Nutrient Management for Enhancing Productivity and Nutrient Use Efficiency in Rice

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SUMMARY

Development of appropriate management strategy for enhancing nutrient use efficiency, and ensuring environmental sustainability of rice production system is a priority area of research. Considerable progress has been made so far from broad based blanket nutrient recommendation to supply and demand based site specific nutrient recommendation. The nutrient management researches in rice till dates mostly focus on “4 R” stewardship i.e. right dose, right time, right source and right place of nutrient application. Numerous technologies, tools and products such as soil test crop response (STCR) based N, P, K recommendation, optical sensor based real time N management, enhanced efficiency fertilizer materials have been developed and evaluated in rice and rice based systems to ensure 4 “R” principles of nutrient application and enhance yield and nutrient use efficiency. Further research is needed to fine tune these technologies for its wider adaptability and also to redefine nutrient management strategy in the context of climate change, next generation super, high protein and abiotic stress tolerant rice. It is essential to devise ecological intensification based nutrient recommendation that takes in to account ecological processes as well as the interactions among themselves to reduce negative environmental impact of chemical fertilizers.

1. INTRODUCTION

Rice is one of the input intensive crops in the world and input of nutrient contributes approximately 20–25%to the total production costs of rice. At present rice production alone consumes nearly 24.7 Mt of fertilizer (N + P_2O_5 + K_2O) which accounts for approximately 14.0 % of total global fertilizer consumption in a year. Scientists have predicted that a hike of at least 60% in rice yield is essential in order to ensure food and nutritional security of 9 billion populations that are expected to inhabit the globe by 2050. With increasing demand for food production, demand for nutrients is likely to increase further.

Despite several decades of research the average recovery efficiency of N, P and K in rice is only 30-35%, 20-25% and 35-40%, respectively. At present, India imports 30% of nitrogenous, 70% of phosphatic and 100% of potassium fertilizer. Both N and P fertilizers are highly energy intensive and at the same time also have very low use efficiency. In addition, there are several drawbacks in the prevailing practices of nutrient management such as non-judicious blanket nutrient application, skewed

NPK ratio, and nutrient mining etc., that pose severe threats to the productivity and sustainability of intensive rice production systems. At the same time inappropriate use of these nutrients has several socioeconomic and ecological consequences such as enhanced fertilizer cost, fossil fuel burning, greenhouse gas emission, pollution of water bodies etc. Therefore an appropriate nutrient management strategy apart from enhancing nutrient use efficiency, productivity and profitability should also aim at enhancing eco-efficiency and environmental sustainability.

Voluminous research has been done to develop and optimize appropriate nutrient management strategy for rice and rice based systems in varying agro-ecological conditions. Most of the early researches focused on broad based blanket nutrient recommendations for similar agro-climatic region. However, these recommendations did not consider field-to-field variability of soil nutrient status which is often led to either excess or deficit nutrient application resulting in loss of nutrient, reduced yield poor nutrient response and low nutrient use efficiency. During past few years tremendous progress has been made in the nutrient management research in order to satisfy"4 R" criteria i.e. right dose, right time, right source and right place ,required for enhancing nutrient use efficiency. This led to development of numerous tools and technologies that can be used in rice cultivation across the agro-ecosystem such as soil test crop response (STCR) based N, P, K recommendation, Site Specific Nutrient Management (SSNM) using omission plot technique and targeted yield approach, Real Time N Management (RTNM) using leaf colour chat, chlorophyll meter and green seeker, use of enhanced efficiency fertilizer materials (EEFs) such as urea super granules, coated urea, and nano-fertilizers etc.

Considering the fact that relationship between soil fertility status, nutrient use efficiency and yield at farm level is highly scattered and show great degree of variation, and a common nutrient management strategy may not be appropriate for farmers of different agro-ecology and socioeconomic background. Efforts have been made to upscale the data base with respect to soil fertility management from field to regional level. Accordingly, management zones of rice cultivation have been delineated using GIS, GPS and remote sensing tools.

Nutrient use efficiency depends on plant's ability to uptake nutrient from soil either native or applied and to convert it into final economic product and is controlled by complex interactions of physiological, developmental and environmental processes in soil-plant-atmosphere continuum. Multidisciplinary approach involving agronomy, soil science, microbiology, plant physiology and genetic studies is being followed to identify controlling factors of nutrient use efficiency of rice, developing efficient genotypes and devising appropriate nutrient management strategy (Fig. 1). Apart from that nutrient management research requires a thorough understanding of fate of nutrients in soil, water, plant and atmosphere in emerging scenarios of climate change, development of next generation rice (super rice, high protein rice, multi abiotic stress tolerant rice etc.) and promotion of conservation agricultural practices for bringing in new innovations in the management of N,P,K and micronutrients in rice.

Fig. 1.Graphical presentation showing multidisciplinary approach for understanding regulatory factors of nutrient use efficiency.

Objective of this chapter is to discuss about the progress, which have been made so far in management of nutrients for enhanced productivity and nutrient use efficiency of rice and rice based production system, and how to fine tune the existing technology for its wider adaptability. This chapter will also discuss about the need of redefining nutrient management strategy in the context of climate change, next generation super, high protein and abiotic stress tolerant rice.

