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REVIEW ARTICLE

Integrated Nutrient Management in Sugarcane

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Abstract Integrated nutrient management holds great promise in meeting the growing nutrient demands of intensive sugarcane agriculture and maintaining productivity at higher levels with overall improvement in the quality of resource base. It helps to improve and sustain soil fertility and provides a sound basis for crop production systems to meet the changing needs. Balanced use of organic, inorganic and biofertilizers is essential to maintain a good soil physical and chemical environment and also serve as energy source for the soil microbial biomass. Sugar productivity can be sustained by replenishing the nutrients removed by crops through proper recycling of crop residues and factory wastes along with biofertilizers. As organic manures often leave profound residual effect, recommendations need to be made on cropping system basis.

Keywords Sugarcane · Integrated nutrient management · Organic manure · Biofertilizers · Balanced fertilization

Introduction

The challenge for agriculture in the coming decades will be to meet the ever increasing demand for food, fibre and energy while maintaining, if not improving soil fertility and productivity. Declining soil fertility, mismanagement of plant nutrients and deteriorating soil physical environment have made this task more difficult. While recycling and transfer of nutrients from non-crop areas, crop residues and animal manures can partially make up for exports of mineral nutrients by harvested produce, application of mineral fertilizers is essential to meet crop requirements and to increase and sustain productivity. The nutrient turnover in the soil–plant system is considerably high under intensive farming and the plant nutrients depleted from the soil due to crop removal and/or soil erosion, need to be supplied through an efficient and effective nutrient supply system (Singh and Yadav 1992) to restore and sustain the fertility and productivity of soils. Integrated nutrient management (INM) is an age-old practice but its importance was not very much realized in the pre-green revolution era due to low nutrient demands of the subsistence agriculture. INM approach improves and sustains soil fertility and provides a sound basis for crop production systems to meet the changing needs (FAO 2001) through optimization of the benefits from all possible sources of plant nutrients in an integrated manner. It envisages exploitation and use of all the available sources of nutrients such as compost, farm yard manure (FYM), oil cakes, crop residues, animal wastes, green manures, green leaf manures, industrial byproducts and biologically fixed nitrogen in conjunction with fertilizer materials. These components possess great diversity in terms of chemical and physical properties, nutrient release efficiencies, potential availability, crop specificity and farmer acceptability.

Nutrient Requirements of Sugarcane

Sugarcane being a long duration crop with C_4 metabolism produces very heavy biomass and demands large amounts of moisture, nutrients and sunlight for its optimum productivity. It has been estimated that the crop removes 0.56–1.20 kg of N, 0.38–0.82 kg of P_2O_5, 1.00–2.50 kg of K_2O, 0.25–0.60 kg of Ca, 0.20–0.35 kg of Mg,

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0.02–0.20 kg Na and 2.0–2.7 kg of SO_4 besides micronutrients for every tonne of cane produced (Zende 1990). An average crop of sugarcane removes 208, 53, 280, 30, 3.4, 1.2, 0.6 and 0.2 kg N, P, K, S, Fe, Mn and Cu respectively from the soil to yield about 100 t of cane ha^{-1} (Singh and Yadav 1996). The nutrient requirement also varies from soil to soil (Natesan et al. 2007) and varietal differences in nutrient use efficiency as determined by the amount of nutrients removed per tonne of cane harvested have also been reported (Rakkiyappan et al. 2004, 2005). According to projections, 450 million t of sugarcane will be produced from an area of 4.50 million ha during the year 2020 and this will deplete 0.90, 0.24, 1.26 and 0.135 million t of N, P, K and S from the soil which needs to be replenished. About 0.88 million t of nutrients comprising 0.70 million t of N, 0.06 million t of P and 0.12 million t of K in addition to 55,000 t of S, 10,000 t of Zn and 5,000 t of Fe will be applied to harvest 450 million t of cane in the year 2020 (Singh and Yadav 1996).

Continuous cultivation of sugarcane removes huge quantities of nutrients from soil. In a virgin soil in Australia, King et al. (1953) found that the N contents were 4.8 g kg^{-1} which was reduced to 2.2 g kg^{-1} after 22 years of sugar cane cultivation. Humbert (1959) reported from Hawaii that sugarcane yields declined due to soil compaction, acidification, nutrient depletion and changes in biological properties of the soils. Changes in soil chemical properties were also reported from sugar cane areas in Fiji (Masilaca et al. 1985), Philippines (Alaban et al. 1990), India (Sundara and Subramanian 1990; Yadav and Prasad 1992) and South Africa (Schroeder et al. 1994). Hartemink (1998) found a decline of topsoil pH by 0.3 units and cation exchange capacity of 34 $mmol_c\ kg^{-1}$. Total N levels declined from 2.5 to 1.9 g kg^{-1} and available P from 36 to 27 mg kg^{-1}. Exchangeable potassium also declined by 1.3 $mmol_c\ kg^{-1}$. The decline in nutrients was severe in the 0–15 and 15–30 cm soil horizons.

Long term experiments on manures and fertilizers in sugarcane were conducted at Anakapalle (Andhra Pradesh), Padegaon (Maharashtra), Mandya (Karnataka), Pusa (Bihar), Muzaffarnagar and Shahjahanpur (Uttar Pradesh). The results (Singh and Roysharma 1968; Singh and Yadav 1994) indicated that: continuous application of ammonium sulphate in alluvial soils having no limiting factors gave higher cane yield than that was obtained with organics; the cane yield was higher with basal application of compost than without it; application of fertilizers increased the cane yield several fold to that without it; green manuring or legumes prior to sugarcane proved useful in producing more sugarcane; application of organics and chemical fertilizers alone failed to maintain the productivity of soils and sugarcane and balanced application of nutrients through an integrated use of organics and chemical fertilizers showed promise in sustaining the cane productivity and fertility of soils. The yield of unmanured sugarcane decreased considerably in the cereal based cropping systems and even fallowing, whereas inclusion of legumes like sunnhemp and lucerne in the cropping systems not only sustained the yield of unmanured sugarcane, but also improved the productivity of manured sugarcane (Singh and Yadav 1996).

Fertilizers

Fertilizer Recommendations

As sugarcane is one of the largest consumers of fertilizers and responds very well to fertilizers, research on nutrient requirement of sugarcane and improving fertilizer use efficiency has received attention since early days. Fertilizer is the most important component of integrated nutrient supply system for sugarcane production as it is responsible for nearly 50% yield increase. The fertilizer recommendations for sugarcane in major sugarcane growing states of India vary from state to state depending upon the soil type, crop duration, yield level and irrigated/rainfed conditions. The doses recommended range from 70–400 kg N, 0–80 kg P_2O_5 and 0–141 kg K_2O ha^{-1} (Singh and Yadav 1996). The fertilizer doses recommended are generally higher in tropical states compared to subtropical states. Saini et al. (2006) also reported that application of nutrients up to 400 kg N, 170 kg P and 180–190 kg K ha^{-1} is recommended for sugarcane depending upon its duration and fertility status of the soil.

