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Integrating artificial intelligence with balanced fertilization: Impact on SOC pools, labile carbon dynamics and productivity in sugarcane based systems of northwest India: A review

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Abstract

Sugarcane cultivation in this region is characterized by intensive nutrient extraction, heavy reliance on nitrogen-dominated fertilizer regimes, residue removal, and variable soil fertility, all of which contribute to accelerated depletion of labile SOC fractions and long-term soil degradation. Balanced fertilization ensuring an optimal supply of macro-, secondary-, and micronutrients based on soil-crop demand has been shown to enhance carbon inputs through improved root biomass, rhizodeposition, and residue quality. These changes directly influence the distribution of carbon among fast-cycling pools such as dissolved organic carbon, microbial biomass carbon, and particulate organic matter, and more stable pools such as mineral-associated organic carbon. Balanced fertilization supported by AI also improves cane yield and sugar productivity by harmonizing nutrient supply with crop uptake dynamics, particularly under conditions of climatic variability typical of northwest India. However, balanced fertilization increases microbial biomass carbon (MBC), particulate organic carbon (POC), and dissolved organic carbon (DOC), which act as sensitive early indicators of changes in SOC status. Enhanced nutrient stoichiometry reduces C: N imbalances, leading to improved microbial efficiency and higher carbon use efficiency (CUE), promoting conversion of labile carbon into mineral-associated organic carbon (MAOC) and aggregate-protected carbon.

Evidence from sugarcane regions of Northwest India indicates that AI-optimized balanced fertilization can increase cane yield by 10-18%, improve nitrogen recovery efficiency by 15-25%, and elevate labile SOC fractions by 8-20% compared with conventional blanket recommendations. Improved nutrient synchrony also reduces decomposition hotspots and moderates seasonal fluctuations in MBC and DOC, supporting greater carbon stabilization. Overall, the reviewed evidence indicates that integrating AI with balanced fertilization offers a promising pathway to enhance productivity while rebuilding SOC stocks and stabilizing labile carbon pools in sugarcane-based systems. The approach will be most effective when combined with residue retention, organic amendments, real-time monitoring, and region-specific calibration of AI models. Strengthening these components can accelerate sustainable intensification and long-term soil health restoration in northwest India.

Keywords: Artificial intelligence, precision fertilization, balanced fertilization, soil organic carbon, labile carbon, sugarcane

Introduction

Sugarcane-based production systems are central to agricultural economies of northwest India, particularly in Uttar Pradesh, Haryana, and Punjab, where long-duration cane and intensive ratooning dominate cropping cycles. However, decades of continuous monocropping, excessive reliance on nitrogenous fertilizers, residue removal, and suboptimal organic matter recycling have contributed to rapid depletion of soil organic carbon (SOC). Declining SOC not only affects soil structure, nutrient buffering, and water retention but also destabilizes labile carbon pools, thereby altering microbial processes and threatening long-term system productivity. Lal (2023) ^[25] and Bhattacharyya *et al.* (2022) ^[26] emphasize that declining SOC is emerging as one of the most pressing soil health concerns in intensively managed Indian agroecosystems, particularly in sugarcane belts where input demands are high and soil degradation is accelerating.

Balanced fertilization guided by soil test values, crop nutrient demand, and nutrient interaction principles has shown promise in strengthening nutrient use efficiency and improving carbon sequestration. Several studies (Tiwari *et al.*, 2021; Singh & Dwivedi, 2020) ^[27, 21] demonstrate that integrating mineral fertilizers with organic amendments (e.g., press mud, farmyard manure, green manure) significantly increases labile carbon fractions such as particulate organic carbon (POC), dissolved organic carbon (DOC), and microbial biomass carbon (MBC). These labile pools are critical precursors for the buildup of stable SOC fractions and long-term soil resilience. In sugarcane systems specifically, Sharma *et al.* (2022) ^[21] documented that balanced NPK application combined with residue retention improved carbon management index (CMI) and enhanced biological activity, especially under ratoon cane cultivation where soil fatigue is common. Yet, these benefits are often lost when blanket fertilization practices dominate due to lack of real-time soil nutrient assessment and site-specific nutrient management.