2. STATUS OF RESEARCH

2.1. Nitrogen

Nitrogen is one of the most essential and most limiting nutrient for rice production and application of synthetic N fertilizer plays a crucial role in enhancing the yield. Globally rice cultivation consumes approximately 9 to 10 million tons of fertilizer N in a year which accounts for about 10% of the total fertilizer N production in the world. However, only 30 to 40% of the applied N is recovered by the crop resulting in large losses of reactive N, which not only negatively affects yield but also drains national exchequer and pollutes environment simultaneously. Cost of remediation of the socio-environmental side effects of N pollution such as global warming, ground water pollution and eutrophication etc. is huge. Hence, enhancing N use efficiency of rice has always been a researchable topic for both plant nutritionist and environmental scientists.

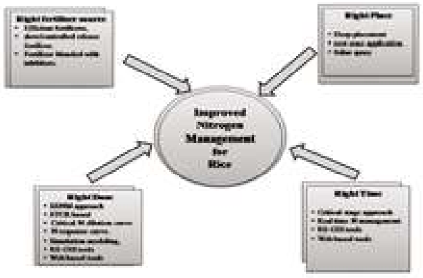

Fig.2. Four “R” approach of nitrogen management for enhanced N use efficiency in rice.

Studies on N management in rice mostly revolve around four ‘R’ principles of nutrient application i.e. right fertilizer source, right dose, right time and right place (Fig. 2).

Among inorganic sources of N, urea is the most widely used nitrogenous fertilizer in rice because of its high N content and favorable physical properties. However, the major disadvantage with urea is that once applied to waterlogged soils of low land rice, it undergoes rapid transformation processes such as hydrolysis, nitrification, denitrification, leaching and volatilization etc. resulting in loss of up to 50% of applied urea N.

Efforts have been made to develop slow release or controlled release urea fertilizers by coating urea prills with less soluble chemicals such as sulfur, polymers and other products like plaster of paris, resins and waxes. These coated urea products were tested both in laboratories and in field condition with varying degree of effects on urea hydrolysis and N recovery efficiency. Besides this several chemical and natural inhibitors for inhibiting and/or slowing down the hydrolysis of urea (urease inhibitors: NBPT - N-(n-butyl) thiophosphoric triamide – Agrotain, N-phenyl phosphorictriamides (2-NPT), Hydroquinone (HQ), Phenyl phosphorodiamidate (PPD/PPDA)) and biological oxidation of ammonical-N to nitrate-N (nitrification inhibitors: Nitrapyrin, DCD, N (2,5 dichlorphenyl) succinic acid monoamide (DCS), 3,4-dimethylpyrazole phosphate (DMPP)) have been identified and evaluated. The fertilizer products with the coatings of less permeable material and one or more inhibitors as extra additive within the formulation or as in the coating are known as enhanced efficiency fertilizers (EEFs). The EEFs are generally designed to regulate either nitrification or urea hydrolysis or both in order to reduce N loss and increase N uptake by plant. A comprehensive analysis of hundreds of studies all over world with respect to effectiveness of different EEFs showed that urease inhibitors could increase yield and N use efficiency up to 9% and 29%, respectively and reduce in N loss up to 41% in rice-paddy system (Li et al. 2017).

Presence of thin oxidized layer overlying reduced zone in soil is one of the reasons behind rapid loss of N from the rice ecosystem in various forms when it is broadcasted to surface soil. Studies on right place of N application indicated appropriate method or place of N application may vary according to time and source of N application. Basal incorporation of urea in puddled soil of transplanted rice has been observed to reduce NH_3 volatilization as compared to surface broadcasting of urea to flooded soil, but its impact on yield depends on other factors like water management and tillage practices during incorporation. Inter row band application of urea during top dressing in direct seeded rice and deep (5-7 cm below surface) placement of USGs in reduced zone in transplanted rice was found to be superior in terms of enhancing N use efficiency and reducing N loss over surface broadcasting of urea. Considering the drudgery and labor involved with manual deep placement method, several attempts have been made to develop continuous operation type and non-continuous injector type USG applicator for both basal and top dressing in transplanted rice. These applicators, however, need to be fine-tuned to make those more user friendly and efficient with respect to metering and uniform depth of application. Technique of injecting dissolved urea into the upper soil layer, has also been developed which is equally effective as deep placement of USG and at the same time less laborious and can be used for top dressing too. Recent study on one-time root zone fertilization (RZF) technique showed that basal application of urea into 10 cm deep holes dug at a distance of 5 cm from the rice roots reduced fertilizer-N loss by 56.3–81.9% compared to urea surface broad casting (Liu 2016). In addition to soil application, foliar spray of urea has been suggested to avoid the complex interactions of urea in flooded soil of rice. Its effect on grain N content mainly cultivar specific and varies with time of application, however spraying of urea at flowering stage led to a more efficient dry matter partition to the grain, higher grain number m^{-2} and finally increased grain yield (Sarandon and Asborno 1996).