Fertilizer-Use Efficiency

Nitrogen flux pathways in the soil are beneficially influenced by the management techniques including mounding of the rows, subsurface banding in narrow fertilizer bands, reduced fertilizer rates, trash retention and timing of fertilizer application to coincide with conditions optimum for uptake by the plant (Reghenzani et al. 1996). The nitrogen use efficiency depended upon initial available N status, N applied and site variability for soil and climate (Chattopadhyay et al. 2004). Generally under farmers' field conditions, the use efficiency of applied nitrogenous fertilizers is very low and ranges from 30 to 40% (Singh and Yadav 1996). Nkrumah et al. (1989) also reported that nitrogen use efficiency hardly exceeded 40% in sugarcane. Based on ^{15}N isotopic studies, Vallis et al. (1996) have reported that crop recovery of fertilizer nitrogen applied as subsurface bands was in the range of 20–40%. Gava et al. (2005) reported that nitrogen use efficiency of urea by the sugarcane ratoon was 21%. Ambrosano et al. (2011) reported that the recovery of N by the first two consecutive harvests accounted for 19–21% of the N applied as leguminous green manure and 46–49% of the N applied as ammonium sulphate. Cesar et al. (2011) reported that 15.9% of total nitrogen uptake by shoot was from ^{15}N-urea. Reports from Brazil indicated that nitrogen derived from fertilizer (NDDF) contributed up to 40% of the total N in the plant cane at initial stages of development and decreased to approximately 10% of total N at harvest. In the first ratoon, application of N fertilizer was more effective for crop nutrition, constituting up to 70% of total N in initial stages of development and decreasing to approximately 30% at harvest (Franco et al. 2011).

The major pathways of nitrogen losses are leaching of nitrates, volatilization of ammonia from soil and crop tops, denitrification as nitrogen oxides and crop uptake (Dey 2003). The loss of nutrients is also influenced by soil types. Isa et al. (2006) reported higher recovery of applied nitrogen in a non saline soil. In a saline soil, recoveries were lower but depended on the form of N, being lower with urea than with ammonium sulphate. Leaching and gaseous losses were reported to be major nitrogen loss pathways in plant and ratoon crops of sugarcane in Australia (Reghenzani et al. 1996). Allen et al. (2010) estimated that between 1.0 and 6.7% of applied N fertilizer was emitted as N_2O from subtropical sugarcane soils in Australia. Freney et al. (1992) reported that in the dry climatic zone of Australia, there was a slow but steady pattern of ammonia loss over a period of 6 weeks resulting in losses of 32 and 39% of the applied nitrogen. In the wet zone, heavy rainfall apparently washed the urea from the trash layer into the soil and limited ammonia loss to 17%. Experiments conducted at Hawaii (Davidson et al. 1996) revealed that the highest nitrification potentials and N_2O emissions occurred near irrigation lines and the lowest values between plant rows. Production of N_2O was controlled primarily by 'when and where' fertilizers were applied. Weier et al. (1996) reported that denitrification was a major cause of fertilizer nitrogen loss from fine textured soils, with nitrous oxide being the major gaseous N product when soil nitrate concentrations were high. In an ultisol in Brazil, 15% of applied N was leached N (Ghiberto et al. 2009). Average recoveries of applied nitrogen for different sources of fertilizers was reported to be in the following order: ammonium sulphate (27.3%) > potassium nitrate (23.0) > urea (19.0%) while for soil types the order was loamy sand (25.9%) > loam (20.5%) (Dey 2003).

Nitrogen

Nitrogen is the primary nutrient influencing the yield and quality of cane. Response to applied nitrogen is universal. Nitrogen increases the source capacity, namely leaf area index, leaf area duration, early canopy closure and the rate of photosynthesis (Hunsigi 1993). An increased sugarcane yield following nitrogen addition is attributed to the increased number of tillers and yield attributes like stalk length, stem diameter and number of millable canes (Abayomi 1987). Gascho et al. (1986) observed that foliar nitrogen concentration should be maintained above 15 g kg^{-1} throughout the grand growth phase for optimum yield. Each kg of soil-applied nitrogen had given a yield response of 0.07–0.35 t of cane (Yadav and Singh 1995). Seasonal nitrogen use efficiency was estimated at 0.841 t of cane kg^{-1} N (Chattopadhyay et al. 2004). Rates of nitrogen application in the various sugarcane growing countries of the world range from 50 to 300 kg N ha^{-1} and 1 kg of nitrogen results in an approximate response of 0.5–1.2 t ha^{-1} (Hunsigi 1993). Verma (2004) summarized the response to nitrogen application observed in experiments conducted all over India. The nitrogen need of sugarcane varied from 67.5 to 450 kg ha^{-1} because of variations in soil type, crop duration and water availability. It is generally lower (100–225 kg N ha^{-1}) for subtropical India in comparison to tropical states (100–450 kg N ha^{-1}). Jadhav et al. (1997) reported response up to 400 kg N ha^{-1} in pre-season sugarcane while for *suru* sugarcane 304 kg ha^{-1} was found optimum (Sondge et al. 1992). Lakshmikantham (1983) suggested that as a simple rule of thumb, 1 kg N t^{-1} of cane expected is given for plant cane and 1.25–1.50 kg N t^{-1} of cane expected for ratoon crops. The optimum for ratoons is at least 25% greater than that for plant cane.

Nitrogen deficient canes show uniform yellowing of the leaves, retarded growth, stalks of smaller diameter, premature drying and senescence of old leaves (Humbert and Martin 1955). Excess application of nitrogen not only brings down cane yield but also adversely affects the cane juice quality (Singh and Yadav 1996). Production of water shoots with higher reducing sugar content under high and late nitrogen application also lowers juice quality. The detrimental effect of higher dose of N on juice quality is also attributed to the accumulation of nitrogenous substances and reduction in P_2O_5 content (Srinivasan 1995). Chiranjivi Rao et al. (1974) reported depression in cane yield and sugar content at higher levels of N application in the variety Co 6304. Excess application of nitrogen makes the plants succulent and soft, which become more susceptible to pests and diseases. The crop also tends to lodge because of heavy top (Verma 2004).

Varieties differ widely in their nutrient requirement. Considerable differences in the response of sugarcane varieties to applied nitrogen has been reported from Tamil Nadu (Srinivasan 1995) and Andhra Pradesh (Naga Madhuri et al. 2011). Nicole et al. (2007) reported considerable genetic variation for internal nitrogen use efficiency (iNUE i.e., biomass produced per unit tissue N) in sugarcane. When nitrogen was applied in graded doses, the varieties showed a differential response and at Pravaranagar in Maharashtra, for the same dose of fertilizer N, midlate varieties showed higher response than early varieties (Zende 1984). The optimum levels of N were found to be 270, 275, 300, 239, 279 and 302 kg ha^{-1} for varieties Co 86002, Co 86027, Co 86032, Co 86038, Co 87025 and Co 87044, respectively based on quadratic analysis (Ramesh and Mahadevaswamy 1996). Srinivasan (1993) showed that absolute production was higher with better conversion efficiency in varieties which respond more to first 100 kg N ha^{-1} as was the case with Co 8145. The nitrogen use efficiency in different varieties ranged from 206 to 454 kg cane kg^{-1} applied nitrogen.

