PLANT SCIENCE TODAY
Vol x(x): xx–xx
https://doi.org/10.14719/pst.9627

eISSN 2348-1900

REVIEW ARTICLE

Perspectives on nutrient management through different farming practices for sugarcane production

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Received: 26 May 2025; Accepted: 08 July 2025; Available online: Version 1.0: 21 August 2025

Cite this article: Mathesh S, Sanbagavalli S, Geetha P, Janaki P, Gnanachitra M, Sritharan N. Perspectives on nutrient management through different farming practices for sugarcane production. Plant Science Today (Early Access). https:/doi.org/10.14719/pst.9627

Abstract

India ranks second among the world's leading producers of sugarcane and in recent decades, input usage has more than doubled to meet the growing global demand for bioenergy. This surge has contributed to climate change mitigation and reduced dependence on fossil fuels. However, the long-term sustainability of sugarcane production is increasingly uncertain due to the adverse environmental impacts of intensive input use and non-optimized production methods. As the crop's potential for ethanol and green energy gains prominence, it is imperative to simultaneously enhance environmental performance. Nutrient depletion in plant crops often results in yield decline in subsequent ratoons, leading to reduced productivity and economic viability. Sustainable sugarcane production can be achieved by adopting natural and organic farming systems that promote resource conservation and minimize ecological damage. Organic nutrient management offers a viable alternative to maintain soil fertility, reduce input dependency and improve produce quality by avoiding harmful residues. In this context, the adoption of optimal nutrient management practices through natural and organic system has emerged as a research priority for ensuring long-term sustainability. Organic farming systems have attracted increased interest and can address some of the problems faced by humans as well as the agriculture sector. These systems not only contribute to environmental protection and the conservation of non-renewable resources but also address concerns related to food quality, ecosystem balance and farm profitability.

Keywords: integrated nutrient management; natural farming; organic farming; sugarcane

Introduction

Sugarcane (*Saccharum* spp.) is a major economic crop cultivated in tropical and subtropical regions. It is grown in more than 110 countries. Brazil and India led global sugarcane production, together accounting for roughly 61 % of the world total: Brazil alone produced about 38 % and India contributed 23 % of global output. Sugarcane is grown on approximately 26.45 million hectares worldwide, yielding a total production of 1,865 million tonnes and an average productivity of 70.48 tonnes per hectare (1). In Indian agriculture, sugarcane occupies a significant position, contributing substantially to the national economy. In India, sugarcane is cultivated over an area of approximately 5.88 m ha, producing 494.22 million tonnes with a productivity of 84.01 t ha^{-1}(1).

Among the major sugarcane growing states, Tamil Nadu ranks sixth in area (1.46 lakh ha) and production (15.50 million tonnes), but leads in productivity (106.73 t ha^{-1}) and sugar recovery (2). More than 60 million farmers in India depend on the sugar business for their living, making it an essential part of the country's rural economy and generating direct employment for around 500000 skilled and semi-skilled workers (3). India holds the position of the world's sec-largest producer of sugar, following Brazil, contributing approximately 15 % to the global sugar output and around 25 % to the total sugarcane production worldwide. Over 50 million farm-based peoples are involved in sugarcane farming and related industries and maximizing yield plays a crucial role in increasing their economic well-being, along with stakeholders across more than 550 sugar mills, wholesalers and distributors (4). With a domestic sugar demand of approximately 25 million tonnes annually, sugar and jaggery remain essential sources of affordable energy, contributing nearly 10 % to the daily calorie intake in Indian diets (5).

Sugarcane is increasingly recognized as a crop of the future, offering sugar and renewable green energy through bioethanol, bioelectricity and other bio-based products. With India's per capita sugar consumption projected at 22 kg and the population expected to reach 1.5 billion by 2030, the estimated demand for white sugar will be around 33 million tonnes. To meet this demand, an estimated 520 million tonnes of sugarcane will be needed, assuming an average sugar recovery rate of 10.75 %, with 60 % of the harvested cane allocated for sugar production and 15 % diverted for ethanol. To achieve this, productivity levels must reach 100-110 tonnes per hectare, even as the sugarcane cultivation area stabilizes at approximately 5 million hectares (6).

Despite growing market demands, sugarcane productivity in has plateaued, partly due to changing climatic conditions. Enhancing productivity must therefore be a priority. Technologies like region-specific sugarcane varieties, advanced planting techniques, heat treatment, meristem-derived quality seeds, drip irrigation, fertigation, site-specific nutrient management and integrated approaches to stress and weed control hold considerable promise for substantially enhancing sugarcane yields (7). Sustainable solutions for these advancements are essential to meet the growing global demand for food, fibre and fuel, especially given the constraints on expanding agricultural land. Hence, increasing vertical productivity while preserving soil health is crucial. Continuous use of chemical inputs has degraded soil fertility. A comprehensive approach that incorporates organic manures is essential for revitalizing soil biodiversity and improving both the physicochemical properties of the soil. Organic amendments, either alone or in conjunction with inorganic fertilizers, have been shown to sustain productivity while improving long- term soil fertility and ecosystem health.