Synchronization of N supply with that of crop N demand is the key for enhancing N use efficiency of crop, deciding time and rate of N application is an area of active research in the field of nutrient management in rice. Timing of N application or the decision on split application of N depends on the N requirement pattern of the rice plant. The N absorption in early duration rice varieties is continuous from transplanting to flowering after which there is almost no absorption. In medium and late duration varieties the dry matter and N accumulation is vigorous from transplanting to maximum tillering stage after which it slows down during the vegetative lag phase and again becomes vigorous with onset of panicle initiation and continues little after flowering. Thus there is a single peak of N requirement in early varieties and two peaks of N requirement in medium and late duration varieties, suggesting the importance of basal N application in early varieties and split application in medium and late duration varieties. The number of split is also decided on the basis of soil texture. In soils of relatively finer textures, N is applied in three splits with 50% at basal dressing, 25% at 21 days after transplanting (DAT) and the rest 25% at panicle initiation. But in soil of lighter textures, N application in three splits of 25:50:25 proportions are considered best. For hybrid rice, N is applied in four equal splits doses- 25% of N at basal dressing, 25% at 21 DAT, 25% at PI and the rest 25% at panicle emergence. However, in rainfed lowland direct seeded rice the entire dose of 60 kg N ha^{-1} along with 30 kg P_2O_5 and 30 kg K_2O ha^{-1} is applied in seed furrows at the time of dry sowing. Response of crop to applied N is highly field specific and varies with soil condition hence correct N recommendations requires information on N availability from all possible sources and crop requirement. The site specific N management (SSNM) recommendation based on indigenous N supply, expected N demand of crop and the expected fertilizer N use efficiency resulted in an increase in N-use efficiency of irrigated rice by 30–40% and grain yield by 7% in more than 100 field experiments in Asia (Dobermann et al. 2002). Going a step further, ways and means were also devised to address the real time need of crop which generally varies according to growth stage and environmental condition. Hand held optical sensors such as chlorophyll meter, green seeker etc. are promising real time N management tools which indicate crop N status non-destructively on the basis of greenness of leaf. Recently leaf colour chart (LCC) is being widely tested and promoted as an easy to use cheap and farmer's friendly diagnostic tool of real time N application. The extensive field research in several parts of Asia indicated up to 25% saving of N in rice production could be achieved by using LCC.

Crop simulation based decision support tools such as DSSAT, ORYZA-2000, Info Crop have been developed to help determine N fertilizer recommendations matching with crop requirement. These tools consider complex interaction of N transformation processes in soil-plant-atmosphere continuum and are useful to predict N management option in different scenarios of agronomic management. Development of light and portable hyper-spectral sensors and new generation satellites which obtain higher resolution images offer the possibility to detect in season N status of crop on the basis the normalized vegetation index to provide recommendation for larger areas at affordable prices.

Nitrogen fertilizer is an integral component of green revolution in India and most of the initial researches on N recommendation were related to agronomy trials on yield response in different agro-climatic zone. Few studies on site specific N recommendation have been initiated in several rice growing regions like Punjab, Odisha, Bihar etc. Rice Crop Manger is such an initiative by IRRI in collaboration with ICAR institutes that gives field specific N recommendation on the basis of past crop management history. Recently Bijay-Singh et al. (2015) recommended a moderate amount of N application at transplanting, followed by sufficient N fertilization at active tillering, and an optical sensor-based N application at panicle initiation stage for enhanced yield and N use efficiency in transplanted rice. However, the real time N management tools like chlorophyll meter and green seekers etc. are confined to experimental purposes only. Extensive studies on standardization and evaluation of leaf colour chart based in season N application have been conducted in farmers' fields in different parts of India.

Studies on use of EEFs for enhancing N use efficiency of rice in India are limited to experimental stations only. Several attempts have been made for identification and field scale evaluation of plant based natural inhibitors. Nimin, a tetraterpenoids extracted from neem (*Azadirachtaindica*) cake and karanjin, a flavonoid obtained from the seeds of the karanj (*Pongamiapinnata*) are reported to have nitrification inhibition property. Technology has been developed to produce Neem coated urea by coating urea prills with neem (*Azadirachtaindica*) oil emulsion.Field trials with rice indicated reduced N loss, enhanced yield and N use efficiency with NCU as compared to normal urea. Today according to the order of Government of India all urea manufactured in India are coated with neem oil emulsion.

Development of appropriate N management strategy has always been an integral component of rice research at ICAR-NRRI. Number of studies has been conducted to understand fate of urea in low land rice under different improved N management options. The time of complete urea hydrolysis in irrigated and rainfed rice ecosystems was found to be 2-3, 5-7, and 7-14 days for broadcasting of urea onto flooded soil, deep placement of USG in flooded soil and urea basal application in dry soil, respectively (Nayak and Panda 2002). Relative ammonia volatilization and surface runoff loss from rice field was estimated to be 0.4% and 6-8%, respectivelywith USG deep placement and 6.0% and 78% with urea broadcasting on waterlogged soil (Nayak and Panda 2002). Subsurface placement of urea through thorough incorporation of applied urea into wet soil by puddling in absence of any standing water and deep placement urea mud balls in the reduced zone of submerged rice soil, also decreased N losses and improved N use efficiency in rice (Kabat 2001). Coating of urea with neemcake or shellac for basal dressing also reduced ammonia loss (Mishra et al.1990). Nayak and Panda (1999) tested efficacy of different nitrification inhibitors found that hydroquinone was more effective in alluvial and laterite soils and alcoholic extract of neem cake was better in black soil than dicyandiamide. In direct seeded rice, seed furrow placement of urea produced higher grain yield than broadcasting method.

