



## Climate-Smart Agronomic Strategies for Mitigating Nitrous Oxide (N<sub>2</sub>O) Emissions in Sugarcane Production

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Sugarcane (*Saccharum officinarum* L.) is an important commercial crop and a major source of sugar and renewable biomass in India. Owing to its high biomass production and prolonged growth duration, sugarcane requires substantial quantities of nitrogen (N) to support vegetative development, canopy formation and cane yield. Nitrogen is therefore one of the most critical nutrients influencing sugarcane productivity and profitability. However, inefficient N management, particularly excessive application, inappropriate timing and poor placement, can result in substantial nitrogen losses through volatilization, leaching and denitrification. These losses not only reduce nitrogen-use efficiency but can also contribute to nitrous oxide (N<sub>2</sub>O) emissions, a potent greenhouse gas associated with agricultural soils. Improving the synchronization between nitrogen availability and crop demand is therefore essential for enhancing fertilizer-use efficiency while minimizing environmental impacts. The 4R nutrient stewardship approach, encompassing Right Source, Right Rate, Right Time and Right Place provides a systematic framework for improving nitrogen management in sugarcane. Its effectiveness can be complemented by soil-test-based fertilizer recommendations, split N application, nitrification inhibitors and enhanced-efficiency fertilizers. Precision irrigation, particularly drip irrigation combined with fertigation, can further improve the spatial and temporal distribution of nutrients and water within the crop root zone. Weather-based fertilizer scheduling may also reduce the risk of nitrogen losses under conditions conducive to leaching and denitrification. Integrating these management practices plays an important role for improving nitrogen-use efficiency, sustaining sugarcane productivity and profitability and reducing N<sub>2</sub>O emissions under Indian production conditions.

**Key words:** Nitrogen management, Nitrogen-use efficiency, Nitrous oxide emissions, 4R nutrient management, Nitrification inhibitors

### Introduction

Sugarcane is one of the major commercial crops of India and is grown under a wide range of tropical and subtropical conditions. Adequate nitrogen (N) supply is essential for proper vegetative growth, tillering and development of cane biomass. At the same time, excessive or poorly managed nitrogen fertilization can result in substantial nutrient losses through ammonia volatilization, nitrate leaching, denitrification and nitrous oxide (N<sub>2</sub>O) emission.

Nitrous oxide ( $\text{N}_2\text{O}$ ) is an important greenhouse gas associated with agricultural soils. In fertilized fields, it is mainly produced through microbial nitrification and denitrification. The amount of  $\text{N}_2\text{O}$  released from sugarcane fields is influenced by several factors, including nitrogen fertilizer source and dose, soil properties, soil pH, organic carbon content, temperature, soil moisture, rainfall, irrigation, crop residues and the interval between fertilizer application and crop uptake (Dalal *et al.*, 2003).

Management of  $\text{N}_2\text{O}$  emissions, therefore, requires a combination of agronomic practices rather than dependence on a single technology. Improving nitrogen-use efficiency (NUE) is particularly important because better recovery of applied nitrogen by the crop can reduce the amount of surplus nitrogen available for environmental losses (Otto *et al.*, 2016). The Intergovernmental Panel on Climate Change (IPCC) has recognized improved fertilizer management, appropriate fertilizer rate and timing, suitable placement, enhanced-efficiency fertilizers, nitrification inhibitors, soil testing and integrated nutrient management as important approaches for reducing  $\text{N}_2\text{O}$  emissions from agricultural land.

### Nitrogen Management Based on the 4R Principle

The 4R nutrient-management concept, consisting of Right Source, Right Rate, Right Time and Right Place, provides a useful framework for efficient nitrogen management in sugarcane. The basic idea is to provide the crop with the required nutrient in a form, quantity, time and location that favour maximum crop recovery. When nitrogen is supplied in excess of crop requirements, part of the nutrient remains in the soil as ammonium ( $\text{NH}_4^+$ ) or nitrate ( $\text{NO}_3^-$ ). The unused nitrogen can subsequently be lost through nitrification, denitrification, leaching and volatilization (Moro *et al.*, 2025). Improving the efficiency of fertilizer application can therefore reduce both economic losses and environmental impacts.