This paper reviews the current needs, status and research findings related to nutrient management through different farming practices on sugarcane production

Conventional farming

In sugarcane cultivation, agronomic management is pivotal to maximizing cane productivity. Among agronomic practices, optimal planting and nutrient management significantly influence yield potential by ensuring an ideal stalk population per unit area. However, the advent of the green revolution, while successful in increasing productivity, has also contributed to environmental degradation manifested through soil and water pollution, ecosystem imbalance and health hazards. Sugarcane, as a long-duration and nutrient-demanding crop, has also been significantly impacted by these challenges.

Indiscriminate and imbalanced use of synthetic inputs has evidence in a marked deterioration of soil health and resulting in stagnated or reduced productivity in sugarcane. To address these concerns and to ensure long-term sustainability of soil health, alternative systems such as organic farming have emerged. Organic agriculture minimizes the use of synthetic inputs and focuses on harnessing ecological processes. It enhances biodiversity by utilizing natural nutrient cycles that are well-suited to the specific environmental conditions of the area (8). It is increasingly recognized for its potential in promoting food security, rural development and conservation of natural ecosystems. It is estimated that nearly 75 % of crop yield improvements since the mid-1960s are directly or indirectly attributable to fertilizer use (9). However, over-dependence on urea and restricted use of phosphorus (P) and potassium (K) fertilizers has led to nutrient imbalances and deterioration of the natural agro-ecological balance (10).

In nutrient-depleted soils, inorganic fertilizers may initially help restore fertility, but continuous application without organic amendments adversely affects long-term soil productivity (11). Sugarcane extracts approximately 2.05 kg of N, 0.24 kg of P and 2.28 kg of K per tonne of cane harvested (12). To produce a yield of 100 tonnes per hectare, sugarcane removes substantial amounts of nutrients from the soil, including 205 kg of nitrogen (N), 55 kg of phosphorus (P), 275 kg of potassium (K), 30 kg of sulfur (S), 3.5 kg of iron (Fe), 1.1 kg of manganese (Mn), 0.66 kg of zinc (Zn) and 0.22 kg of copper (Cu) (13). While balanced NPK fertilization is crucial for ensuring nutrient availability and promoting tillering, exclusive dependence on chemical fertilizers should be avoided to prevent the long-term decline in soil health (14). Transitioning from conventional to organic farming involves significant changes, particularly in the mindset and practices of farmers. Conventional systems often emphasize symptomatic solutions without addressing the underlying causes of soil and crop health decline. In contrast, organic systems prioritize preventive management strategies, with a focus on cultural practices, organic nutrient sources and natural pest suppression. During the transition phase, farmers are encouraged to foster soil fertility and build populations of beneficial organisms that contribute to ecosystem balance (15).

Integrated nutrient management and its impact on sugarcane productivity

In sugarcane cultivation, the integrated use of plant nutrients aims to maintain soil fertility and optimize plant nutrient supply to ensure sustainable crop production by utilizing all available sources of plant nutrients in a cohesive approach. The primary goal of INM is to enhance and sustain soil fertility, addressing evolving agricultural demands and establishing a strong foundation for crop production systems. The core principle of Integrated Nutrient Management (INM) involves the careful and efficient use of chemical fertilizers alongside organic manures, such as farmyard manure (FYM), vermicompost and pressmud to protect soil health, maintain agricultural productivity and enhance farmer profitability. To mitigate long-term environmental impacts, combining chemical fertilizers with the nutrients from organic waste offers a sustainable approach to prevent nutrient depletion and foster long-term sugarcane productivity. Areas growing sugarcane routinely recycle organic materials such as pressmud, sugarcane trash, biocompost and distillery effluent, reducing reliance on chemical fertilizers and boosting sugar productivity (16).

Most Indian soils are poor in accessible nitrogen (N). Nitrogen application ranges from 200 to 400 kg ha-1 in the tropics and 120-150 kg ha in the subtropics (17). Sugarcane typically utilizes only 30-40 % of applied nutrients given, while the remainder is lost through various channels such as leaching, surface runoff, volatilization, denitrification, soil erosion and soil fixation (18). Thus, efforts must be made to improve fertilizer efficiency. To address yield stagnation and low fertilizer efficiency in sugarcane, it's important to use both organic and inorganic nutrients wisely. Yield stagnation in sugarcane caused by factors like continuous monocropping, imbalanced fertilization and declining soil health. This can be managed by integrated nutrient management approaches that combine organic inputs like FYM, vermicompost and pressmud with biofertilizers and site-specific chemical fertilizers.

Integrated Nutrient Management (INM) has proven to be an effective strategy for boosting sugarcane productivity while preserving soil fertility. The fertilizer application rate of 250:125:125 kg NPK ha^{-1} significantly boosted both the number of productive canes and the overall cane harvest, reaching 87.2 t ha^{-1}. However, similar yields were attained through various integrated treatments that partially substituted chemical fertilizers with organic and biological inputs. For example, a treatment combining 50 % of the recommended fertilizer dose, 25 % nitrogen from vermicompost, biofertilizers and trash incorporation produced comparable results, while also reducing nutrient costs by 25-50 % (19).