Yield response trials were conducted to optimize N dose for semi-dwarf rice in wet season (40-80 kg ha^{-1}), rainfed lowland direct sown rice varieties, (56-62 kg ha^{-1}) and hybrid rice (100 kg N ha^{-1} in *kharif* and 120-135 kg N ha^{-1} in *rabi* season). In addition to this, nitrogen accumulation pattern of different rice cultivars was investigated in different agro-ecological conditions to ascertain the pattern of N requirement and decide number and time of split N application accordingly. Efforts have been made to optimize N doses for several medium to long duration rice varieties grown at different planting dates by crop simulation approach using of ORYZA 1N model.

Recently a five panel customized leaf colour chart (CLCC) was developed for real time nitrogen management in rice of different agro ecologies by ICAR-NRRI. The CLCC provides cultivar specific recommendation of basal as well as top dressing of N (both time and dose) in terms of kg urea per acre for rainfed favorable lowland, submerged and flood prone lowland, rainfed upland, and irrigated rice (Nayak et al. 2013). Field trials indicated yield advantages of 0.5-0.7 t ha^{-1}with CLCC based N application over recommended practice. Application of neem coated urea (NCU) on the basis of CLCC reading enhanced yield and N recovery efficiency (REN) by 21.2-22.9% and 16.3-18.0%, respectively, over conventionally applied urea (RDF-Urea) in aerobic direct seeded rice (DSR) and by 14.6-15.9% and 11.6-14.6%, respectively in puddled transplanted rice (PTR). Further, in aerobic direct seeded rice, NCU when applied on the basis of leaf colour chart reduced NO_3-N leaching and N_2O-N emission by 26% and 11-21%, respectively as compared to conventionally applied urea (Mohanty et al. 2017). Web based nutrient management tool-rice crop manager (RCM) was developed in collaboration with IRRI to give field specific recommendation for the farmers of Odisha on the basis of past cropping and management history information. Rice crop manager recommendation provided rice grain yield advantage of 9.8 to 39.6% with an average of 22.6% over farmer’s practice (FFP). Remote sensing and GIS tools were used to provide recommendation of N application for homogenous management zone in few selected pockets of Odisha. Site specific N recommendations of 66-100 kg ha^{-1} with an average of 80 kg ha^{-1} were computed using historical soil data, yield target and expected agronomic N use efficiency. Site specific fertilizer N recommendation (SSFN) map was generated for Ersama block, Jagatsingpur district of Odisha using appropriate semi-variograms and interpolating SSNM values by kriging.

Research has been initiated at ICAR-NRRI to fine tune technique of urea briquette deep placement to make it more efficient and user friendly. The breakability of the briquettes was reduced by mixing urea with oils of neem (*Azadirachta indica*) and karanj (*Pongamia pinnata*). Apart from being good binding agent, the oils used contain active ingredients that reportedly inhibit nitrification activity in soil. Mixing oil increased the strength of briquettes and reduced the breaking percentage to 2-5% as compared to 25-30% of urea briquette without a binding agent. In addition to this, agglomerated urea briquettes were prepared by mixing suitable amendments viz. phospho-gypsum, fly ash, silica powder, neem cake and rice husk as filling materials and biodegradable binding agents with urea (Nayak et al. 2017). Use of amendments and binders improved the crushing strength of briquettes. Additionally, amendments acted as filler material and reduced the concentration of urea in pellet which will ensure its uniform distribution in the field. Efforts were also made to improve the existing urea applicator and develop new prototypes. Manually pulled 2, 3 and 4 row drum type urea briquette applicators for basal application, briquette applicator mounted on conoweeder for top dressing, injection type briquette applicator for both basal and top dressing are fabricated and tested in the field.

2.2. Phosphorous

About 50% of agricultural soils, on a global scale, are suffering from deficiency of phosphorus (P), which has been majorly observed due to two prime factors, (i) insufficient P replacement in agricultural soil, and (ii) P-fixing properties of a particular soil causing P unavailability to plants. In highly weathered soils around the world, mostly belongs to the orders Oxisols and Ultisols, P deficiency has been noticed as a common factor hampering the agricultural production. Apart from the inherent soil conditions to supply P, large imbalances in the rates of P fertilizer also exist, showing the variations of lower or inadequate P application in many developing countries of Asia, Africa and South America but adequate or excess P application in the Europe, USA and few Asian countries (China, Japan and Korea) as reported by few analysis over the years.

Response to P application is highly erratic due to direct and indirect influences of several factors operating in the soil system on P availability to the plants. In general, the response of lowland rice is usually lower than other dryland crops including upland rice Reduced soil conditions normally increase the P availability to lowland rice. Therefore, in many soils, P availability is not a yield-limiting factor for rice and significant response of modern rice varieties to fertilizer P may be observed after several years of intensive cropping. Thus management must focus on the buildup and maintenance of adequate available P levels in the soil, so that P supply does not limit crop growth. P fertilizer applications exhibit residual effects thus maintenance of soil P supply requires long-term strategies on site-specific basis. Organically amended plots (FYM, rice straw, and green manuring) in eastern India showed an improved PUE than control. While others have found that effect of FYM application on P use efficiency was not very prominent in irrigated rice rather it helps in recycling P. Application of phosphorous solubilizing bacteria (PSB) to lowland rice ecology had no significant impact while addition of phosphatic fertilizers and vermicompost governed the soil P availability in the same occurrence (Kumar et al. 2016). Upland rice-based crop rotation with maize and horse gram promoted native arbuscular mycorrhizal fungi (AMF) colonization (in a tune of 10.4–38.8%) and ensured better P uptake (2.2–2.6 mg P g^{-1} plant) by rice crop which further reflected in higher grain yield (Maiti et al. 2012).

