Integrated Nutrient Management for Sustainable Production of Rice-Wheat Cropping System in Sodic Soils

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About 20% of the world's arable lands have become less productive or, in extreme cases, uncultivable wastelands due to waterlogging and salinization. The soils having either excess soluble salts and/or exchangeable sodium are termed as salt-affected soils (SAS). In South Asia (including India), about 52 million hectares (M ha) and in India, nearly 6.74 M ha (comprising of 3.79 M ha sodic and 2.95 M ha saline area) of land is salt-affected. Three-fourth of salt-affected soils in India are confined to five states namely Gujarat, Uttar Pradesh, Maharashtra, West Bengal and Rajasthan (2.23, 1.37, 0.61, 0.44 and 0.38 M ha, respectively) that together make up ≈75% of the total salt-affected soils in India (www.cssri.res.in). Current estimated area of SAS in India is estimated to increase to 16.2 M ha by 2050. ICAR-CSSRI, Karnal estimated huge salt-induced losses in annual food grain, oilseed and cash crop production with salinity and sodicity causing annual loss of about 5.66 and 11 million tonnes (M t) valued at ≈ INR 80 and 150 billion, respectively (Sharma *et al*., 2016a&b).

Based on the values of soil saturation paste extract electrical conductivity (ECe), pH (pHs) and exchangeable sodium percentage (ESP), soils are classified as normal, saline, sodic and saline-sodic. Sodic soils contain excess salts like carbonates, bicarbonates and silicates of sodium and have exchangeable sodium sufficient enough to interfere with the growth of most of the crops. Sodic soils are those, which have EC_e less than 4, pH_s greater than 8.2, dominated by exchangeable sodium percentage (ESP) greater than 15 and sodium absorption ratio (SAR) greater than 13. High ESP (>15) deteriorates the structure, impedes the water and air flows, reduces water intake capacity and hampers the root penetration in sodic soils. Presence of hard pan of calcium carbonate in the deeper root zone also restricts downward movement of both water and roots. These soils are characterized with high bulk density and very poor hydraulic conductivity.

The rice-wheat cropping system (RWCS) is one of the most prominent cropping systems prevailing on the Indian subcontinent and is considered to be of utmost importance for national food security and livelihood. The RWCS occupies about 13.5 million hectares spread over the Indian subcontinent, namely India, Pakistan, Nepal, Bangladesh, Sri Lanka, and Bhutan, and accounts for one-fourth to one-third of total food grain production. This cropping system covers about one-third of the total rice cultivation and two-fifths of the total wheat cultivation in the Indian subcontinent. The recent studies indicate that the sustainability of RWCS is being questioned because of stagnation in yield, decline in underground water table, degradation of soil and the changing climate (Gathala *et al*., 2011; Bhatt *et al*., 2015). The low yield and stagnant productivity in this system can be attributed to uncontrolled exploitation of the natural resource base (Pathak *et al*., 2003). The soils under the RWCS are now showing signs of fatigue and are no longer showing increased production with an increase in fertilizer use. Even with the use of the recommended rate of fertilizer, a negative balance of primary nutrients has been recorded. During the last three decades, the intensive agriculture involving exhaustive high yielding varieties and imbalanced and indiscriminate use of chemical fertilizers has led to heavy withdrawal of nutrients from the soil and deterioration in soil quality (John *et al*., 2001). Further, the productivity of these nutritionally drained soils remained low and unstable owing to climate and soil-related constraints.