Further research has shown that applying 75 % of the recommended NPK through inorganic fertilizers, along with 25 % from organic manures and incorporating biofertilizers and biopesticides (such as *Pseudomonas, Trichoderma*, or neem cake), resulted in the highest plant and ratoon yields, achieving 90 t ha^{-1} and 76 t ha^{-1}, respectively. These were statistically on par with treatments such as (i) 100 % N through organic sources (vermicompost + biofertilizers) along with soybean intercropping (Rhizobium inoculated) andchemical pest/ disease management (85.3 t ha^{-11} and 74.8 t ha^{-1}), (ii) use of biopesticides (neem cake), cultural practices and detrashing (85.2 t ha^{-1} and 74.5 t ha^{-1}) and (iii) 75 % recommended dose of nutrients (RDN). Through organics + biofertilizers + 25 % RDN through inorganics + biopesticides (87.7 t ha^{-1} and 75.4 t ha^{-1}). All these treatments outperformed the fully inorganic option, i.e., recommended NPK + micronutrients + chemical control (84.6 t ha^{-1} and 72.0 t ha^{-1}) (20). A study (21) observed that the application of 20 t ha^{-1} of farmyard manure (FYM) along with 75 % of the recommended NPK dosage (169:84:126 kg ha^{-1}) significantly enhanced key growth parameters including germination rate (58.33 %), cane height (266.78 cm), cane diameter (2.63 cm), number of internode (17.00), internode length (13.33 cm) and the Number of Millable Canes (NMC) (120,000 ha^{-1}). This combination ultimately led to a cane yield of 118.33 t ha^{-1}.

A study was conducted at Sirugumani-TNAU, reported that use of recommended NPK levels supplemented with biofertilizers including Azospirillum and Phosphate Solubilizing Bacteria (PSB) and incorporating dhaincha at 45 days after planting (DAP), resulted in peak commercial cane sugar (CCS) content (13.9 %), along with superior cane yield (144 t ha^{-1}) and sugar yield 20.1 t ha^{-1} (22). In calcareous soils of Bihar, applying 75 % of the recommended NPK through inorganic fertilizers, combined with 25 % nitrogen from organic manures, along with biofertilizers (*Azotobacter* and PSB) and biopesticides such as neem cake significantly improved crop performance. For the ratoon crop, a similar nutrient approach was followed, with additional practices including enhanced mulching using sugarcane trash, incorporation of greengram as a green manure crop treated with *Rhizobium*, planted in alternate rows and neem cake application, which together contributed to improved soil fertility and crop productivity. This integrated strategy not only sustained sugarcane productivity but also improved fertility of soil and provided higher economic returns under the plant-ratoon system.

Organic farming in sugarcane

Organic farming is a comprehensive agricultural management strategy designed to promote better health and resilience of the agro-ecosystem. It emphasizes on enhancing biodiversity, maintaining nutrient cycles and promoting soil microbial and biochemical activity. The method favours ecological mechanisms and naturally available resources over chemical or synthetic alternatives, relying on organic manures, green manuring, biological pest control and cultural practices to manage crop health and productivity.

It promotes long-term soil health and reduces negative environmental impacts by strictly banning synthetic chemicals and pesticides. The transition to organic farming serves as a viable alternative to conventional systems, emphasizing renewable inputs and ecological balance. It is particularly relevant for nutrient-exhaustive crops like sugarcane, where maintaining soil health and sustainable productivity is paramount (23).

Organic farming significantly contributes to improved soil microbial population, nutrient cycling and overall agro-ecosystem health, thereby offering a more sustainable path for sugarcane production in the long run (24).

Organic farming plays a crucial role in achieving sustainable agriculture. It has been highlighted that organic farming will gain significant focus from all stakeholders in order to fully realize its potential for boosting profitability and ensuring long-term agricultural sustainability (25). Organic products typically contain higher levels of antioxidants, lower cadmium content and fewer pesticide residues (26).

Perceptions of organic agriculture vary; however, there is widespread agreement on its environmentally friendly qualities and its natural capacity to safeguard human health. Numerous studies have demonstrated that organic farming is both effective and sustainable. While organic foods tend to be more costly in developed countries due to its labor-intensive nature, in India. Where ever labor is abundant and cost-effective, organic farming presents a significant opportunity to address the environmental and health issues caused by chemical farming practices. The Indian government has implemented several initiatives to encourage organic farming and various organizations have been set up to promote the sale of organic produce. The increasing consumer demand for organic food in developed nations, coupled with India's policies to boost organic exports, has led to the rise of Indian organic food sectors. This sector holds the potential to enhance India's economic growth and improve the health standards of the population (27). Organic matter helps neutralize soil pH, as most nitrogenous fertilizers tend to make the soil acidic. Organic inputs, especially organic manures, provide all the vital nutrients for plants while also enhancing the physical properties of the soil. The carbon from decomposed organic matter acts as an energy source for soil microbes, which are crucial in the process of soil structure development.

The research conducted in Thailand found that the execution of organic agricultural methods was low among sugarcane farmers with low adoption rates on small (61.06 %), medium (58.23 %) and large (49.33 %) farms. Only very large farms were able to implement organic standards at a moderate level. To enhance the adoption of organic farming practices, it is essential to provide knowledge and training to women sugarcane farmers, as they are more interested to adopt organic practices (28).