**Right Source:** Selection of the nitrogen source should consider soil conditions, crop requirement and the method of fertilizer application. Urea is widely used in sugarcane because of its high nitrogen concentration and availability. However, slow-release, controlled-release and stabilized fertilizers can provide nitrogen over a longer period and may reduce the concentration of readily available nitrogen in the soil (Reeves *et al.*, 2024). Nitrification inhibitors used along with ammonium-based fertilizers can slow the conversion of ammonium to nitrate. This may reduce nitrate accumulation and lower the possibility of N loss through denitrification under favourable conditions.

**Right Rate:** Nitrogen fertilizer should be applied according to crop requirement rather than following a uniform dose for every field. Soil-test information, expected yield, crop history and nutrient contributions from organic manures should be considered when deciding the fertilizer requirement. Application of nitrogen beyond crop demand does not necessarily result in a proportional increase in yield (Li *et al.*, 2025). Instead, excess nitrogen is subjected to loss by different pathways. Avoiding unnecessary nitrogen application is therefore an important component of  $\text{N}_2\text{O}$  mitigation (Takeda *et al.*, 2021).

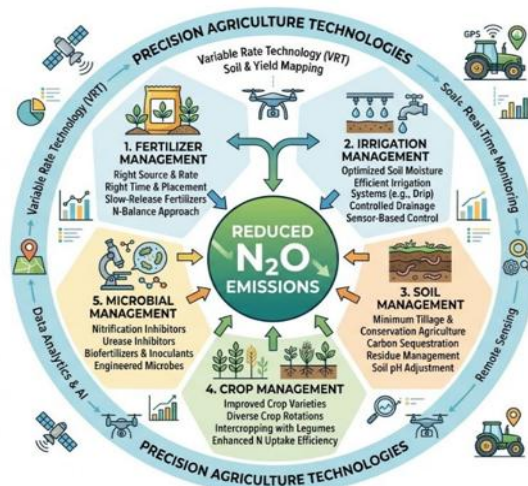


Fig. 1: Integrated  $\text{N}_2\text{O}$  mitigation framework

**Right Time:** Nitrogen should be applied during periods when sugarcane has maximum root activity and can utilize the nutrient effectively. Applying a large quantity of nitrogen just before heavy rainfall or excessive irrigation can increase the possibility of nitrogen loss. Dividing the nitrogen dose into suitable application allows nutrient supply to be better matched with crop growth (Allen *et al.*, 2010). Split application is particularly useful during periods of rapid crop development when nitrogen demand is high.

**Right Place:** Placing nitrogen close to the active root zone improves crop uptake and limits the exposure of fertilizer nitrogen to loss processes. Fertilizer placement should be adjusted according to root distribution, soil characteristics and irrigation method.

Thus, adoption of the 4R principle can improve nitrogen-use efficiency using better management of existing fertilizer resources.

### Nitrification Inhibitors for N<sub>2</sub>O Mitigation

Nitrification inhibitors have received considerable attention as a means of reducing N<sub>2</sub>O emissions from fertilized soils. During nitrification, soil microorganisms convert ammonium into nitrite and subsequently nitrate:  $\text{NH}_4^+ \rightarrow \text{NO}_2^- \rightarrow \text{NO}_3^-$

N<sub>2</sub>O may be released during this transformation. In addition, the nitrate formed during nitrification can subsequently be reduced under oxygen-limited conditions through denitrification, with N<sub>2</sub>O occurring as an intermediate product (Bateman and Baggs, 2005).

Compounds such as **dicyandiamide (DCD)** and **3,4-dimethylpyrazole phosphate (DMPP)** can suppress the activity of ammonia-oxidizing microorganisms. As a result, conversion of ammonium to nitrate is slowed and nitrate accumulation may be reduced. Studies conducted in sugarcane production systems have shown considerable reductions in N<sub>2</sub>O emissions following the use of nitrification inhibitors under specific experimental conditions. For example, one field experiment reported reductions of approximately 87 % during the dry season and 63 % during the wet season following inhibitor application. Another study involving sugarcane soil treated with mineral nitrogen and vinasse observed an average reduction of about 80 % in N<sub>2</sub>O emissions with DMPP under laboratory conditions. Such values should, however, be interpreted carefully. The performance of nitrification inhibitors is affected by soil type, temperature, soil moisture, fertilizer rate, rainfall, irrigation and the characteristics of the inhibitor used. Therefore, the reductions observed in individual experiments cannot be directly applied to all sugarcane-growing regions of India. The technology may have particular value in areas where high nitrogen rates, frequent irrigation, prolonged soil wetness or substantial monsoon rainfall increase the possibility of nitrate formation and denitrification.