Sustainable agriculture involves successful management of resources for increased agricultural production to satisfy changing human needs while maintaining or improving the environmental quality and natural resources (Gill *et al*., 2008). The solutions needed to achieve sustainable soil quality and plant production in sodic agro-ecosystems are- affordable reclamation and neutralization amendments, salt-tolerant varieties, sound cropping strategies, favorable agronomic conditions, balanced nutrition, need based irrigation management (cyclic or conjunctive use), monitoring of soil and irrigation water properties etc. The management of nutrients is one of the most important components for sustainable crop production in sodic soils or the soils irrigated with alkali waters. Optimum supply of nutrients to plants provides essential elements and help in overcoming the adverse effects of salt stress. Similar to the behavior of ameliorants, the rate and time of nutrient supply, and the processes governing their availability to crop differ widely depending upon the nature of salt problem in soil. Availability, chemical forms, solubility and transformations of many essential nutrients is adversely affected by the excess ESP, high pH_S (>8.2), presence of substantial amounts of $CaCO_3$, soluble $NaHCO_3$, unstable soil structure and poor physical condition of sodic soil or in soils irrigated with alkali water. These soils are deficient or low in calcium (Ca), nitrogen (N), zinc (Zn), iron (Fe), manganese (Mn) and other micro-nutrients. Both soluble and exchangeable Ca are deficient in sodic soils because of the precipitation of soluble Ca into sparingly soluble $CaCO_3$ resulting in its reduced availability to plants. High ESP and SAR causes Na antagonism to Ca uptake, thereby affecting the crop plants i.e. accumulation of toxic Na levels in sensitive plants and reduced Ca availability due to lack of adequate supply in highly sodic and moderately sodic conditions, respectively. Sodic soils are also very low in organic carbon (OC) and available N throughout the soil profile. Nitrogen transformations are adversely affected in high pH and soil sodicity conditions. Lack of aeration (due to the reduced infiltration and poor physical condition) restricts the mineralization of organic matter (OM) and organic forms of N to ammonification stage, thus increase the N losses through N volatilization. Also, due to low level of OM, the sodic soils don't respond to low levels of N application in rice and wheat crops, ultimately leading to high N application for getting good yields in RWCS. Sodic soils do not affect the availability of P and K much because of formation of sodium phosphate (soluble nature) and presence of K bearing minerals, respectively i.e. these are reported to contain high amount of soluble P and available K. Similarly, these soils are found to be sufficient in total Zn but low in its available proportion (only 3.3 % of the total). Availability and solubility of Fe and Mn are governed by the pH status and oxidation-reduction status of soil, therefore, gets reduced in sodicity conditions due to increased pH and reduced conditions. The use of organic sources of nutrients in agriculture is rapidly gaining favor but, owing to the problems related to the lack of availability of a good quality and quantity of organic materials, the system may not be sufficient to achieve and sustain the production of cereal crops in the amounts required for food security.

Integrated nutrient management (INM) helps in achieving efficient synthetic fertilizer use in integration with organic sources of nutrients. INM is developed with an understanding of the interactions among crops, soils, and climate, which advocates the integration of inorganic and organic sources of nutrients. This approach is based on the maintenance of plant nutrition supply to attain a certain level of crop production by enhancing the benefits from all potential sources of plant nutrition in a cohesive manner, applicable to each cropping pattern and farming scenario. The inclusion of organic manures regulates the uptake of nutrients, positively affecting production, improving soil quality (physical, chemical, and biological), and producing a synergistic effect on crops. INM integrates traditional and recent practices of nutrient management into an environmentally sound and cost-effective farming system that uses remunerations from all probable sources of nutrition (organic, inorganic, and biological) in a careful and effective way. It optimizes the balance between input sources and outputs with the goal of coordinating the crop's nutritional demand and its discharge in surroundings. Thus, INM can provide the right answer for a better livelihood for the resource-poor farmers. Integrated nutrient management can reduce plant requirements for inorganic nitrogen fertilizer, and reduced use of purchased fertilizer nutrients can result in a significant saving of scarce cash resources for small farmers. It also ensures the conservation and efficient use of native soil nutrients, recycling of organic nutrient flows, enhancing biological nitrogen fixation and soil biological activity, and addition of plant nutrients. There is increased emphasis on the impact on the environmental quality due to continuous use of chemical fertilizers. The INM system is characterized by reduced input of chemical fertilizers as well as combined use of chemical fertilizers with organic materials. For sustainable crop production, integrated use of inorganic and organic fertilizers has proved to be highly beneficial and helps in achieving good economic returns as well as providing favorable conditions for higher yield in RWCS. Moreover, INM also reduces erosion, improves water infiltration, soil aeration and plant root growth. FYM, compost, green manuring crops and mulches are the most commonly used organic sources. Inclusion of legumes in RWCS either as a substitute or biomass enriches the soil due to their capability to fix atmospheric N_2 and addition of OM, respectively. Crop residues on the other hand constitute an important source of organic nutrients. Around 80.12 M t crop residues available for recycling with a total nutrient potential of 1.61 M t, can replace 0.80 M t synthetic fertilizers in India (Gill *et al*., 2008). Use of bio-fertilizers is suggested as these contain living cells of different types of micro-organisms which possess the ability to mobilize the nutrients to available form (from unavailable form) through various biological processes. It broadly includes N_2- fixers, both symbiotic and non-symbiotic bacteria, phosphate-solubilizing bacteria and fungi. These approaches can help in sustaining the crop production in RWCS.