Organic farming is a feasible substitute for traditional farming for maintaining an eco-friendly relationship with nature. The demand for organic food is rapidly increasing, as consumers seek healthier and more nutritious options. Organic farming helps sustain soil health and environmental integrity, thereby promoting consumer well-being. Additionally, organic products are experiencing the fastest-growing market globally, including in India. Organic agriculture fosters the health of consumers, the environment and contributes to economic growth by generating income (29). Soon, India has the potential to become a nutritionally, ecologically and economically healthy nation by focusing on organic farming.

A 10-year field study (2003-2013) was conducted to compare organic and conventional sugarcane production systems (30). Sugarcane yields under organic and conventional systems varied, with organic farming showing initial fluctuations but achieving higher productivity in later years. In the first cycle, organic sugarcane yields were 78.6 t/ha in 2003-04 and slightly higher at 80.8 t/ha in 2004-05. During the sec cycle (2006-08), conventional systems outperformed organic, except in the 2007-08 ratoon, where yields were similar. However, from 2009 onwards, organic sugarcane yields consistently surpassed conventional yields: by 14.8 % in 2009-10, 15.5 % in 2010-11 and 4.4 % in 2012-13. Cotton yields, on the other hand, were consistently higher in the conventional system, especially in 2008-09, due to better pest control. Pest control is often less effective in organic farming because synthetic pesticides are not used, limiting immediate and broad-spectrum control options. Instead, organic systems rely on natural predators, biopesticides, crop rotation and resistant varieties, which may be slower to act and less consistent under high pest pressure. This long-term study demonstrates that with effective management, organic farming can sustain and even improve sugarcane productivity over time.

Natural farming

Natural farming, based on agroecological principles, integrates crops, trees and livestock to promote functional biodiversity. This integrated approach helps in reducing production costs by optimizing natural processes and improving resource efficiency, promoting sustainability and minimizing dependence on external inputs (31). The system replaces synthetic fertilizers and pesticides with on-farm preparations such as Jeevamritha, Beejamritha, Neemastra and others, while also encouraging intercropping and mulching practices (32). Jeevamritha is especially recognized for improving soil fertility by stimulating microbial activity, which makes nutrients more available to plants and increases soil organic carbon (33, 34). Natural farming involves several prescribed components; the most widely adopted practices are the use of Jeevamritha, Beejamritha and plant-based protection formulations. Farmers have observed a notable reduction in cultivation costs across various crops, alongside N improvements in soil health, such as enhanced porosity in light -textured soils, an increase in earthworm populations and better moisture retention (35).

The Economic Survey classified natural farming, also known as Zero Budget Natural Farming (ZBNF), under the umbrella of organic farming models. It emphasized the elimination of agrochemicals and the promotion of environmentally sustainable production systems. ZBNF has been associated with improvements in soil fertility, enhanced soil organic matter, reduced water requirements and support for climate-resilient agricultural practices (36).

Natural farming, in contrast to conventional capital-intensive systems, requires minimal or no monetary investment in external inputs likes seeds, fertilizers and plant protection chemicals. This approach reduces input costs, improves crop yields and encourages the use of locally available, non-synthetic resources (37).

Components of natural farming

Jeevamrutha

Jeevamruthais a liquid organic preparation widely used in natural farming to meet plant nutrient requirements and promote microbial activity and earthworm proliferation. At a pH of 7.64, Jeevamrutha contains 1.68 % nitrogen, 0.56 % phosphorus, 0.72 % potassium and micronutrients such as Zn (0.017 ppm), Fe (0.004 ppm), Mn (0.25 ppm) and Cu (0.06 ppm). It also hosts beneficial microbes including nitrogen-fixing bacteria (31.0×10^5 CFUg^{-1}) and phosphate-solubilizing organisms (58.0×10^5 CFUg^{-1}) (38). The standard formulation, as described in previous studies, it consists of 200 L of water, 10 kg of fresh cow dung, 5 to 10 L of cow urine, 1 to 2 kg of jaggery, 1 kg of pulse flour and a hand full of soil (39). The mixture is stirred and fermented for a few days before and applied as soil drench fortnightly. It enhances microbial populations and improves crop yields.

Beejamrutha

Beejamrutha, a traditional seed treatment solution is prepared from locally available organic inputs. It protects seeds during germination and early establishment from soil- borne and seed -borne pathogens. The solution contains a consortium of beneficial microorganisms, including fungi, actinomycetes, nitrogen fixers and phosphate solubilizers (40, 41). Beejamrutha is a vital component of traditional Indian agricultural knowledge and plays a key role in early plant growth and disease resistance, particularly in crops like rice, pulses and vegetables, where its use has been shown to improve seed germination, root development and protection against soil-borne pathogens. It also has major role in boosting crop productivity by enhancing seedling vigour. However, detailed scientific data on its effects on the germination and establishment of major legume crops remain limited (42).

Whapasa

Whapasa refers to a unique soil condition characterized by an ideal balance of approximately 50 % air and 50 % water vapour within the soil pores. This equilibrium significantly reduces the need for frequent irrigation and serves as a key principle in natural farming. The Whapasa technique emphasizes maintaining both air and moisture in the soil, achieved by irrigating during midday and using alternate furrows. This method improves water use efficiency and has helped natural farming practitioners lower their overall water usage. In natural farming, conserving water and applying it precisely based on the crop's needs is essential. Targeted irrigation during midday in alternate furrows supports the maintenance of optimal air and moisture levels in the soil. This strategy is particularly beneficial during early vegetative and active tillering stages when younger, actively growing roots are most efficient at absorbing water and nutrients (43).