### Enhanced-Efficiency Fertilizers

Enhanced-efficiency fertilizers are intended to improve the availability of nitrogen in relation to crop demand. This group includes slow-release fertilizers, controlled-release fertilizers, polymer-coated urea and stabilized fertilizers containing nitrification or urease inhibitors. Following application, conventional urea is rapidly hydrolysed and can temporarily increase the concentration of mineral nitrogen in the soil. When the rate of crop uptake is lower than the rate of nitrogen release, the remaining nitrogen becomes susceptible to different loss processes. Controlled-release and stabilized fertilizers can moderate nitrogen release and potentially improve fertilizer recovery. Studies in ratoon sugarcane have indicated that controlled-release fertilizers and nitrification-inhibitor treatments can reduce N<sub>2</sub>O emissions compared with conventional urea under particular experimental conditions. However, the response of enhanced-efficiency fertilizers is influenced by soil and climatic conditions. Research in sugarcane-producing regions outside India has also demonstrated differences in the performance of polymer-coated fertilizers and nitrification inhibitors between locations. For Indian agriculture, these fertilizers should therefore be evaluated under representative regional conditions before making broad recommendations. They may be especially useful where farmers have difficulty making several fertilizer applications during the crop season.

## Drip Irrigation and Fertigation

Water and nitrogen management are closely related in sugarcane production. Excessive irrigation can increase soil moisture and reduce oxygen availability in the soil. Such conditions may favour denitrification and consequently increase N<sub>2</sub>O production. Drip irrigation provides water more directly to the crop root zone and allows irrigation to be managed according to crop requirement. When fertilizer is supplied through fertigation, nitrogen can be delivered in small quantities along with irrigation water. This provides an opportunity to synchronize nutrient supply with crop demand.

Important advantages of drip fertigation include:

- Better matching of nitrogen supply with crop demand;
- Possibility of applying nitrogen in several small doses;
- Improved fertilizer-use efficiency;
- Better regulation of soil moisture;
- Reduced water loss;
- Lower risk of excessive nitrate accumulation;
- Greater flexibility for split nitrogen application.

Despite these advantages, adoption of drip fertigation depends on several factors, including installation cost, farm size, availability of irrigation water, maintenance facilities and technical knowledge. Hence, the technology should be promoted according to local farming conditions and economic feasibility rather than being considered suitable for every sugarcane farmer.

## Integrated Nutrient Management

Efficient nitrogen management should be considered as part of overall soil fertility management. Integrated nutrient management combines mineral fertilizers with organic and biological nutrient sources to maintain soil fertility and improve nutrient-use efficiency. Farmyard manure, compost, vermicompost, crop residues and suitable biofertilizers can contribute nutrients and support soil biological activity. However, the nutrient contribution from these materials should be considered while calculating fertilizer requirements. Vinasse is another important nutrient source in sugarcane-based industries. Where vinasse is used as a soil amendment or nutrient source, its nitrogen and other nutrient contributions should be considered in the overall nutrient budget. Excessive application can increase the quantity of reactive nitrogen available for loss. Consequently, integrated nutrient management should focus on supplying adequate nutrients for crop growth while avoiding unnecessary accumulation of nitrogen in the soil.

## Soil Testing and Precision Nitrogen Management

Soil testing is an important tool for developing appropriate fertilizer recommendations. Fields may differ considerably in soil fertility, nutrient availability and crop productivity, therefore uniform fertilizer application may not always be appropriate. Precision agriculture provides additional opportunities for improving nutrient management. Soil nutrient mapping, GPS-based fertilizer application, remote sensing, crop sensing and other sensor-based technologies can help identify differences in crop nutrient requirements within and between fields. Integration of soil-test information with crop monitoring and weather data can facilitate site-specific nitrogen management. Variable-rate fertilizer application may further improve fertilizer-use efficiency by adjusting nutrient application to field variability. Although precision technologies may not yet be accessible to all farmers, their use is likely to become increasingly relevant in commercial and mechanized sugarcane production.