Sugarcane crop does not show any marked preference to different sources of fertilizers except under specific conditions (Blackburn 1984). Salgado Garcia et al. (2001) using isotopic methods compared the efficiency of different sources of nitrogen and concluded that there were no significant differences in Fertilizer Nitrogen Recovery Efficiency among ammonium sulphate, urea and potassium nitrate. However, Schumann (2000) reported that though calcium ammonium nitrate, ammonium sulphate and urea suffered similar field losses of nitrate-nitrogen by leaching and denitrification, urea was subjected to additional ammoniacal-N losses by volatilization in both acid and alkaline non-irrigated soils. However, since all sources of fertilizer N are equally effective in producing cane yield under field conditions, the choice for using a fertilizer rests on its relative cost and availability (Singh and Yadav 1996). Urea is the most commonly used fertilizer and on equal N basis, cane yield and juice quality are not influenced by the different nitrogen carriers. However, source of fertilizer plays a significant role in saline soils. Application of urea in a saline soil led to a reduction of more than 50% in dry matter due to low N recovery (34%) as compared to ammonium sulphate where the recovery was higher (Isa et al. 2006). Attempts have also been made to improve the use efficiency of applied nitrogen through slow release nitrogenous fertilizers and nitrification inhibitors. Urea super granules, tar coated urea, sulphur coated urea, urea blended with neem or karanj cake, etc., have been tried in several locations. In most of the cases, they helped to save 50–100 kg N ha^{-1}, simultaneously increasing the yield of sugarcane (Hunsigi 1993; Srinivasan 1995; Verma 2004). However these slow release fertilizers were not better than the traditional prilled urea (PU) in terms of ratoon yield as these fertilizers did not leave significant N residues for the subsequent ratoon crop (Yadav 2008). Coating of urea by sulphur increased its efficiency for sugarcane only when applied on the surface of a calcareous soil (Dalal and Prasad 1975). Yadav et al. (1990) reported that uptake and recovery of N were significantly greater using urea super granules, neem-cake-coated urea and dicyandiamide-treated urea than using the traditional source of prilled urea. It is possible to reduce nitrate-nitrogen leaching to ground water by application of LPS160, a controlled release N-fertilizer and N application rates by 40% without any yield reduction (Masuda et al. 2003). However, owing to their high cost, the acceptability of slow release fertilizers is very low.

Phosphorus

Phosphorus is essential to hasten the formation of shoot roots and to increase tillering but its availability depends on the fixation of native and applied P. Improved yield following P application is attributable to an increase in tiller production, weight per cane and final stalk population. At optimum level of P application, sugar content and purity of juice are also enhanced (Elamin et al. 2007). Several studies in the past have indicated that sugarcane does not respond significantly to application of phosphorus (Singh and Yadav 1996) or the response is erratic (Verma 2004). However, in an experiment conducted at Indian Institute of Sugarcane Research, Lucknow significant response in terms of improvement in cane yield due to soil as well as foliar application of phosphorus in plant as well as ratoon crops has been reported.

In several experiments, applied phosphorus did not influence yield or quality of sugarcane ratoon to an appreciable extent due to the fact that in most of the cases, the soils were high in available phosphorus status. However, the need for phosphate application ranging from 30 to 100 kg P_2O_5 ha^{-1} has been reported. In general, ratoon crop of sugarcane is relatively more responsive to P application than the plant cane as observed at Mandya (Karnataka), pockets of Haryana and Jalandhar and Kheri in Punjab. Andreis and McCray (1998) reported significant positive sugar production responses to P application in the ratoon crops, demonstrating the importance of maintaining adequate soil P levels. In Bihar (Pusa) application of 35.0 kg P ha^{-1} to sugarcane recorded significantly higher mean growth (tillers, cane length, and leaf area index), yield attributes (millable canes, single-cane weight and cane diameter) and cane yield (Navnit Kumar and Sinha 2008). Experiments conducted at Florida Histosols revealed positive responses to both cane and sugar yields (McCray et al. 2010), but the results also indicated the need for an updated soil test calibration that should be applicable over a wide pH range. Ratoon yield response per kg of P_2O_5 ranged from 75 kg at Mandya to 263 kg at Jalandhar (Verma 2002).

Deficiency of P results in stunted stalks, reduced tillers, narrow leaves, restricted root development and slow growth. According to Hunsigi (1993), P deficiency is manifested by poor tillering and rooting, delayed "close-in" and shorter internodes which taper rapidly at the growing point. Phosphorus is generally applied as a single dose at the time of planting. Soluble P sources like single super phosphate, diammonium phosphate etc. should preferably be placed in bands near the seed pieces or "setts" to minimize fixation. But insoluble sources like powdered rock phosphate (RP) should be thoroughly mixed with the soil.

Potassium

Potassium fulfils a number of important roles in plant growth and metabolism. Its role in regulating the uptake of water and leaf stomatal opening, maintenance of cell turgidity and formation of proline during moisture stress is of particular interest in view of the periodic drought conditions that affect the sugar industry. Potassium is also essential for the synthesis and translocation of proteins and carbohydrates and for accumulation of sucrose. Agronomic value of K rests with increased cane volume, girth and weight per cane, drought and disease resistance and reduced lodging. K application often increases the percentage of sugar in the cane and juice recovery, particularly when harvest is delayed (Hunsigi 2011).

Response to K application in terms of yield increase or better juice quality is generally not common. Based on a critical review of the response of sugarcane to K fertilizers, Verma (2004) recommended application of 50–200 kg K_2O ha^{-1} in tropical states where significant response is observed. But responses were very limited in subtropical states. However, application of 66 kg K_2O ha^{-1} with irrigation water in the standing plant cane before harvest improved bud sprouting, dry matter accumulation and nutrient uptake in ratoon crop in subtropical India (Shukla et al. 2009). In several field experiments conducted all over India, it has been reported that ratoon sugarcane rarely responds to applied potassium except in some localized areas of Karnataka, Tamil Nadu and Andhra Pradesh. This lack of response is reported to be due to the sufficient K reserves in the soil and the exchange reactions among various forms of potassium in the soil (Verma 2002). Ng Kee and Deville (1989) opined that in areas with a rainfall of less than 2000 mm annum^{-1}, K fertilizer banded in the rows at planting can meet the requirements of six sugarcane crops. In Brazil, significant response to K application in terms of sugarcane growth, shoot number, cane yield and sugar yield was reported by Otto et al. (2010).

Deficiency of potassium is seen first in older leaves and the leaf margins, and tips become brown with necrotic spots, which coalesce and show typical "marginal firing" (Hunsigi 1993). The excess K in plant tissues may interfere in sugar processing due to scale formation in pans (Hunsigi 2011). Meyer and Wood (2001) also indicated that excessive potassium uptake and high K level in the juice might influence the exhaustibility of final molasses and the colour and ash content of raw sugar.

Method of Fertilizer Application

Adoption of proper method of fertilizer application is essential to minimize the loss of nutrients from the soil and to increase fertilizer use efficiency. Besides increasing cane yield, proper placement also reduces volatilization loss of nitrogenous fertilizers and lowers fixation of phosphatic fertilizers. Placement can be made by making 8–10 cm deep furrows on either side of the cane rows using implements, placing the fertilizers in the furrows and then covering them. Proportion of fertilizer nitrogen recovered in the crop was 33% when urea was buried in the soil, but it was only 18% when urea was broadcast (Chapman et al. 1994).

Foliar feeding of nitrogen as urea in sugarcane is a well recognized technique. Foliar application can be resorted to under adverse soil moisture conditions like water logging and limited water supply situations. The use efficiency of foliar applied nitrogen could be as high as 90–95% (Singh and Yadav 1996) and foliar spray helps to save about 20–30% fertilizer nitrogen (Srinivasan 1995). Application of 180 kg N ha^{-1} through soil in two splits at 30 and 60 days and a third dose of 50 kg N ha^{-1} as foliar spray at 90 days was found equal to the soil application of 270 kg N ha^{-1} both for cane yield and juice quality in three splits under sub-tropical conditions. Foliar application of urea with potash during the formative phase [2.5% each of urea and KCl at 60, 90 and 120 days after planting (DAP)] was found to be beneficial when moisture was limiting and increased cane yield by 18.6% over control. Soil application 75% K and foliar application of the remaining 25% at 90 DAP was found beneficial under Kerala conditions where soils are having poor K status (Mathew et al. 2004).