Mulching

The word *mulch* is derived from the German term *molsch,* which refers to something that decomposes readily and its use in vegetable farming can be traced back to ancient agricultural practices (44). Mulching entails the application of various materials to the soil surface with the aim of minimizing water loss through evaporation, inhibiting weed proliferation and enhancing overall crop yield (45, 46). In addition to conserving moisture, mulching offers several environmental benefits, including regulation of soil and root zone temperature, reduced nutrient loss, prevention of soil erosion and compaction and enhancement of soil physical properties (47, 48). Mulching with organic materials under the Zero Budget Natural Farming (ZBNF) approach can have immediate and direct benefits by regulating soil temperature and moisture, thereby enhancing crop yields. Commonly used mulching materials include sugarcane trash, crop residues, dried leaves, straw and green manure plants such as sunhemp and dhaincha (49). These effects occur due to changes in surface albedo and reduced evaporation, particularly in arid environments (50). Sugarcane trash mulching at a rate of 6.0 tonnes/ha resulted in a significantly higher commercial cane yield due to the combined positive effects on both yield and quality parameters, compared to no mulching. Additionally, it helped maintain soil fertility (51).

Intercropping

Intercropping involves cultivating two or more crops together on the same land using a specific row pattern to enhance productivity per unit area. With growing population pressure, increasing food demand, limited land availability and the diverse needs of small-scale farmers for both food and income, intercropping systems have become essential. In sugarcane farming, the spaces between rows often remain unused for the first 90-120 days due to the crop's slow initial growth. This provides a significant opportunity to increase overall productivity in India by utilizing intercropping-especially with cereals, millets, oilseeds, legumes and fibre crops. Because sugarcane is a long-duration crop, intercropping offers considerable potential. Introducing annual intercrops during the early growth phase (first 90-120 days) can significantly enhance resource use efficiency (52). For an intercropping system to be biologically effective, it is essential to adopt appropriate agronomic practices. These include proper fertilizer management, optimal seed rates for both the intercrop and the main crop and the selection of compatible crop varieties. Such measures help minimize any negative impact the intercrop may have on sugarcane while enhancing the overall productivity and profitability of the intercropping system (53). The four pillars of natural farming given in Fig. 1.

Components of organic farming

Green manure

Green manuring refers to the process of enhancing soil fertility by incorporating fresh plant biomass into the soil, either grown on-site or sourced from elsewhere (54). This practice is commonly employed in organic farming systems to sustain soil organic matter levels. Green manuring involves growing specific plant species with the intention of incorporating them into the soil to enhance organic matter levels and sustain or even improve soil fertility. Soil organic matter plays a crucial role in safeguarding against degradation while enhancing the physical, chemical and biological characteristics of the soil. Various strategies exist to boost soil organic matter and green manure has proven effective across farms of all sizes. Additionally, supplying both organic and mineral inputs supports the activity of soil microorganisms. These microbes, particularly those capable of atmospheric nitrogen fixation, help reduce reliance on synthetic nitrogen fertilizers, thereby promoting more climate-resilient sugarcane cultivation (55).

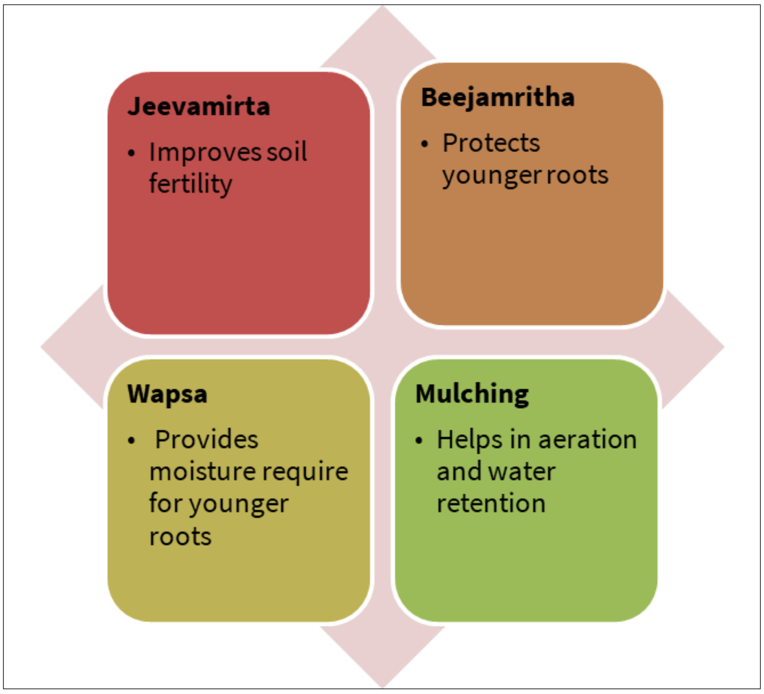

Fig. 1. Four pillars of natural farming.