Better phosphorus use efficiency (PUE) can be addressed through two clear-cut approaches: 1. Genetically P efficient cultivars, and 2. P management by external means. Scientists working in rice crop globally follow similar ways to enhance PUE. Genotypes grown well at low soil P level but responded well to added P is the most desirable trait for screening P efficient rice genotypes. The study further identified two factors, shoot weight and P uptake, are the most crucial to identify P deficiency. Moreover, PUE was identified higher in roots over shoots in rice grown under acid soils that decreased with increasing levels of soil P (Fageria and Baligar1997). By cutting edge approach of recent times, scientists have explored the possibility of genetic manipulation in rice for improved PUE, including the identification of *PSTOL1* (phosphorus starvation tolerance 1) gene, which is a key gene responsible for the natural variation in phosphorus starvation tolerance, induce enhanced grain yield in P-decient soil by promoting early root growth and Pi acquisition, over a range of intolerant and tolerant rice genotypes like Kasalath (Gamuyao et al. 2012).

2.3. Potassium

In tall *indica* rice, there was limited response to K application in earlier years, but with the introduction of high yielding varieties and intensive agriculture, response in grain yield was recorded. The mean response of rice over several years in intensive cropping systems of the long term fertilizer experiments ranged from 4 to 10 kg grain for every kg of K_2O applied. In view of high uptake of K by the high yielding varieties of rice, application of a maintenance dose of 30 kg K_2O ha^{-1} for lowland rice is suggested. In light textured acid upland soils, K deficient areas, in biotic and abiotic stress situations and in hybrid rice, split application of K or K top dressing along with N at panicle initiation in addition to a basal dressing of K is beneficial for increasing rice yield. Rice is mostly cultivated under submerged condition. Under such condition potassium fertility level changes immediately after inundating the soils due to release of soluble ferrous (Fe^{2+}) and manganous (Mn^{2+}) ions. These ions displaced K in the exchangeable pools and released into the soil solution. Thus, availability of K increased after submergence. However, contrasting reports are also available showing decrease in K content due to the formation of sparingly soluble Fe-K complexes. Hence, application of potassium along with other nutrients is very important for sustaining rice yield.

Application of inadequate and unbalanced fertilizer excluding potassium is one of the reasons for declining K nutrition in rice fields. In a long-term study in China, it is observed that proper potassium fertilizer management control rice yield in the double rice cropping system (Liao et al. 2013). It was further observed that the yield of both early and late rice increased over time in the treatments that received fertilizer K or combined application of fertilizer with rice straw. Decline in yield of rice is reported when unbalanced fertilizers are applied (Liao et al. 2013). Rice removes large amount of K from soil. Due to high K removal, a negative K balance prevail in rice and rice

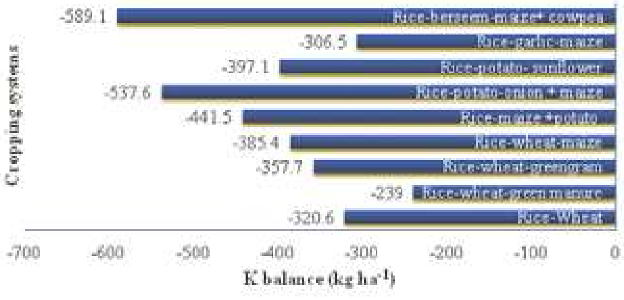

Fig. 3.Potassium balance in rice-based cropping systems (modified after Sharma et al. 2008).

based cropping system even after recommended fertilizer application. Sharma et al. (2008) reported a net negative K balance for nine different rice-based cropping systems (Fig. 3).

Rice straw is a rich source of K, its incorporation into soil at the rate 5-10 t ha^{-1} markedly increases available K content and improves K nutrition of rice crop. Therefore, effective straw management by returning a considerable portion back into the field is another option for effective K management (Bijay-Singh and Singh 2017). Split application of potassium in rice field increased the yield and potassium use efficiency of rice in light textured soil. However in a long term fertilizer experiment at NRRI, response to applied K was observed after 30 years of rice-rice cropping, nevertheless treatment effects were most prominent on release threshold concentration (RTC), followed by cumulative K release, K-release rate constants, and K-fixation capacity. Rice cultivation without K fertilizer application resulted in lower values of soil K parameters than the K fertilized treatments (Debrup et al 2018).

2.4. Micronutrients

Micronutrients more particularly Zn, B and Fe play key roles in growth and metabolism of rice plant hence are essential for enhancing yield of low land rice. Zinc deficiency is the most commonly observed micronutrient disorder in rice based cropping system. In contrast, Fe toxicity is the major problem in the most wetland rice soil in humid tropical regions of Asia due to drop of redox potential under submerged condition which elevates the release of Fe(II) in the soil. However, in upland and aerobic rice systems Fe could be a limiting nutrient for rice yield. Additionally, nutrient mining and emerging trend of micronutrients deficiency in soils of many intensively cultivated rice growing regions warrants for a judicious and need based micronutrient application strategy in rice cultivation. Study on effect of micronutrient application on rice yield showed number of tillers per square meter, spikelets per panicle and paddy yield was maximum with combined use of zinc and boron and 1000-grain weight was recorded highest where all three micronutrients (zinc, boron and iron) were applied in combination. The maximum healthy kernel percentage was recorded where zinc was applied along with iron (Qadir et al. 2009).