Fertigation can be a more efficient means of applying crop nutrients, particularly nitrogen and potassium, so that nutrient application rates could be reduced in fertigated crops. Thorburn et al. (2003a) studied the response of cane and sugar production to different N rates (0–240 kg ha^{-1} year^{-1}) applied through drip fertigation in Australia. The cane and sugar yields were not significantly increased by applying more than 80 kg ha^{-1} of N through drip irrigation, whereas the recommended dose for conventional irrigation systems was 160 kg ha^{-1} year^{-1}. They suggested that the high soil water contents maintained with daily application of irrigation water through the trickle system promoted mineralisation of soil organic matter and stressed the need to avoid over-application of N in fertigated sugarcane. Simulation studies showed that benefits of sub-surface application of water and N will be either a saving in N fertilizer for a similar yield or an increase in yield for similar N inputs (Thorburn et al. 2003b). Productivity can be maintained and N losses to the environment can be minimized in fertigated sugarcane with a 25–50% reduction in N fertilizer compared to conventional systems (Thorburn et al. 2000). Kwong et al. (1999) using ^{15}N labeled fertilizer found that under the soil and climatic conditions prevailing in Mauritius, fertilizer nitrogen rates in sugarcane could be reduced by 30% by adopting drip irrigation. For drip irrigated sugarcane in Southern Africa splitting nitrogen applications evenly over the first 4 months of crop development was found to be more efficient (Butler et al. 2002). The economic benefit from applying the liquid fertilizer to sugarcane was found significant (Tang et al. 2006).

Raskar and Bhoi (2001) in their studies found that the yield obtained due to application of 75 and 100% of the recommended dose of fertilizers was on par indicating 25% saving in fertilizer. The quality parameters viz., Brix, pol, purity and CCS percent were improved with increasing levels and number of splits of fertigation. In a medium black soil in Belgaum district (Karnataka), drip fertigation of N and K at 6-day intervals from 30 to 240 DAP produced 24.34% higher yield and saved 46.52% more water compared to surface irrigation with the recommended dose of fertilizers. Quality parameters such as Brix, pol and commercial cane sugar percent were not affected by fertigation (Rajanna and Patil 2003).

Time of Fertilizer Application

The time of fertilizer application assumes great significance in maximizing the benefits. According to van Dillewijn (1952), maximum amount of nitrogen is absorbed within 90 DAP. Therefore for a 12–14 month crop, nitrogen should be applied within 60–90 DAP. When nitrogen is applied within 90 days, two or three splits are made depending on the soil type, with sandy soils receiving three splits, while loams and sandy loams receive nitrogen in two splits (Hunsigi 1993). Singh and Yadav (1996) reported that application of N in two or three splits within 45–90 DAP increased the nitrogen use efficiency of sugarcane in tropical and subtropical conditions and recommended application of nitrogen in three equal splits at planting time, soon after germination and before the onset of monsoon for obtaining the highest cane yield. For a 2-year crop, or for areas with two rainy seasons a late supplementary N application is beneficial. Extending nitrogen application up to 135 days had favourable influence on seed quality with lower sucrose and higher glucose content in seed cane (Lakshmi et al. 2006). Delayed N application may result in late tiller production and prolongation of the maturity phase with greater accumulation of reducing sugars. This may result in poor juice quality. Reduction in quality may be associated both with too high a rate and with delayed application of N. Experiments conducted at Tamil Nadu Agricultural University (Srinivasan 1995) have established the adverse effect of late application of nitrogen not only on juice quality, but also on cane yield.

Fertilizer Management in Ratoon

Ratoon crops follow the plant crop or the preceding ratoons on the same soil. Due to the impoverished soil physical conditions and relatively poor root system development, absorption of nutrients by the ratoon cane may also be affected. It is necessary that ratoons are given adequate quantities of manures and fertilizers to get good yields. Several experiments have proved the need for early fertilizer application to ratoon sugarcane. For ratoon crop, nitrogenous fertilizers may be applied in two or three splits. Even in cases of split application, 1/3 to half the dose of N should be applied immediately at the time of ratoon initiation to ensure adequate amount of available nitrogen in the soil to overcome the temporary immobilization of nitrogen due to microbial activity on the decomposing stubbles. Full dose of phosphorus should be applied at the time of first dose of N application at ratoon initiation (Verma 2002). To produce 1 t of ratoon cane, more nitrogen is required than in the plant crop. The nutrient use efficiency is also reported to be the highest in plant cane and it decreases with successive ratoons. Reduced nutrient use efficiency in ratoons is ascribed to an imbalance in the shoot–root ratio at the juvenile stage, delayed shoot–root development and relatively inefficient stubble roots. Response to higher level of nitrogen application in the ratoon crop has been reported from all the sugarcane growing states. It has been found that ratoon crop generally needs 25–50% more nitrogen than the plant cane. Application of 25% extra nitrogen 5–7 days after ratoon initiation operation produced the highest cane and sugar yields in Tamil Nadu (Mahendran et al. 1995). Yield response to applied nitrogen at the recommended dose in the case of ratoon sugarcane was reported to be 254 kg of cane per kg of applied nitrogen at Anakapalle, 215 kg at Kanpur, 160 kg at Shahjahanpur, 160 kg at Muzaffarnagar, 136 kg at Mandya, 120 kg at Lucknow and 119 kg at Jalandhar (Verma 2002).

Fertilizer Management Under Moisture Stress

Under moisture stress, fertilizer application should aim at development of a deeper root system and adequate tillering before the stress sets in. Therefore basal manuring of phosphorus along with small quantities of N and K, followed by an early N and K top dressing may be desirable. This may be followed by another top dressing with the last irrigation before the stress period. Final manuring should be done soon after the stress is over. When moisture stress was imposed only for a short period of 6 months (Wiedenfeld 2000), response to N application was not affected and no significant interaction between irrigation treatments and nitrogen application rates was observed. However, when moisture stress was induced throughout the growing season, irrigation level had a strong influence on the quality responses to nitrogen application (Wiedenfeld 1995). Under drought conditions, cane and sugar productivity could be improved with the application of potassium. Naidu et al. (1983) reported 30.8 and 28.2% increase in cane and sugar yields in sandy loam soil due to application of K under drought conditions. The increase in loamy soil was however less, being only 5.9% for cane yield and 5.0% for sugar yield. Combined application of urea and muriate of potash each at 2.5% concentration during the drought period at 15–20 days interval is helpful to retain more number of vigorous shoots till the moisture condition becomes favourable.

Improving Fertilizer Use Efficiency Through Soil Testing and Tissue Analysis

Attempts have been made to improve the fertilizer use efficiency through several approaches like soil and tissue analysis, DRIS, simulations, computer programmes, etc. besides adjusting the time and method of application.

Fertilizer recommendations based on soil and leaf analysis have provided a useful guide for determining the nutrient requirements of cane (Wood 1990). Foliar nutrient analysis is a useful diagnostic tool to complement soil testing as a best-management practice with sugarcane (McCray et al. 2010). Leaf analysis has the potential to play a more vital role in cane growers' fertility programs. A plant nutrient-response curve typically includes a response range—linear increase in growth with increases in the supply of the nutrient, a sufficiency value—the point on the response curve above which luxury consumption occurs, and sufficiency range—further increases in nutrient supply result in no further growth increase (Gauch 1972). The critical concentration of a nutrient is the point at which growth is reduced by 5 or 10% from optimum and below which deficiency symptoms appear (Ulrich and Hills 1973). Sugarcane leaf nutrient critical values and optimum ranges suggested by University of Florida are given in Table 1 (McCray et al. 2009).

Table 1 Sugarcane leaf nutrient critical values and optimum ranges

Nutrient	Critical value (%)	Optimum range (%)
Nitrogen (N)	1.80	2.00–2.60
Phosphorus (P)	0.19	0.22–0.30
Potassium (K)	0.90	1.00–1.60
Calcium (Ca)	0.20	0.20–0.45
Magnesium (Mg)	0.12	0.15–0.32
Sulfur (S)	0.13	0.13–0.18

There is a need to take into account the cultivar differences, age of the crop at sampling, climatic conditions and soil properties when interpreting leaf analytical data (Schroeder et al. 1999). However, Morris et al. (2005) were of the view that leaf P concentrations could not provide accurate P fertilization rates that will give maximum sugarcane yields and prevent over-fertilization of P in organic soils of Florida.