Farmyard manure (FYM)

FYM is a decomposed blend of animal dung and urine, mixed with bedding material and leftover roughage or fodder fed to livestock. It is a bulky organic manure, slow-acting and low in nutrient concentration, but highly valuable for improving soil physical properties and supplying essential nutrients. The nutrient content of FYM varies depending on the nature and quality of materials used. FYM contains 0.62 % of N, 0.13 % of P and 0.71 % of K (56). Previous studies reported higher values of NPK as 1.73 %, 0.28 % and 1.02 %, respectively, along with 0.34 % sulphur and 0.79 % calcium. (58) Found FYM to contain 0.64 % nitrogen, 0.31 % phosphorus and 0.55 % potassium (57). FYM samples from various research stations of the University of Agricultural Sciences, Bangalore and reported wide variations: at ARS, Balajigapade, the manure contained Fe (8036 ppm), Zn (132.4 ppm), Mn (13.2 ppm), K (0.8 %), P (0.63 %) and Cu (30.4 ppm); at ZARS, Mandya, it had N (0.58 %), P (0.32 %) and K (0.52 %); and at ARS, Chintamani, N (0.42 %), P (0.30 %), K (0.40 %), Zn (102 ppm), Mn (698 ppm),and Cu (40.4 ppm) were recorded (59).

Goat manure

Goats serve as a valuable source of animal protein through their meat and milk and their manure also holds significant potential as an organic fertilizer, contributing to the improvement of soil fertility and sustainable agriculture. As reported by (60), raw solid goat manure comprised approximately 46.58 % organic carbon, 1.34 % nitrogen, 0.54 % phosphorus in the form of P_2O_5 and 1.56 % potassium expressed as K_2O. After undergoing composting for 30 days, its nutrient composition improved significantly, reaching 2.23 % nitrogen, 1.24 % P_2O_5 and 3.69 % K_2O.

Vermicompost

Vermicompost is a stable, finely textured organic material created through the decomposition of organic matter by earthworms. Its granular structure, along with hygroscopic mucus secretions, enhances soil aeration and water retention. Rich in macro- and micronutrients, vermicompost also serves as a chelating agent, improving the bioavailability of metallic micronutrients to plants (61). Vermicompost has nutrient values of 0.8 % nitrogen, 1.1 % P_2O_5 and 0.5 % K_2O, similarly other researcher, found 1.15 % of organic carbon, 1.3 % N, 1.3 % P and 2.6 % K composition in vermicompost (61, 62). The ratio of nutrient contents of N (1.4 %), P (0.36 %), K (0.60 %), Fe (522 mg kg^{-1}) and Zn (54 mg kg^{-1}) was also recorded (63).

Panchagavya

Panchagavya is an indigenous organic preparation made from five key products obtained from native (desi) cows: dung, urine, milk, fermented milk (curd) and ghee (64). It is enriched with both major (N, P, K, Ca) and minor micronutrients (Zn, Fe, Mn, Cu) and harbors beneficial biofertilizers including *Azospirillum*, *Azotobacter*, Phosphobacteria and *Pseudomonas*, along with *Lactobacillus* species (65, 66). It also provides plant growth-promoting substances and enzymesthat improve plant health and productivity (67).

Pressmud

Pressmud, a by-product generated from sugar processing, serves as a nutrient-dense organic amendment, especially rich in organic phosphorus. Its application positively influences soil properties by improving water movement, retention ability, density, porosity and organic carbon concentration (68). When used in combination with nitrogen fertilizers, pressmud also improves nitrogen use efficiency. Former studies recorded nutrient contents of 0.90 % nitrogen, 1.50 % phosphorus and 0.5 % potassium in pressmud (69). Typical pressmud composition includes 1.0-1.5 % nitrogen, 2.5-3.5 % phosphorus and 0.5-0.8 % potassium. It significantly enriches the soil's organic matter, boosting microbial activity and aiding the conversion of organic nitrogen into plant-available forms (70).

Impact of organic nutrient sources on yield performance of sugarcane

Green manure

According to (71), the integration of leguminous green manure crops into sugarcane cultivation has been shown to enhance yield outcomes. Notable improvements were observed in stalk height, the number of tillers per plant, overall crop vigor and yield performance at both six- and twelve-months following planting. A series of Front-Line Demonstrations (FLDs) conducted (72) over three years in the Bagalkote region evaluated the effectiveness of *in situ* green manuring with *Sesbania aculeata* (dhaincha) in sugarcane cultivation. The practice aimed to mitigate soil salinity, enhance nitrogen content for subsequent sugarcane crops and sustain overall soil fertility. The findings demonstrated that *in situ* green manuring resulted in a substantial yield increase of approximately 10 tons per hectare and an additional net income of ₹25000 per hectare. Notable soil improvements included a marginal rise in organic carbon content (from 0.45 % to 0.46 %), a decrease in soil pH (from 8.16 to 7.99) and an increase in available nitrogen (from 186.40 to 190.50 kg per acre).