The importance of INM practices has been mentioned in several researches in the Indian subcontinent. Organic matter in soil is critical for better soil health and higher soil productivity. Addition of organic fertilizer results in increased soil OC levels in the soil, while chemical fertilizer result in decreased soil OC and basic cation contents, and lowering of soil pH. As a result, a positive effect on soil results in modification of soil structure thereby increasing the yield in the long term. Maintenance of soil OC levels under intensive cultivation could be achieved with the application of 100% NPK + FYM, however the 100% NPK and control resulted in continuous decrease in OC (Sarkar, 2000). Along with the improvement in soil chemical properties, soil physical properties are also enhanced by the use of INM, as it reduces soil erosion and increases cycling of organic residues. Thus it improves both nutrient and water retention capacity of the soil. This management also improves the soil structure, water infiltration, and soil aeration (Das *et al*., 2014). Organic amendments like mulches and composts also improve the cation exchange capacity, water retention and plant nutrient availability in saline and sodic soils. Use of crop residues as mulch increases the soil OC, and helps in formation of water-stable aggregates and water retention. Mulching also reduces rain drop impact insulating the soil against run-off induced erosion. Mulched soils are less affected by scorching heat resulting in reduced evaporative loss of water and low salt movements to the surface.

The microorganisms perform a key role in nutrient cycling for sustaining the productivity of the soils; because they are the source and sink for mineral nutrition and can carry out biochemical transformations. Basal and glucose-induced respiration, potentially mineralizable N, and arginine ammonification are higher in soils amended with organic manures with chemical fertilizers, indicating that more active micro-flora is associated with integrated nutrient supply system i.e. use of both organic manures and chemical fertilizers together, which are important for nutrient cycling. Compared to the sole application of organic fertilizers, the use of organic fertilizers together with chemical fertilizers, had a positive impact on microbial biomass and hence soil health (Hati *et al*., 2008). The INM changes the chemical and biological properties in soils, it improves the soil OC and OM content, total N, P, K status, microbial biomass (C and N), and long-term soil productivity in the tropics with low soil OM content. Soil biomass is increased by INM as these amendments supply readily decomposable organic matter in addition to increasing root biomass and root exudates due to better crop growth (Vineela *et al*., 2008). The enzyme activities i.e. the urease and alkaline phosphatase activities of soil increased significantly with a combination of inorganic fertilizers and organic amendments as enhanced enzyme activities are always related to soil OM content (Goyal *et al*., 1999). Studies indicated that incorporation of ammonical fertilizers in soil resulted in reduced N losses through volatilization. The losses of NH_3 volatilization were also reduced with FYM or green manuring combined with urea- N application as compared to the urea-N application alone (Yaduvanshi, 2001). Application of $ZnSO_4$ @ 25 kg/ha/annum is also advised to obtain adequate supply of Zn so that its unavailability could not hamper the crop performance.Some researchers also noticed substantial improvement in OC, available N, P, K and Zn as compared to the initial status of soil, when the rice and wheat crops were supplied with integrated application of gypsum or FYM or green manuring along with 100 % recommended dose of inorganic fertilizers. The results from another study indicated an increase in OC and infiltration rate, and decrease in pH and SAR of sodic water irrigated soil with no-tillage practice as compared to the conventional tillage. The wheat crop sown in non-tilled soils either alone or with residual effects of FYM or gypsum or pressmud also sustained higher yields in RWCS; along with saving irrigation water (7.22 cm), and three disking and plankings. Soil fertility and environment are also closely interlinked. Depletion of soil fertility means degradation of the environment and likewise, its improvement also leads to the better environment. Moreover, if an unbalanced organic fertilizer is supplied at levels that satisfy the demands of the limiting nutrient (S or P), a large surplus of other nutrients, especially N, would be supplied, with a probable risk for leaching (nitrate) or volatilization losses (ammonia), and thereby adversely affecting the environment (Heeb *et al.,* 2005). The INM practices also helps in reducing the emission of greenhouse gases (nitrous and nitric oxides).