The concept of 'crop logging' based on critical nutrient concentrations and standardizing index tissues for sampling was developed by Clements (1980) as a comprehensive system to guide fertilizer application in sugarcane. For crop logging purposes, nitrogen content of 3–6 leaf blades and P, K and moisture contents of 3–6 leaf sheathes are generally estimated and the indices are used to fix the critical levels and for making recommendations on economic use of fertilizers and irrigation water to improve yield and ripening of the crop. In India, research work on crop logging in sugarcane was carried out at Anakapalle, Padegaon, Rudrur and Cuddalore. However, due to vast differences in soil and climatic conditions, this method could not become popular (Verma 2004).

Attempts have also been made to work out fertilizer requirement of sugarcane for different yield targets. Soil test crop response studies were conducted to work out efficiency of soil and fertilizer nutrients and to make fertilizer recommendations based on targeted yield (Prasad et al. 1984; Murugappan et al. 1988). Soil efficiency, fertilizer efficiency and targeted yield equations have been worked out for different varieties. Site specific fertilization based on soil analysis and crop nutrient requirement gave higher cane yield and improved the sugar recovery and relative economic benefit than blanket recommendation and farmer's practice (Phonde et al. 2005).

Meyer (1981) had tested the Diagnosis and Recommendation Integrated System (DRIS) originally developed by Beaufils (1973) to estimate fertilizer recommendations for sugarcane in South Africa, Brazil, Florida and Hawaii. In this method, ratios of tissue nutrient concentrations are used to work out DRIS indices, which help to diagnose not only nutrient deficiencies, but also imbalances. DRIS is insensitive to factors like age, position of leaf, cultivar, etc.

and therefore it is a more efficient tool for nutrient management. It is also especially suited to reveal antagonism among the nutrients. DRIS approach allows more flexibility in time of sample collection compared to the critical value approach (Beaufils 1973; Beaufils and Sumner 1976; Meyer 1981). A low number of leaf samples are sufficient to develop norm data banks and preliminary DRIS norms for nutritional diagnosis of sugarcane (Galíndez et al. 2009). But the DRIS norms should be locally calibrated. Norms developed under one set of conditions only should be applied to another if the nutrient concentrations of high-yielding plants from these different set of conditions are similar (Reis et al. 2002).

Gaddanakeri et al. (2007) suggested the use of Leaf Colour Charts for efficient nitrogen management in sugarcane. Thorburn et al. (2011) suggested 'N Replacement system' which relies on soil N cycling to 'buffer' differences in crop N needs and N fertilizer supply to individual crops, and aligns N applications with actual cane production over the longer-term rather than potential production for efficient N management. An integrated approach encompassing the concepts of understanding soils and soil related processes, regular soil testing, adoption of soil-specific nutrient guidelines, leaf analysis and good record keeping termed as "Six Easy Steps approach" is being popularized in Australia (Schroeder et al. 2005).

Prammanee et al. (2005) have developed a computer programme, CaneFert 1.0, to accurately determine recommendations for the application of N, P and K using the properties of the soils under sugarcane production throughout Thailand. The programme involves cane growth simulation using CANEGRO 3.5 to determine the effect of water and nitrogen and economic analyses of chemical fertilizer recommendations. The recommendations generated by CaneFert 1.0 have been confirmed by validation trials. Similar attempts have also been made in Brazil (Palma Lopez et al. 2002) to derive fertilizer recommendations for different soil types based on expected yields in each soil type, dry matter production, nutrient accumulation and nutrients supplied by soil as well as fertilizer efficiency. Van Der Laan et al. (2011) suggested that Canegro-N can be used to improve our understanding of N dynamics in sugarcane production systems and to guide management practices and future research.

Organics

Manuring soils is a common agricultural practice since time immemorial. With the advent of chemical fertilizers, the essentiality of organic manures has been forgotten. With declining soil organic carbon status, the response to applied fertilizers is dwindling and the crops are suffering from unbalanced nutrition and harsh physical and chemical environments. Hence, integration of chemical and organic sources is the right option for the present agricultural and socio-economic scenario. Their efficient management has shown promise in not only sustaining the productivity and soil health, but also in meeting a part of chemical fertilizer requirement of crops (Rabindra et al. 1990; Hegde and Dwivedi 1993). Sugar productivity can be sustained by replenishing the nutrients removed by crops through proper recycling of agricultural wastes (Sumner 1999). Integrated application by nutrients recycling from organic wastes of press mud at 10–20 and rice mill ash at 10 t ha^{-1} along with 25–50% reduced chemical fertilizers (N, P, K, S and Zn) gave higher yields in plant and ratoon sugarcane and higher economic return (Paul and Mannan 2007).

FYM and Compost

Organic manures like FYM and composts have been traditionally important inputs in crop production for maintaining soil fertility and yield stability. Long term studies (Joshi and Zende 1971; Singh and Yadav 1994) have indicated the necessity for basal application of FYM or compost for maintaining optimum soil fertility status. Integrated use of mineral fertilizers with organic manures also helps to arrest the decline in cane yield. Several experiments have been conducted in almost all the sugarcane growing states to study the response of sugarcane to the application of 25 t of FYM per hectare (Kailasam 1999). The mean response in terms of increased cane yield in different states ranged from 3.7 t ha^{-1} in Bihar and Gujarat to 11.7 t ha^{-1} in Andhra Pradesh. The overall average response was of the order of 8 t ha^{-1} of cane.

At Mandya, integrated use of ammonium sulphate (250 kg N ha^{-1}) and 25 t FYM ha^{-1} increased the cane yield to 120 t ha^{-1} from 108 t ha^{-1} and organics application tended to improve the quality. The permanent manurial experiments conducted at Sabour (Bihar), Chingusalu (W.B.), Gurdaspur (Punjab) and Kanpur (U.P.) have shown that application of 18.7 t FYM ha^{-1} increased the soil organic carbon by three times (1.23%) compared to control (0.37%) (Singh and Yadav 1994). Consequent to the addition of organic manures, the augmented microbial activity can tap the N from the atmosphere, reduce the leaching loss of N and regulate the supply of P. Although vast potential lies in the country for production and use of FYM and composts, it is not being harnessed fully.

Legumes

Legumes in sugarcane farming systems are grown either in sequence or as intercrops for green manuring, grain or fodder. With the easy availability of fertilizers and adoption of highly intensive cropping systems, the practice was almost given up but there has been a revival of interest in green manuring in recent years. Sunnhemp and Sesbania are the most common green manure crops in India. Misra (1971) reported that leguminous green manure crops added 41–71 kg N ha^{-1} and increased the yield of spring planted cane in subtropical India by 27–43% over monsoon fallow. It was further reported (Misra 1971) that on equal N basis, green manuring was as effective as fertilizer and twice that of FYM in increasing cane yield. The observed response was 2.43, 2.25 and 0.97 q of cane per kg of additional N in the case of green manuring, chemical fertilizer and FYM, respectively. Integrated use of green manure crops with mineral fertilizers increased the use efficiency of nitrogenous fertilizers and reduced the N requirement of sugarcane by 41–85 kg ha^{-1}. Sugarcane after sunnhemp green manuring produced 29.3% higher yield than that after maize at Pusa (CSRS 1959). Singh (1965) resolved the green manure effect into two components namely 'green matter effect' and 'legume effect', both of which were additive and nearly equal.