Farmyard manure (FYM)

Application of FYM significantly enhances sugarcane productivity. (73), working at the Padegaon Research Station in Maharashtra, It was observed that application of FYM at 25 t ha^{-1} in combination with the recommended dose of NPK resulted in higher cane yield (117 t ha^{-1}) in plant crops, with potential nitrogen savings of up to 30 %. Substituting 25 % of nitrogen with FYM or pressmud produced yields comparable to those achieved with 100 % chemical NPK (74). Moreover, this substitution strategy increased ratoon cane yields by 7-10 t ha^{-1} (71). FYM application resulted in increased cane yields ranging from 58.6 to 70.1 t ha^{-1}. Integrating organic and inorganic nutrient sources not only increases revenue and net returns but also enhances crop growth, yield, quality and nutrient uptake while conserving agro-ecosystem sustainability (21).

Goat manure

The effect of ratoon age and goat manure dosage on the vegetative growth of sugarcane, the experiment used varying ratoon ages (2, 4, 6 and 11 times) and goat manure doses (0, 14, 28 and 42 tons/ha). Results showed that applying 42 tons/ha of goat manure significantly improved sugarcane growth parameters notably improving plant height, number of leaves, tillers, biomass and leaf area even in older ratoons, indicating its potential to sustain productivity in ratoon crops subjected to repeated cutting (75).

Vermicompost

Vermicompost is abundant in total and available nitrogen, phosphorus, potassium, secondary nutrients, micronutrients, beneficial microorganisms, soil enzymes and growth-promoting hormones, making it more effective than other bulky organic manures. According to (76), applying vermicompost at 10 t ha^{-1} led to plant cane yields of 76.7 and 75.3 t ha^{-1} and ratoon cane yields of 77.7 and 78.16 t ha^{-1}in subtropical India. These results were comparable to the yields achieved with a full recommended nutrient dosage (NPK) 150:60:60 kg ha^{-1}, which produced 76.1 and 78.10 t ha^{-1} in plant and ratoon crops, respectively. Additionally, the highest soil organic carbon content (0.54 %) was noted in the vermicompost-treated plots.

Panchagavya

A nursery and a field experiment were conducted from 2010 to 2012 to study the response of various levels and sources of nutrients on sugarcane chip buds and their effects in the field. The experiment was designed and planted at the Department of Agronomy trial site at Annamalai University, Annamalainagar, Tamil Nadu application of 3 % Panchagavya as foliar spray showed moderate improvement in plant height (213cm), root length and seedling vigour compared to the control (77). While Panchagavya (3 % foliar spray) provided a notable organic alternative, it was less effective than chemical treatments in maximizing growth and yield. However, it can be part of integrated nutrient management systems aimed at reducing chemical inputs and enhancing sustainability (78).

Pressmud

Pressmud, a soft and amorphous residue generated by the sugar industry, is rich in organic matter, coagulated colloids, fiber, waxes and inorganic salts, with its composition varying based on the quality of sugarcane and the juice clarification methods used (79). The study found that applying pressmud at 20 t ha^{-1} in combination with 200 kg N ha^{-1} led to a 20-30 % increase in sugarcane yield compared to untreated control plots (80). Similarly, reported notable improvements in plant height, tiller count, total shoots, individual cane weight and an 11 % yield boost when 4 t ha^{-1} of pressmud was applied along with Azotobacter and a full nitrogen dose (81). Also noted that applying 4 t ha^{-1} of pressmud enhanced shoot population, resulted in an increased millable cane population, with a 12 % improvement in total cane production and a 10.5 % rise in sugar yield, while also reducing phosphorus fertilizer requirements by 20 kgha^{-1}(82). Impact of various organic manures on sugarcane yield and growth given in table 1, Effect of pressmud and integrated nutrient practices on sugarcane juice quality and yield parameters given in table 2.

Potential of organic inputs in enhancing soil's physical, chemical and biological characteristics

Soil enzymes serve as key biological catalysts in the decomposition of organic matter and nutrient cycling, directly mediating the biological catabolism of soil organic and mineral components. These enzymes are closely associated with soil organic matter, microbial activity and overall soil physical properties. Their activity provides sensitive and early indicators of changing soil health, often responding more rapidly than other chemical or physical parameters. Enzyme activities are widely recognized as reliable indicators of soil microbial dynamics and productivity.

Enhanced soil enzymatic activity is commonly associated with intercropping systems due to their ability to support diverse and active microbial communities. The microbial community secretes extracellular enzymes that play a pivotal role in decomposing plant residues and maintaining nutrient cycles. Crop diversification fosters a favourable microclimate and stimulates root exudation, thereby promoting microbial growth and activity. Intercropping systems have been reported to increase soil enzyme activity by up to 13 % (95). Organic amendments significantly influence soil enzyme activity and microbial biomass. Organic manures and root exudates enhance microbial activity, subsequently increasing enzymatic activity (96). A comparative study revealed that the application of organic inputs also improved soil organic carbon and nutrient availability (NPK), with no adverse effects on soil pH and electrical conductivity (97). The study demonstrated that substituting 25 % of chemical fertilizers with biocompost, enriched pressmud, or biofertilizers can maintain yield and quality while improving soil health.