Flooding the soil alters availability of micronutrients like Fe, Mn and Zn which interact among themselves and determine their uptake by plant. However, the soil test based approach is considered best for application of these nutrients. Among the different available Zn fertilizers $ZnSO_4$ is the most commonly used Zn fertilizer because of its high solubility. In Zn deficient soil one time application of 20 to 25 kg $ZnSO_4$ ha^{-1} as basal has been recommended. However foliar spray of 0.5% $ZnSO_4$ in 200 litre water ha^{-1} has been suggested in emergency condition of Zn deficiency during rice growth period. In calcareous soil incorporation of Zn fertilizer with green manure is generally considered better than broadcasting.

Apart from upland condition, Fe deficiency also occurs in, calcareous, and alkaline low land soil with low organic matter content. Management practices like application of organic manure before sowing and green manuring with dhaincha before rice transplanting have been proved beneficial to alleviate Fe deficiency in rice. Ponding of water in nursery beds during dry spell and irrigating rice fields as soon as chlorosis appears have also been suggested to deal with Fe deficiency. In addition to this broadcasting of $FeSO_4.7H_2O$ rate of the 30 kg Fe ha^{-1} as basal and spraying 1% $FeSO_4.7H_2O$ solution 2-3 times at 10 days interval have been recommended. Application of lime (75% LR) along with Zn and other limiting elements such as K and Mn ameliorated iron toxicity in some lowland iron rich rice soils (Shahid et al. 2014).

Manganese deficiency mainly occurs in alkaline and sodic soil with low organic matter, leached and acid sulphate soils and degraded soils containing large amount of soluble iron. Integrated application organic manures like FYM, compost or green manure along with 25 kg $MnSO_4$ ha^{-1} as basal could be the best management strategy to address the problem of Mn deficiency in rice. In addition, spraying of 0.5% $MnSO_4$ has been recommended for rapid correction of Mn deficiency.

Rice grown in highly weathered, acid upland, coarse textured sandy soils and calcareous soils mostly suffers from B deficiency. Generally, soil test based application of borax at the rate of 5-10 kg ha^{-1} as basal has been recommended for B deficient soil. However, spraying of 0.2% boric acid or borax at pre flowering or heading stages has been proved to be effective in taking care of hidden deficiency. For quick recovery from B deficiency, spraying of borax or boric acid at the rate of 0.05% has also been suggested.

2.5. Integrated nutrient management

Integrated approach of using both organic manures (Farm yard manure (FYM), green manure (GM), crop residues, biological N_2 fixation and biofertilizers) and chemical fertilizers have been often recommended for managing soil fertility and nutrients in intensive rice based cropping system to arrest the trend of yield stagnation and minimize adverse environmental impact of chemical fertilizers. Numerous studies have been conducted to ascertain the beneficial effects of organic manure application on soil health and subsequent positive impact on growth and yield of rice. Sustainability yield indices calculated for intensive rice production system often show comparatively higher value when part of the recommended nutrient is applied through organic sources such as FYM or GM than chemical fertilizer alone. Continuous application of chemical fertilizers along with FYM to a 44 year old rice-rice system in tropical India resulted in improvement in soil physical and chemical properties and biological activity leading to higher soil quality index and greater sustainability (Shahid et al. 2013). Studies conducted at CRRI, Cuttack revealed that growing Azolla before rice transplanting or after transplanting produces an additional grain yield of more than 0.5 t ha^{-1} and is equivalent to application of 30 kg of fertilizer-N. Free living bacteria Azotobacter can fix 10-30 kg N ha^{-1} in aerobic soil, the associative bacteria Azospirillum can fix 7 kg N ha^{-1}; with its inoculation, grain yield increased by 8-30% over uninoculated

3. KNOWLEDGE GAPS

Despite volumes of research and adoption of innovative technology, the N use efficiency of low land rice has not been improved substantially. The recent approach of SSNM along with RTNM has the potential to ensure efficient utilization of applied N; however these technologies need to be simplified while retaining their effectiveness to ensure large scale adoption by the small and marginal farmers growing rainfed rice. Deep placement of urea super granules/urea briquettes in the reduced zone has been proved to enhance N use efficiency and decrease N loss but in absence of a cost effective efficient applicator for uniform application, deep placement technology has not made any desired impact. Quantitative understanding of the complex interacting processes taking place in soil as well as in plant that influence N use efficiency of rice is still insufficient. Source sink relationship of super rice/next generation rice and high protein rice is inadequately understood. Methods for estimation of various N loss from rice ecosystem are yet to be standardized and up-scaled in different agro-climatic conditions, the limited data generated following these methods are associated with great degree of uncertainties. The fate of USG deep placement in light sandy loam textured soil and in direct seeding rice in unpuddled soil, where substantial amount of leaching takes place has not been properly known. Integrating satellite based real time monitoring of soil and plant nutrient status with weather forecasting for fertilizer recommendation advisory is another potential area of research. Similarly ,microbial processes like anaerobic ammonia oxidation and phyllospheric N fixation which could have a bearing with N loss and N use efficiency of urea deep placement is poorly understood.