Sugarcane, being a slow growing crop grown in wider row spacing is amenable for raising a short duration, quick growing intercrop like a green manure or a pulse crop which can be of great advantage in fixing atmospheric nitrogen and adding organic matter to the soil. Erect growing, short duration and dwarf varieties of leguminous crops are more suitable for intercropping (Singh and Yadav 1992). The intercropping of pea, lentil and methi with autumn sugarcane and mung bean, cowpea and urd bean with spring sugarcane are better options to augment soil productivity under subtropical conditions (Saini et al. 2006). After the harvest of the grains of the leguminous intercrops, the crop residues could be incorporated into the soil and part of the fixed N will be available to the sugarcane crop by the decomposition of root system including root nodules and the residues. It has been estimated that green manure intercrops like daincha and sunnhemp can add 7.3–7.6 and 4.8–5.0 t of green biomass per hectare respectively when 75–100% of the recommended dose of fertilizers was applied. Sunnhemp intercropped for green manure purposes in sugarcane produced a green biomass of 12.6 t ha^{-1} by 45 DAP and 15.5 t ha^{-1} by 60 DAP, which added substantial amounts of nitrogen (Kailasam 1999). Contrary to the above reports, Singh et al. (2003), in their study on intercropping of two rows of daincha for green manure purposes in sugarcane grown at 90 cm row spacing and incorporation at 60 days after sowing, observed decrease in the yield of plant crop of sugarcane by 6.8 t ha^{-1} due to reductions in biomass accumulation, leaf area and tiller numbers. However, in situ intercropping significantly increased the ratoon cane yield and improved soil organic carbon content. Growing of intercrops with sugarcane also prevented the leaching of nitrate-N due to ramification of roots leading to higher nitrogen utilization (Singh and Yadav 1996). Singh et al. (1993) have reported that intercropping of green manure legumes along with or without nitrogen application had a beneficial effect on the yield of late planted sugarcane and its first ratoon and had shown potential for effecting fertilizer-N economy. Incorporation of intercropped legume residues improved cane yield substantially and was associated with increased mineralisable N for up to 6 months (Hunsigi 1993). Though green manure intercropping with *Sesbania aculeata* did not improve the of plant crop of sugarcane, the ratoon yields were increased by 9–10% through increased number and length of millable canes (Yadav and Yaduvanshi 2001). *Crotalaria juncea* contributed more nitrogen to the soils (56.7 kg N ha^{-1}) when ploughed down than *Sesbania aculeata* (40 kg N ha^{-1}).

Garside et al. (1999) reviewed the potential for legumes in sugarcane cropping systems in Australia and concluded that legumes could be more widely used in the cropping systems with benefits in terms of nitrogen nutrition of sugarcane, amelioration of yield decline and direct cash benefits if grown as cash crops. Careful management, selection of right species and end use (grain or green manure) for local climatic conditions were the important considerations in maximizing the benefits. Grain legumes between two sugarcane cropping cycles led to a positive soil N balance. Groundnut stover added 146 kg N ha^{-1} to the soil (Hemwong et al. 2008). Treatments containing green manure plus mineral N changed the soil attributes by increasing Ca and Mg contents, sum of bases, pH and base saturation and decreased potential acidity (Ambrosano et al. 2005). Park et al. (2010) opined that inorganic N fertilizer to the plant crop of sugarcane crop can be substantially reduced, or even eliminated by 'good' legume fallow crop that is not harvested. Potential reductions in fertilizer application rate could be up to approximately 100% in the first ratoon and 60, 25 and 10 in the subsequent ratoons. Umrit et al. (2009) estimated that N returns to soil from leguminous green manure crops ranged between 100 and 267 kg N ha^{-1} of which between 50 and 70% was obtained from biological fixation and suggested that current rate of fertilizer N for plant and first ratoon cane following a leguminous green manure crop may be reduced by half without a loss in the yield. But organic matter, total N, available P and S of the soil was only slightly increased by the incorporation of green manures (Bokhtiar et al. 2003).

Crop Residues and Recyclable Wastes

India has a vast potential of crop residues and farm/industrial wastes such as rice or wheat straw, rice husk, sugarcane trash, non-edible cakes, pressmud, forest litter, water hyacinth, etc. According to an estimate, only about one-third of the residue potential is available for utilization in agricultural production. The estimated residue production from sugarcane is about 85 t ha^{-1} (Ernest and Buffington 1976). The availability of sugarcane crop residues in India was estimated as 15.6 million t with an average nutrient content of 0.45, 0.08 and 1.20% NPK, respectively and nutrient potential of 0.27 million t (Bharadwaj and Gaur 1985). Verma and Yadav (1988) reported a saving of 66 kg N ha^{-1} due to intercropping with potato, which was primarily due to incorporation of potato residues. The optimum N doses worked out for sugarcane were 152, 175, 186 and 213 kg ha^{-1}, when grown in association with potato, coriander, mustard and wheat fertilized with 120, 150, 60 and 100 kg N ha^{-1}, respectively.

Sugarcane Trash

During crop growth cycle, sugarcane leaves a large amount of recyclable residues in the field in the form of root biomass and stubbles (6–8%) and dry leaves called trash (7–10%) (Yadav 1995), which have a key role in maintaining soil organic carbon. The gross input of carbon by the sugarcane crop was estimated to be 11.7–12.4 t ha^{-1} year^{-1} (Suman et al. 2009). Trash is a useful source of plant nutrients and contains 0.42% N, 0.15% P and 0.57% K besides 26, 2045, 236 and 17 ppm of Zn, Fe, Mn and Cu, respectively (Yadav et al. 1987). At many places, farmers prefer to burn the trash before harvest for convenience and even after harvest due to handling difficulties and its decomposition is not as easy as that of other crop residues. During burning of sugarcane trash, large amounts of C, N and S, present in the plant residues are lost via volatilization (Hemwong et al. 2009).

Trash could be recycled as mulch or converted into organic manure by proper composting. It also offers scope for rearing earthworms and production of vermicompost. The trash can also be used as a substrate for growing oyster mushrooms and the spent waste can be used as organic manure. Compost making from sugarcane trash is a slow process due to its very high C:N ratio. Many fungal cultures, viz. *Pleurotus* and *Trichoderma viride* have been found to hasten the process of trash decomposition and improve the compost quality. Sprinkling of urea (5 kg t^{-1} of pressmud) to reduce the C:N ratio and fresh cow dung (50 kg t^{-1} of pressmud) as a starter quickens the composting process. The time required for decomposition and composting is 15–20 weeks (Rakkiyappan 1995). Half decomposed mixture of trash and pressmud in the ratio of 1:2 can also be used for the preparation of vermicompost. Sugarcane trash mulching significantly decreased surface bulk density and electrical conductivity and increased soil organic carbon, soil moisture and cane yield compared to unmulched control (Dahiya et al. 2003). Rana et al. (2002) reported that organic carbon content of soil declined with removal (1.27%) and burning of trash (1.26%), but increased with mulching and additional use of 25 kg N ha^{-1} (1.31%). Trash mulching also helped in maintaining P and K status over trash removal and trash burning.

Instances from North as well as South India can be cited where incorporation of 5 t of cane trash ha^{-1} along with N fertilizers increased the cane yield and economized fertilizer N to the extent of 75 kg ha^{-1}. A saving of 75 kg N ha^{-1} may be obtained by the integrated use of 5 t of cane trash with 75 kg N ha^{-1} in the sub-tropics (Yadav et al. 1987) and with 175 kg N ha^{-1} in the tropics (Shinde et al. 1984). In a multiple ratooning system, keeping trash in furrows and pocket manuring using crow bar was found to be a better technique of trash and fertilizer management with higher benefit:cost ratio. After the harvest of the fourth ratoon, the organic carbon, N, P and K contents of the soil was increased in the treatment of keeping trash in furrows (Jadhav et al. 2005). At Cuddalore trash mulching gave 7.76 t more cane yield than non-mulched plots. Trash mulching was found to reduce weed growth as well as the incidence of early shoot borer to a substantial extent besides improving the soil moisture in the first 4 months of crop season.