Table 1. Impact of various organic manures on sugarcane yield and growth

Organic Manure	Cane Yield With Manure (t ha^{-1})	Cane Yield Without Manure (t ha^{-1})	Yield Increase (t ha^{-1})	Increase (%)	Reference
Sesbania aculeata	144.5	104.9	39.6	37.75 %	(83)
Vermicompost	93.88	87.42	6.46	7.38 %	(84)
Sugarcane trash	59.30	47.0	12.3	26.17 %	(85)
Biomethanated distillery effluent	72.13	58.50	13.63	23.29 %	(86)
Biocompost	74.14	58.70	15.44	26.30 %	(87)
Biogas slurry	70.20	57.0	13.2	23.15 %	(88)

Table 2. Effect of pressmud and integrated nutrient practices on sugarcane juice quality and yield parameters

Organic source	Key results	References
250 kg of N by urea + 50 kg of N by pressmud	Increased brix, pol, CCS % and sugar yield	(89)
Pressmud @4t ha^{-1}	10.5 % increase in sugar yield	(90)
Ratoon crop + dhaincha (green manure) + 100 % recommended N *via* fertilizers	CCS % improved to 11.35 %	(91)
Pressmud cake @10tha^{-1} + PSB@2.5 kg ha^{-1}	Better cane quality than recommended NPK application	(92)
Pressmud application	Enhanced yield and juice quality parameters	(93)
Pressmud @25t ha^{-1}	Higher brix (20.32 %) and pol (19.00 %)	(94)

A study on sugarcane intercropped with sunn hemp recorded the highest cane length (133.3 cm), followed by soybean (131.3 cm) and cowpea (125.0 cm). The maximum cane diameter (2.926 cm) and single cane weight (2.225 kg) were observed in the cowpea intercrop treatment. NMC was highest in soybean intercropping (116.5 x 10^3/ha), followed by sunn hemp (113.7 x 10^3/ha) and green gram (111.9 x 10^3/ha). Intercropping sugarcane with legumes, especially soybean, cowpea and sunn hemp, enhanced growth and yield attributes such as cane length and NMC. Green gram showed a marginally better effect on juice quality parameters. Thus, legume intercropping can be a beneficial practice in sugarcane cultivation to enhance productivity without compromising quality (98).

Adding *Sesbania aculeata* as green manure increased soil organic carbon from 0.37 % to 0.49 % and 14.4 % rise in soil available phosphorus over three years when pressmud was applied at 4 t ha^{-1} with 6 kg ha^{-1} of phosphate solubilizing bacteria (PSB) (99). The enriched pressmud was also effective in boosting soil organic carbon and enhancing the availability of phosphorus and potassium. Dhaincha intercropped in sugarcane and incorporated at 60 days after sowing (DAS), along with 75 % of the recommended nitrogen, promoted significant growth in microbial populations, particularly bacteria and fungi (100). Additionally, the application of organic manures resulted in a 44-67 % in soil organic carbon and a 147-185 % boost in microbial activity (101).

In addition to their chemical and biological benefits, organic sources also enhance the physical characters of the soil. A reduction in bulk density from 1.4 to 1.3 g cm^{-3} and an increase in the water infiltration rate from 20 % to 27.5 % following the application of 10 t ha^{-1} of pressmud was observed (102). *Sesbania aculeata* intercropped in between sugarcane rows resulted in a 50 % increase in soil organic carbon in both plant and ratoon crops. A significant reduction in bulk density and improvements in microbial carbon and nitrogen with the application of sulphitated pressmud (10 t ha^{-1}) and farmyard manure 10 t ha^{-1}(103).

A study carried out at IISR (Indian Institute of Sugarcane Research) Lucknow, during 2011 similar improvements were reported. Application of 10 t ha^{-1} each of press mud compost and FYM resulted in a 70.7 % increase in soil organic carbon, 46.7 % higher water infiltration, 61.5 % increase in total nitrogen and an 8.4 % reduction in bulk density at harvest. These findings demonstrate the potential of organic nutrient management to improve soil quality and sustain economically viable sugarcane cultivation.

Conclusion

In India, agriculture is more than a profession it's a way of life linked to the nation's economy, environment and food security. This review compares conventional, organic and natural farming systems in sugarcane cultivation. While conventional farming has boosted productivity, it poses long-term threats like soil degradation and environmental pollution. Organic and natural systems promote sustainability and soil health but face limitations in yield and scalability. Integrating the strengths of both systems through balanced use of organic amendments, green manures, biofertilizers and chemical inputs offers a sustainable path forward. Adopting a holistic approach that combines ecological principles, resource efficiency and technology is crucial for enhancing sugarcane productivity, ensuring environmental conservation and supporting climate resilience and food security. Comparison of farming practices: Summary table given in Table 3.

Acknowledgements

Authors acknowledge the support of Tamil Nadu Agricultural University for writing this review article.

Authors' contributions

SM wrote the manuscript draft and SS and PG revised it. PJ, MG and NS verified contents. All authors read and approved the final manuscript.

Compliance with ethical standards

Conflict of interest: Authors do not have any conflict of interest to declare.

Ethical issues: None

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Table 3. Comparison of farming practices: Summary table

Parameter	Conventional	Organic	INM
Yield Potential	High (short term)	Moderate	High(long term)
Soil Health	Degradesovertime	Improves	Improves
Environmental Impact	High	Low	Moderate
InputCost	High	Moderate–High	Moderate
Adoption Feasibility	High	Moderate	High

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Peer review: Publisher thanks Sectional Editor and the other anonymous reviewers for their contribution to the peer review of this work.

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