Phosphorus is a unique element and indispensable for sustenance of crop plants, microbes and ecosystem. In soil system major form of P is phosphate (PO_4^{3-}) which binds with the available cations (Ca^{2+}, Mg^{2+}, Al^{3+}); however where rice grows in a typical conditions (lowland, puddled, submerged, anaerobic) the availability of P and its dynamics over time with changing pH and redox potential (Eh) is a researchable issue. Moreover, the interaction of P ions with other abundant major (N, K) and micronutrient ions (Fe, Zn, Cu, Mn) demands attention under low land/submerged situation.

The major concern in K research is whether the ammonium acetate extractable K is sufficient to justify the K supply for plant need. At present, additional parameters like the two categories of non-exchangeable K reserve *viz.* step-K and constant rate K and the release and fixation threshold levels of K are important issues. Till date, there is not much report available on the long-term effect of differential nutrient management on potassium supply parameters under different cropping system. Role of micro and macronutrients including K for ameliorating the biotic and abiotic stress in the context of climate change is being focus of current nutrient management research

Studies indicated microbial inoculants can be efficiently integrated in a nutrient management programme to reduce chemical fertilizer input and enhance nutrient use efficiency; however the effectiveness and stability of the inoculants under diversified agroclimatic condition is yet to be properly ascertained.

4. RESEARCH AND DEVELOPMENT NEEDS

4.1. Up scaling N recommendation

Though the leaf colour chart is being widely popular among the farmers as a easy to use diagnostic tools for in season N application, it still is a qualitative indicator of crop N status and provides a non-quantitative recommendation of N application and not helpful for regional scale recommendations. More recently, some non-invasive optical methods based on absorbance and/or reflectance of light by the intact leaf, have been developed. These include ground-based remote sensors and digital, aerial, drone and satellite imageries, which can be used for regional scale and quantitative recommendations to overcome tedious soil and tissue testing. The remote sensing (RS) based techniques have a great potential in formulating cost effective N recommendations for reducing fertilizer doses and environmental risks and improving nitrogen use efficiency and crop yield. But a very limited work has been done in this field, as they have a greater future scope, emphasis should be given towards improving and promoting these techniques. Remotely sensed data collected from plant canopies can be used to formulate vegetation indices that may give an indication of plant health. Several vegetation indices have been developed including, Normalized Difference Vegetation Index (NDVI), Green Normalized Vegetation Index and infrared to red reflectance ratio or simple ratio (SR). This provides opportunity for defining fertilizer N algorithm for optimum N recommendation in different rice growing regions of India on the basis of expected yields and achievable greenness of the leaves using NDVI during the crop-growth period. Research can be directed to delineate N management zone for rice indicating deficit, optimal and surplus region on the basis of RS based Nitrogen Nutrition Index (NNI) approach by taking into consideration the measured N concentration and predicted critical N concentration during growing season.

4.2. Enhancing phosphorus use efficiency

Enhancing phosphorus use efficiency (PUE) and exploring the possibility of harnessing the maximum share of P for crop nutrition from conventional (common phosphatic fertilizers) and non-conventional fertilizer (oilseed cake, bone meal, fish meal, rock phosphate etc.) sources is essential to reduce the dependence on phosphatic fertilizer for rice cultivation. Research is needed to exploit the potential of beneficial soil microbes like AMF alone or in combination with PSMs for improving crop productivity and reduced use of P-fertilizers. Interdisciplinary approach should be followed to investigate the factors affecting P nutrition of rice crop for better understanding of physiological/molecular basis, screening of better P-efficient cultivars and simultaneously devising their management strategies to overcome the problem of P deficiency. More research is needed to develop site specific nutrient management practices for P nutrition in rice that can be easily adopted by the farmers.

4.3. Harnessing microbial resources for enhancing use efficiency of potassium and micronutrients

Microbes play a significant role in cycling of nutrient in soil-plant-atmosphere continuum. Strains of beneficial microbes that directly influence availability of nutrient such as potassium solubilizing bacteria (KSB), Zn-solubilization microbes, siderophores producing microbe have been identified. Most of the studies on these microbes are confined to laboratories; research is needed to explore the possibility of using these bacteria to enhance the use efficiency of both applied and inherent nutrients in field scale. In addition, application of improved molecular tools (metagenomics, q-PCR etc.) is needed to explore the untapped potential of rhizospheric and phyllospheric microbial resources for their utilization to enhance nutrient use efficiency of rice.

4.4. Nutrient management under abiotic stress

Research has been carried out to develop single and multi abiotic stress tolerant rice cultivars that can withstand drought, submergence or both to some extent. Advent of submergence tolerant varieties like Swarna Sub1, IR-64 Sub 1 etc. make it necessary to devise appropriate nutrient management strategy to enhance productivity and reduce the yield loss. Some attempt has been made to develop nutrient management recommendation for submerged rice of flood prone areas of eastern India and found that application of additional (20%) basal P and post submergence N application either as soil application or foliar spray (48 h after de-submergence) along with additional potassium enhanced the submergence tolerance of both Sub-1 introgressed HYV and its recurrent parent. More research is needed to understand the dynamics of different nutrients in soil-plant system under various stress conditions and explore the possibility of revival of stress affected crop through nutrient supplementation. Till now most of the nutrient recommendations generated address only single stress condition such as flood, drought and salinity. However, with emerging trend of frequent occurrence of climatic extreme events it is essential to direct our research towards developing appropriate nutrient management practice under multi abiotic stress condition.

