runner-Up

National Fertilizers Limited, Noida for their film "किसान बेंटोनाइट सल्फर से सफल फसल"

V. AWARD ON PRODUCTION, PROMOTION AND MARKETING OF BIOFERTILIZERS/ORGANIC FERTILIZERS/ CITY COMPOST

Winner

Krishak Bharati Cooperative Ltd., Noida

VI. FAI GOLDEN JUBILEE AWARD FOR INNOVATIVE WORK ON TRANSFER OF IMPROVED FARM TECHNOLOGIES

Winner

Indian Farmers Fertiliser Cooperative Ltd., New Delhi

VII. FAI AWARD ON APPLICATION OF INFORMATION AND COMMUNICATION TECHNOLOGY/DIGITAL TRANSACTIONS IN AGRICULTURE

Winner

Adventz Agri Business, Gurugram

VIII. AWARD ON PROMOTION AND MARKETING OF MICRONUTRIENTS IN INDIA

Winner

Indian Farmers Fertiliser Cooperative Ltd., New Delhi

IX. FAI GOLDEN JUBILEE AWARD FOR EXCELLENCE IN FERTILIZER USE RESEARCH

Winner - Dr. C.M. Parihar, Division of Agronomy, ICAR - IARI, Pusa Campus, New Delhi, Dr. S.L. Jat, Indian Institute of Maize Research, PUSA Campus, New Delhi, Dr. H.S. Jat, Central Soil Salinity Research Institute, Karnal, Haryana and Dr. Yadvinder Singh, Department of Soil Science, Punjab Agricultural University, Ludhiana, Punjab

Dr. C.M. Parihar (ICAR-IARI), Dr. S.L. Jat (ICAR-IIMR), Dr. H.S. Jat (ICAR-CSSRI) and Dr. Yadvinder Singh (PAU/BISA) have made significant contributions in developing and evaluating different precision tools (Optical Sensor and Nutrient Expert, NE) and techniques for efficient fertilizer use, especially for conservation agriculture (CA) based cropping systems. Balanced fertilization using NE based site specific nutrient management (SSNM) approach increased productivity and fertilizer use efficiency of different crops over blanket recommendations across the different locations and soil types. The layering of CA-based practices with precision nutrient prescriptions using SSNM based decision support tools offers a new management paradigm for scaling up of rice- and maize-based systems in India. Their studies showed that fertigation using subsurface drip can increase N use efficiency by more than 25% and water productivity by more than 50% while producing similar or even higher yields of rice - wheat and maize - wheat systems with significant reductions in greenhouse gases compared to conventional systems. The technological advancements made by them for precision nutrient and water management have wider implications for improving nutrient and water use efficiencies, farmers' profitability and soil health, and reducing environmental footprints.

X. FAI GOLDEN JUBILEE AWARD FOR OUTSTANDING DOCTORAL RESEARCH IN FERTILIZER USAGE

Winner - Dr. Debarup Das, Division of Soil Science and Agricultural Chemistry, ICAR-IARI, Pusa Campus, New Delhi

Dr. Debarup Das did his Ph.D. on Effect of Long-term Fertilization and Manuring on Potassium Dynamics in Soils of Varying Mineralogical Make-up from ICAR-Indian Agricultural Research Institute, New Delhi. As long-term effect of intensive cropping and fertilization on K dynamics and clay mineralogy in different soils and its implications on sustained high productivity is less understood, study conducted with three major soil orders of India, *viz.* Inceptisol, Alfisol and Vertisol, is of great academic and practical significance. Long-term application of N and P without K resulted in lower contents of different K pools including NEK compared with those under NPK-fertilized treatments. In Inceptisol, mica content of the clay fraction in surface layer was lower in control, N and NP (42–48%) than the NPK-fertilized treatments (50–57%). He proved that water soluble, ammonium acetate extractable, nitric acid extractable, and non-exchangeable K (NEK) in soil significantly varied under different nutrient supply options after more than four decades of intensive cropping. Dr. Das carried out in-depth research and quantified the adverse effects of K-omission on soil K dynamics and clay mineralogy and clearly demonstrated the potential threat to production sustainability from excessive mining of soil's native potassium.