The benefits of green cane harvesting in increasing soil organic matter and cane yield are well recognized (Vallis et al. 1996; Graham and Haynes 2005; Wood 1991). Green cane trash blanketing technique practiced in Australia increased soil organic carbon by 1.5–14.0% and soil total N by 1.5–21.0% in the top 25 cm of the soil (Robertson et al. 2000). Trash supplies N slowly and in small amounts to the succeeding crop in sugarcane growing areas of wet tropics regardless of trash placement (on the soil surface or incorporated) or soil type (Elizabeth et al. 2006). Basanta et al. (2003) using ^{15}N labeled ammonium sulphate in Brazil estimated that the trash remaining as a surface blanket resulted in an average nitrogen recycling of 105 kg ha^{-1} year^{-1}, while the practice of trash burning produced an average loss of 83.5 kg ha^{-1} year^{-1} from the system. It also increases microbial activity and soil enzymes (Graham and Haynes 2005). Simulation studies in trash-blanketed sugarcane systems showed that sugarcane yields have potential to respond positively to retention of trash in the field over the range of climates (Thorburn et al. 2004). Sugarcane trash laid on the soil surface @ 9 t ha^{-1} in a minimum tillage system contributed 51 kg N ha^{-1}. Trash-N uptake closely resembled urea-N uptake and only 13% of its N content was recovered in the first year, followed by 7 and 3% in the second and third seasons, respectively (Fortes et al. 2011). Calculations of possible long-term effects of converting from a burnt to green cane trash blanketing (GCTB) production system suggested that, soil C could increase by 2–18% and soil N could increase by 4–23%, depending on soil and climatic factors and that it could take 10–35 years for the soils to approach this new equilibrium (Robertson 2003).

Pressmud

One of the important organic sources in sugarcane farming is the pressmud or the filter press cake from the sugar industry. Sugar factories produce about 3 t of filter pressmud for every 100 t of cane crushed. In India, about 4.4 million t of pressmud is available annually. Yadav (1995) reported that on an average, 1 t of oven-dry sulphitation pressmud contains 17 kg N, 36 kg P, 14 kg K and 23 kg S. Press mud has been used in Indian agriculture mainly as a source of nutrients, an amendment for acidic and saline sodic soils, a medium for raising sugarcane seedlings and a source of carrier material for rhizobium cultures. The productivity of the soil can be greatly enhanced by recycling pressmud as manure, which was found to improve the total pore space, hydraulic conductivity, infiltration rate, bulk density and moisture status of sugarcane soils (Zende 1995). An economy of 50–75 kg N ha^{-1} has been obtained in sugarcane based cropping systems by the integrated use of sulphitation pressmud and fertilizer nitrogen (Yaduvanshi et al. 1990; Yaduvanshi and Yadav 1990; Mathew and Varughese 2005). Singh and Yadav (1996) reported that combined application of 10 t of pressmud (80% moisture) with 75–100 kg fertilizer N ha^{-1} increased the N use efficiency by 4–8% and also increased the soil organic matter content and availability of N, P, K, S, Zn and Mn. A yield increase of 12 t ha^{-1} by applying 25 t of pressmud ha^{-1} has been reported (Kailasam 1999).

Raw press mud cannot be used directly as organic manure in sugarcane because of the evolution of large amount of heat during its decomposition. It can be composted with sugarcane trash or cow dung, either alone or in combination. Inoculation with fungal cultures such as *Pleurotus* or *Trichoderma* will hasten the process of decomposition and reduce the time required for compost preparation (Rakkiyappan 1995). Studies conducted during the 50s and 60s have shown that nitrogen contained in the pressmud is nearly 50–66% as effective as that contained in inorganic fertilizers on equal nitrogen basis. However, this does not take into consideration the residual effects and influence on physical, chemical and biological properties of soil. The residual effect (increase in yield) of pressmud applied to the plant crop on the ratoon crop ranged from 8.9 t ha^{-1} at Jalandhar with 20 t PMC ha^{-1} to 20.5 t ha^{-1} at Padegaon with 25 t PMC ha^{-1} (Verma 2004). Maximum decrease in soil bulk density (12%) with an increase in soil aggregate (17%) and water infiltration rate (35%) was obtained with the addition of sulphitation press mud cake (Singh et al. 2007).

Biofertilizers

Biological N fixation is another source, which could be exploited for INM in sugarcane. Biofertilizers help in increasing biological fixation of atmospheric N and enhancing native P availability to the crops. Use of organics such as FYM, compost, trash and pressmud in appreciable quantities, will serve as a source of energy for soil micro organisms and improve the efficiency of N fixation and P solubilization. *Azotobacter* and *Azospirillum* are the two groups of bacteria, which have been identified to be associated with sugarcane and fix sufficient quantity of atmospheric nitrogen. Some of the species of *Azotobacter*, *Azospirillum* and *Bacillus* were reported to economise fertilizer nitrogen requirement by as much as 50% (Ahmad et al. 1978). *Gluconacetobacter diazotrophicus* (earlier known as *Acetobacter diazotrophicus*), a N-fixing bacteria associated with sugarcane as an endophyte, is present in high numbers in the root, shoot and leaves (Cavalcante and Döbereiner 1988). Field trials conducted in India have shown that inoculation by *G. diazotrophicus* together with other diazotrophs or vascular arbuscular mycorrhiza can match yield levels equal to the application of 275 kg N ha^{-1} (Muthukumarasamy et al. 2002). At Coimbatore, *Azospirillum* significantly improved the cane and sugar yield compared to *Gluconacetobacter*, *Azotobacter* and uninoculated control and varieties showed differential response to the application of *Azospirillum*, *Gluconacetobacter* and *Azotobacter* (Hari and Srinivasan 2005). Studies also indicated that inoculation of *Azospirillum* with 180 kg N ha^{-1} of inorganic N could give a yield of 106.4 t ha^{-1} and was better than application inorganic N alone at 240 kg ha^{-1} (Srinivasan, 1995). On-farm trials conducted by Sugarcane Breeding Institute in different soil types indicated that in well drained clay soil and clay loam soil the response to *Azospirillum* application was greater than that to *Azotobacter* application, but the trend was reversed in semi dry loamy soil. The response to both the biofertilizers was comparable in sandy soil (Srinivasan 1986). The juice quality was not affected by the application of biofertilizers. In Gujarat, application of the highest NPK rate (250 kg N + 125 kg P_2O_5 + 125 kg K_2O ha^{-1}) + sett inoculation of *Azotobacter* gave the highest mean cane yield of 89.3 t ha^{-1} (Mehta et al. 1996). Patil and Hapse (1981) reported that soil application of *Azotobacter* @ 5 kg ha^{-1} at planting in medium black soil increased cane yield by 23 t ha^{-1}. In field experiments conducted in various sugar mill zones of Tamil Nadu

(Muthakumarasamy et al. 1994), *G. diazotrophicus* increased sugarcane yield by 17–25 t ha^{-1}, along with 50% saving in fertilizer nitrogen. A saving of 76.3 kg N ha^{-1} was envisaged by the use of *G. diazotrophicus* inoculated FYM with marginal (2.4 t ha^{-1}) decline in the cane yield (Yadav et al. 2009).