4.5. Nutrient management research in a changing climate scenario

Climate change variables including precipitation (amount and distribution), temperature and atmospheric CO_2 concentrations change rice productivity. Agricultural productivity is potentially changed by associated changes in crop nutrient use.

Understanding of crop-specific needs for achieving expected yields and soil-specific nutrient supply characteristics is the primary basis for nutrient management recommendations. In present scenario it is important to study the expected changes in ambient CO_2 concentration, temperature and precipitation which are expected to influence the agriculture. Increases in air temperature and changes in precipitation will significantly impact prevailing root zone temperature and moisture regimes. Nutrient availability, root growth and development are primarily affected by soil moisture and temperature. Limited work have been done to understand N and P dynamics in soil and their subsequent acquisition by crop under elevated CO_2 and temperature condition, however, the nature and extent of the change in these two parameters is highly site- and soil specific. At the same time little information is available regarding impacts of elevated CO_2on nutrient concentrations in solution-phase, whose availability will also be indirectly mediated by temperature and moisture changes. Research is needed to investigate the impact of elevated CO_2 and temperature on dynamics of different nutrient element in soil, availability and mechanism of their acquisition by plant.

4.6. Nutrient management for next generation rice

Development of next generation rice based on the ideotype concept with a yield target of 10-12 t ha^{-1}(super rice) and high protein rice with protein content 10-12% are frontier area of research in rice improvement. New plant ideotype necessitates appropriate nutrient management practices for realizing the potential yields. Nutrient response studies are needed for both super and high protein rice to ascertain their requirement of different macro and micronutrients. Crop simulation models such as WOFOST, QuEFTS (Quantitative Evaluation of the Fertility of Tropical Soil) and Nutrient Decision Support System (NuDSS) will be helpful to calculate the nutrient need of super rice on the basis of potential yield. Understanding source sink relationship and site-specific nutrient management are promising options to estimate the nutrient requirements of super rice based on attainable yields and indigenous nutrient supply.

Studies indicated amount of N uptake in super rice varieties could be as high as 18-20 kg N $t^{-1}$of grain yield and most of the super rice is bred for a high N input condition. Similarly, in case of high protein rice the N requirement could be different than the normal rice. Uncertainties in the crop requirements for N, P and K and other micro-nutrients may result in either excess or deficit application of fertilizers leading to soil nutrient imbalances and associated negative environmental impact. Research is needed to monitor the long term impact of cultivation of these next generation rice on soil health and sustainability and at the same time efforts should be made to develop appropriate nutrient management strategy that ensures environmental sustainability while achieving its potential yield.

5. WAY FORWARD

Most of the straight and complex fertilizers currently being used in rice cultivation are in use for last 50-60 years. Research is needed to identify and develop cheap chemical and organic source of plant nutrients particularly customized fertilizer products specific to crop and region. Blanket recommendations of fertilizers for rice at state and national level are in practice since long time. At present the nature of soil, type of varieties, and environmental conditions have been changed from the time when the fertilizer recommendation was made. Therefore, revised recommendation of fertilizers are required keeping in mind the high level of exhaustion of soil nutrients by high yielding varieties.

Progress has been made so far from blanket crop response based approach of nutrient recommendation to need based site specific nutrient recommendation. However, to enhance eco-efficiency of applied nutrient and minimize negative environmental impact, it is essential to adopt ecological intensification based nutrient management approach which takes into consideration ecological processes and the beneficial interactions among different components of agro-ecosystem.

The 4 'R' stewardship approach of nutrient management need to be relooked in the context of development of sensor based precision real time monitoring system and advent of next generation super, high protein, biofortified and climate resilient rice. In the context of climate change, nutrient management strategy for enhancing tolerance to biotic (disease and pests) and abiotic (drought, submergence, high and low temperature) stresses need to be devised. In addition to this, it is essential to develop nutrient management strategies for low input rice farming particularly in difficult ecology.

Some emerging technologies like nano-technology, seed coating, liquid organic fertilization etc. have potential to bring about substantial improvement in nutrient use efficiency of arable crops. Both strategic and basic research is required to explore the possibility of using nano-fertilizers for N and P nutrition of rice and at the same time assess its undesirable side effects on soil flora and fauna. Liquid organic byproducts of bioreactors that produce bioethanol has been identified as a good source of nutrient and its use as a fertilizer is increasing in many developed countries. Recycling bioreactor waste as a source of nutrient in rice production requires systematic research and development support and involvement of extension machinery.

Production of EEFS in India is very limited, few companies produce SCU, PCU in a small scale and inhibitors are mostly imported. Non availability of these products and associated high cost prevent their wide scale use in rice cultivation. Government policy support in form of fertilizer subsidy could address this problem. Coating seeds with nutrients formulation is a promising technique to enhance nutrient use efficiency and showed positive effect on P and N nutrition however this technique is in nascent stage and require further investigation for it practical use.

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