Soil OC and N are the main nutrition used for crop growth, and also serve as indices of soil quality assessment and sustainable land use management. Many researchers have shown that soil OC and N content are not only affected by climate, altitude, terrain, but also land use management. Soil OC and total N are higher in treatments receiving a combination of inorganic fertilizers and organic amendments in soils, as compared to sole application of inorganic fertilizers. The highest amounts of both OC and total N were observed in soils supplied with wheat straw, and the least OC and total N were present in unfertilized soils. The C:N ratio of soil decreases with fertilization. The organic amendments performed better in decreasing the C:N ratio compared to inorganic fertilizers. Soil OC and N content provides a measurement OM status in soil. The C:N ratio decrease or increase with organic amendments indicates the build-up of N pool in the soil (Goyal *et al*., 1999). An increase in soil OM with the application of inorganic fertilizers is also observed because of greater input of root biomass due to better crop growth. The FYM and crop residue having higher C:N ratio is less resistant to decomposition; addition of inorganic N (50% of the recommended dose) along with these materials reduced the C:N ratio and enhanced its decomposability (Nayak *et al*., 2012).

Achieving high crop yields with more cropping intensity is needed to raise the total production from the country's limited resources. Since the nutrient turnover in soil plant system is considerably high in intensive farming, neither the chemical fertilizers nor the organic and biological sources alone can achieve sustainable crop production in rice based cropping systems. Even with balanced use of chemical fertilizers, high yield level could not be maintained over the years because of deteriorating soil physical and biological environments due to low soilOM content. Along with an improvement in soil fertility status, the integrated use of inorganic fertilizer and organic manure (FYM) also helped in improving the yield and yield attributes when compared with the totally inorganic fertilization (Sharma *et al*., 2007). Higher amount of N fertilizer is also beneficial in taking good crop yields in rice and wheat crops in sodic soils in initial phases of reclamation. Rice and wheat crops gave the maximum yields when N was applied in three equal splits i.e. application as basal and at 3 and 6 weeks after transplanting/ sowing under sodic water conditions (Yaduvanshi and Swarup, 2005). Studies have also shown that integrated use of gypsum or FYM or green manuring with 100% recommended dose of inorganic fertilizers got significantly higher yields of wheat and rice crop as compared to the application of inorganic fertilizers only. The maximum gross returns and benefit cost ratio (B:C) can also be achieved by integrating the dose of inorganic fertilizer with organic manures. The application of 50 % recommended dose of NPK + 50% N substituted by FYM in wheat and rice crops provided significantly highest B:C as compared to all other treatments (Sharma *et al*., 2007; Gill *et al*., 2008).

Conclusions

To keep the pace of sustainable crop production without depleting the natural resource base seems to be a big challenge under the current scenario. Nutrient cycling in the soil-plant ecosystem is an essential component for sustaining the agricultural enterprise's productions.Integrated nutrient management i.e. combined use of organic and inorganic fertilizer sources, is quite helpful in sustaining the system productivity and soil quality. The INM concept is now being broadened to make it more context-specific for the local environmental conditions, farm mechanization, conservation agriculture, shift towards organic agriculture, and the updated soil maps. An innovative approach like INM can harness natural resources appropriately, bring about food security, and improve the livelihood. The provision of appropriate policies, for e.g. providing incentives to adopt INM, and easy and quality availability of organic inputs will motivate the farmers to adopt INM practically.

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