It has also been reported that several Brazilian sugarcane cultivars are capable of obtaining over 80% of their nitrogen (>150 kg ha^{-1} $year^{-1}$) from biological nitrogen fixation, under ideal conditions of nutrient and water supply probably due to the fact that sugarcane in Brazil had been systematically bred for high yields with low fertilizer nitrogen inputs (Boddey et al. 1995). Several species of 'endophytic diazotrophs' including *Gluconacetobacter diazotrophicus*, *Herbaspirillum seropedicae*, *H. rubrisubalbicans* and *Burkholderia* sp. that infected the interior of the plants have been discovered (Boddey et al. 2003). *Pantoea* sp., a new N_2 fixing entophyte capable of producing H_2 and growing in a wide range of conditions has been isolated from sugarcane stem tissue (Loiret et al. 2004).

In recent years, several strains of P solubilizing bacteria and fungi have been isolated. PSB application increased the plant available P status in the soil and improved tillering, stalk population and stalk weight, cane yield, juice quality and sugar yield (Sundara et al. 2002). When used in conjunction with P fertilizers, PSB reduced the required P dosage by 25%. In addition, 50% of the costly super phosphate could be replaced by RP, a cheap source of P, when applied in conjunction with PSB. Shankaraiah et al. (2000) suggested that bacterial cultures viz., *Agrobacterium radiobacter* and *Bacillus megaterium* in plant crop and the fungus *Aspergillus awamori* in ratoon crop are efficient P solubilizers. Studies revealed that integrated use of P solubilizing cultures with low grade RP can add 30–35 kg P_2O_5 ha^{-1} in neutral to mildly alkaline soils. Vesicular-arbuscular mycorrhizae (VAM), a kind of symbiosis between plant roots and certain fungi, substantially enhance P availability and its uptake by the crops as evident from some field studies. Because of the problems in isolation and multiplication of pure strains of VAM fungi, its use as a biofertilizer on a large scale, is yet to become popular. Kelly et al. (2001) opined that application of P fertilizer is not necessary for sugarcane when acid-extractable P is <30 mg kg^{-1} if sufficient VAM propagules are present. Biofertilizers produced from phosphate and potash rocks mixed with sulfur inoculated with *Acidithiobacillus* oxidizing bacteria increased available P and K and exchangeable Ca and Mg and may be used as an alternative source of P and K for sugarcane grown in soils with low available P and K (Stamford et al. 2008). Moutia et al. (2010) reported significant cultivar × water regime × *Azospirillum* inoculation interaction suggestive of a complex interplay of these factors, possibly involving the indigenous plant auxin pool and stressed the need for taking into account plant genotype when recommending bacterial inoculation for direct plant growth promotion.

Integration of Organics, Chemical Fertilizers and Biofertilizers

Use of biofertilizers in combination with organics and chemical fertilizers was found to be more advantageous compared to the use of biofertilizers in combination with only chemical fertilizers. Integrated application of pressmud at the rate of 4 t ha^{-1} + *Azotobacter* at 5 kg ha^{-1} along with fertilizer N ranging from 112 to 224 kg ha^{-1} recorded significantly higher cane yield than the application of chemical fertilizer alone. Application of 112 kg N ha^{-1} along with pressmud and biofertilizers was even superior to the application of the full dose of 224 kg N ha^{-1} alone (Kailasam 1999). In another experiment application of enriched press mud or bioearth (an organic manure prepared from pressmud and distillery effluent) at 10 t ha^{-1} + biofertilizers (*Azospirillum* and Phosphobacteria) along with 75% of the RDF gave higher cane yield (150 t ha^{-1}) than the application of 100% RDF (225:63:100 kg NPK ha^{-1}) without organics and biofertilizers (Rakkiyappan et al. 1999, 2002).

Combined application of 150 kg N ha^{-1} with FYM (20 t ha^{-1}) and sulphitation pressmud cake (20 t ha^{-1}) significantly increased the yield of plant cane under subtropical conditions and showed marked residual effect on the yield of two subsequent ratoons (Singh et al. 2001). Integrated use also improved the soil available N, P and K contents over initial values without significantly changing the soil fertility status rating. Ramesh et al. (2002) advocated the application of the recommended level of P (62.5 kg P_2O_5 ha^{-1}) as RP along with phosphobacteria at preplanting and daincha incorporation at 45 DAP in combination with recommended dose of N and K for higher cane and sugar yields. The above combination also gave the highest net return and benefit cost ratio. Gangwar and Sharma (1997) from Uttar Pradesh in India reported that the highest yield in sugarcane was obtained with the INM practice consisting of the recommended dose of fertilizers (160 kg N + 60 kg P_2O_5 + 60 kg K_2O ha^{-1}), FYM (10 t ha^{-1}) and incorporation of cowpea biomass (6 t ha^{-1}). Experiments conducted at Kolhapir, Maharashtra (Saini et al. 2006) indicated that pressmud cake @ 10 t ha^{-1} for plant crop and trash mulch @ 5 t ha^{-1} for the ratoon crop in conjunction with recommended NPK sustained 13–16 t ha^{-1} more cane yield. Wider row spacing of 120 cm row spacing with cross planting, intercropping blackgram followed by sunnhemp and application of recommended dose of fertilizers along with *Acetobacter* (@

10 kg ha^{-1}) and foliar spraying of micronutrient mixture (1% at 45 and 75 DAP) recorded the highest single cane yield of 150 t ha^{-1} (Manimaran et al. 2009). The highest number of millable canes and cane length were recorded with sulphitation pressmud @ 10 t ha^{-1} + farmyard manure 10 t ha^{-1} (Srivastava et al. 2008). Addition of *Trichoderma* inoculated trash @ 10 t ha^{-1} along with 150 kg N ha^{-1} and *Azotobacter* @ 4 kg ha^{-1} was found beneficial for sustaining soil health, enhancing sugarcane productivity and getting higher net returns (Thakur et al. 2010).

An additional cane yield of 14–27 t ha^{-1} was realized with different organic manures + inorganic fertilizers over inorganic fertilizers alone (Babu et al. 2007). Among different organic sources, FYM, pressmud and poultry manure proved superior in terms of cane yield whereas pressmud followed by poultry manure proved superior in terms of sugar yield. There was a slight reduction in soil pH and increase in electrical conductivity with the application of organic manures. At the end of ratoon crop, the increase in available N and Ca was maximum (38.2 and 24.4%) with the application of FYM. For the sugarcane–plant–ratoon sequence in high clay containing soils of South Gujarat, application of recommended dose of fertilizer (250–125–125 kg N–P–K ha^{-1}) along with either FYM or press mud (supplying 25% i.e., 62.5 kg N) + biofertilizers in plant cane and recommended dose of fertilizer (325–62.5 125 kg N–P–K ha^{-1}) + trash incorporation + biofertilizers in ratoon crop is imperative for sustaining soil health and enhancing productivity (Virdia and Patel 2010). In Nigeria, the best sugarcane growth and yield were obtained from the plots incorporated with cow-dung at 10 t ha^{-1} and also supplemented with in-organic fertilizer at 120N–$60P_2O_5$–$90K_2O$ kg ha^{-1} (Gana 2008).

Conclusions

Integrated nutrient management holds great promise in meeting the growing nutrient demands of intensive sugarcane agriculture and maintaining productivity at higher levels with overall improvement in the quality of resource base. It helps to improve and sustain soil fertility and provides a sound basis for crop production systems to meet the changing needs. Balanced use of organic, inorganic and biofertilizers is essential to maintain a good soil physical and chemical environment and also serve as energy source for the soil microbial biomass. Sugar productivity can be sustained by replenishing the nutrients removed by crops through proper recycling of crop residues and factory wastes along with biofertilizers. As organic manures often leave profound residual effect, recommendations need to be made on cropping system basis.

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