## Fertilizer Timing, Rainfall and Soil Moisture

The interaction between nitrogen availability and soil moisture is an important factor controlling N<sub>2</sub>O production. Shortly after fertilizer application, the amount of mineral nitrogen in the soil increases. If heavy rainfall or excessive irrigation occurs during this period, soil pores may become saturated with water and oxygen availability may decline. Under oxygen-deprived conditions, denitrifying microorganisms can use nitrate in place of oxygen during

their metabolic processes, resulting in the formation of  $\text{N}_2\text{O}$  and eventually  $\text{N}_2$  (Bateman and Baggs, 2005). Thus, the risk of  $\text{N}_2\text{O}$  formation generally increases when readily available nitrogen coincides with high soil moisture and limited oxygen availability. Seasonal variation is also important. Sugarcane research has indicated greater  $\text{N}_2\text{O}$  emissions following nitrogen application during wet periods than during relatively dry conditions (Moro *et al.*, 2025). Therefore, practical measures include:

1. Avoiding heavy nitrogen application immediately before expected rainfall;
2. Avoiding unnecessary irrigation soon after fertilizer application;
3. Applying nitrogen when the crop is actively growing;
4. Dividing nitrogen into suitable split applications;
5. Preventing prolonged waterlogging or excessive soil saturation;
6. Using local weather information when planning fertilizer application.

These practices require relatively little additional investment and can therefore be useful in a wide range of sugarcane production systems.

### Integrated Approach for Indian Sugarcane

$\text{N}_2\text{O}$  mitigation is more effective when several compatible management practices are used together. A practical framework for Indian sugarcane can be represented as:

Soil testing → Assessment of crop N requirement → 4R nitrogen management → Split N application → Efficient irrigation/fertigation → Appropriate use of nitrification inhibitors or enhanced-efficiency fertilizers → Weather-based fertilizer scheduling → Monitoring of yield and NUE. The main objective should be to obtain the required cane yield with minimum unnecessary nitrogen remaining in the soil. Such an integrated approach brings together fertilizer management, irrigation management, soil fertility management and weather information. It also provides flexibility to modify practices according to soil type, climate, irrigation facilities and farm resources.

### Region-Specific Considerations

Sugarcane is cultivated under highly variable conditions in India. Differences in rainfall, soil texture, temperature, irrigation, cropping systems and farm resources can influence both nitrogen-use efficiency and  $\text{N}_2\text{O}$  emissions (Dalal *et al.*, 2003). Therefore, mitigation practices should be selected according to local conditions. The major practices that can be considered include:

- **4R nitrogen management:** Provides a general framework for improving fertilizer-use efficiency.
- **Soil-test-based fertilizer recommendation:** Helps avoid unnecessary nitrogen application.
- **Split nitrogen application:** Improves synchronization between nitrogen availability and crop demand.
- **Nitrification inhibitors:** Can be considered where conditions favour nitrate accumulation and denitrification.
- **Enhanced-efficiency fertilizers:** May be useful where gradual or stabilized nitrogen release is beneficial.
- **Drip irrigation and fertigation:** Particularly useful in irrigated sugarcane where suitable infrastructure is available.
- **Weather-based fertilizer scheduling:** Helps reduce the risk of fertilizer application immediately before heavy rainfall.
- **Efficient irrigation:** Helps prevent unnecessary periods of excessive soil moisture.
- **Integrated nutrient management:** Combines mineral, organic and biological nutrient sources according to crop requirements.
- **Vinasse and organic-input management:** Requires consideration of their nutrient contribution to avoid excess nitrogen application.

## Conclusion

Nitrous oxide ( $\text{N}_2\text{O}$ ) emissions from sugarcane can be reduced by improving synchronization between nitrogen supply, crop demand and soil conditions. The 4R nutrient-management approach, supported by soil testing, split nitrogen application and appropriate fertilizer placement, can improve nitrogen-use efficiency and reduce nutrient losses. Nitrification inhibitors, enhanced-efficiency fertilizers, drip fertigation and weather-based fertilizer scheduling provide additional opportunities for  $\text{N}_2\text{O}$  mitigation. An integrated, region-specific nitrogen-management strategy is therefore essential to sustain sugarcane yield and sugar recovery while minimizing surplus nitrogen and environmental losses under Indian conditions.

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