XI. IZA-FAI AWARD ON PROMOTING THE USE OF ZINC IN INDIAN AGRICULTURE

Winner - Dr. Vijay Pooniya, Division of Agronomy, ICAR-IARI, New Delhi

Dr. Vijay Pooniya has done outstanding research work on zinc ferti–fortification in cereal–based cropping systems. He has conducted number of field experiments on zinc nutrition in major cereal–food crops i.e., rice, wheat and maize/corn and tested for enhanced zinc content in aromatic rice, wheat, corn, and rice–wheat rotation. He has also contributed significantly in developing techniques for micro–(Zn) and secondary (S) nutrients enrichment for increasing the efficiency of fertilizers in maize, rice & wheat crops. Dr Pooniya conducted intensive trials as well as field demonstrations to study Zn fertilization for enhancing productivity, Zn content and profitability. He has also tested various Zn fertilization techniques *viz.* seed coating, foliar application, ZnO slurry, soil + foliar application on different crops and cropping systems.

XII. BEST ARTICLE AWARDS

A. RASHTRIYA CHEMICALS AND FERTILIZERS LIMITED AWARDS IN PRODUCTION AND TECHNOLOGY

First Prize

Mr. A. K. Nayak and Mr. J. Sondhi, Krishak Bharati Cooperative Ltd., Surat for their article **"Inspection and Maintenance of Rotating Machinery in Fertilizer Plant"** published in the May, 2019 issue of *Indian Journal of Fertilisers*.

Second Prize

Mr. Debashis Banerjee and Mr. Ashok Rathore, Shriram Fertilisers & Chemicals, Kota for their article "**Electrical System Maintenance and Reliability Improvement Practices at SFC Kota"** published in the July, 2019 issue of *Indian Journal of Fertilisers.*

B. SHRIRAM AWARDS IN MARKETING

First Prize

Mr. R.M. Deshpande, Nagarjuna Fertilizers and Chemicals Ltd., Hyderabad for his article **"DBT Issues and Remedies"** published in the September, 2019 issue of *Indian Journal of Fertilisers.*

Second Prize

Mr. Sanjay Chhabra, DCM Shriram Limited (Unit : Shriram Fertilisers & Chemicals), New Delhi for his article **"Marketing of Value Added Fertilizers"** published in the September, 2019 issue of *Indian Journal of Fertilisers.*

C. DHIRU MORARJI MEMORIAL AWARD IN AGRICULTURAL SCIENCES

First Prize

Dr. Shailendra Pratap Singh, Dr. Vikas Kumar Singh and Dr. Subhendu Bhadraray, erstwhile Tata Chemicals Limited for their article **"Smart Cluster: An Agri-input Management Service with a Difference"** published in the October, 2018 issue of *Indian Journal of Fertilisers*.

Second Prize

Dr. H. Pathak, Dr. D. Chattarjee, ICAR- National Rice Research Institute, Cuttack, Odisha and Dr. S. Saha, ICAR- Research Complex for North Eastern Hill Region, Umiam, Shillong, Meghalaya for their article **"Fertilizer and Environment Pollution: From Problem to Solution"** published in the March, 2019 issue of *Indian Journal of Fertilisers*.

D. SHRIRAM KHAD PATRIKA AWARD (HINDI)

First Prize

Dr. Kapila Shekhawat, Dr. Sanjay Singh Rathore, Dr. Parvin Kumar Upadhyay, Dr. Bipin Kumar, Dr. Ram Swaroop Bana, Dr. Rajiv Kumar Singh and Dr. Vinod Kumar Singh, Division of Agronomy, Indian Agricultural Research Institute (IARI), Pusa Campus, New Delhi for their article on **"रबी फसलों में संरक्षण खेती एवं परिशुद्ध पोषक तत्व प्रबंधन"** published in October, 2018 issue of *Khad Patrika.*

Second Prize

Dr. Tarunendu Singh and Mr. Yogendra Kumar, Indian Farmers Fertiliser Cooperative Ltd., New Delhi for their article on **"ड्रिप फर्टिगेशन प्रणाली–किसानों की लाभदेयता व टिकाऊ खेती के लिए आवश्यक"** published in the December, 2018 issue of *Khad Patrika*.

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