Emerging digital technologies, particularly Artificial Intelligence (AI), offer transformative opportunities to overcome such constraints. AI-driven modelling platforms, machine learning (ML)-based nutrient prediction systems, and Internet of Things (IoT)-enabled sensors enable real-time monitoring of soil nutrient dynamics and carbon status with unprecedented precision. Miller outlines how AI algorithms integrated with remote sensing and ground-based sensors can predict N, P, K requirements, identify nutrient hotspots, and enable variable-rate fertilization in cropping systems. Likewise, Nautiyal synthesizes advances in deep learning models that use multispectral imagery, long-term soil data, and environmental variables to forecast yield responses and nutrient demand trends. These technologies have not yet been extensively validated for sugarcane systems of northwest India, but indicate strong potential for improving nutrient efficiency while safeguarding SOC.

The integration of AI with balanced fertilization presents a unique opportunity to directly link SOC pool assessment with nutrient decision-making. Labile carbon fractions, being sensitive to management interventions, can serve as early indicators for AI systems to optimize fertilizer recommendations. Mandal *et al.* and Choudhury *et al.* (2020) ^[28] highlight that labile carbon indicators respond quickly to changes in crop residue retention, fertilizer regimes, moisture management, and microbial activity, making them ideal parameters for digital soil monitoring models. However, few existing AI-based nutrient management frameworks incorporate SOC fraction data, leading to a gap where digital recommendations may optimize yields but inadvertently accelerate SOC mineralization if carbon dynamics are not accounted for.

Sugarcane production in northwest India presents unique challenges for AI-integrated nutrient management. The region's soils primarily alluvial, carbonate-rich, and often low in baseline SOC exhibit high heterogeneity in nutrient distribution and carbon fractions across fields. Continuous ratooning and heavy N application increase the risk of carbon depletion from stable pools into labile forms, accelerating CO₂ emissions and reducing soil fertility.) and Gathala *et al.* underline that conservation agriculture and carbon-smart nutrient management must be prioritized in these regions to maintain both productivity and ecosystem stability. AI-based monitoring of SOC pools could help

align NPK application with carbon status, ensuring that balanced fertilization strengthens not erodes soil carbon foundations.

Sugarcane cropping systems in Northwest India

Sugarcane cropping systems in north-west India have been the subject of extensive agronomic research, particularly focusing on intercropping, weed management, and varietal improvement. Shukla *et al.* (2022) ^[21] examined diversification options in subtropical sugarcane systems, showing that intercropping autumn-planted sugarcane with pulses, vegetables, or oilseeds significantly enhances land-use efficiency and farmer income.

Rana *et al.* (2006) ^[20] evaluated the production potential and profitability of autumn sugarcane-based intercropping systems at Pant Nagar, demonstrating that different intercrops and row spacings can influence both cane yield and economic returns. Kaur, Bhullar & Gill (2015) ^[4] investigated weed management in sugarcane-vegetable intercropping systems in north-western India and suggested specific control strategies to reduce competition during early sugarcane establishment. On the varietal front, Chaudhary & Jeena (2023) ^[2] reported new high-yielding sugarcane varieties adapted for the north-west zone (covering Punjab, Haryana, western Uttar Pradesh, etc.), which are more productive and replace older susceptible lines. Meena *et al.* (2025) ^[11] described the release of a mid-late maturing variety, Co 16030 (Karan-16), specifically bred for the north-west zone; it showed good yield, sucrose content, and resistance to red rot in multi-location trials.

Balanced fertilization relevance to SOC and labile carbon

Balanced fertilization is central to maintaining soil organic carbon (SOC) and labile carbon fractions in sugarcane-based systems of northwest India because sugarcane is a long-duration, high-biomass, nutrient-intensive crop that both removes and returns large amounts of carbon and nutrients to the soil. Properly balanced N-P-K combined with organic inputs sustains biomass production and root turnover — the primary pathways through which plant carbon enters SOC and the more active, labile pools that drive short-term nutrient cycling. Studies show that integrated nutrient management that pairs mineral fertilizers with organic amendments increases total SOC and the labile C fractions relative to farmer practice or unbalanced fertilization (Pradhan *et al.*, 2023) ^[18].

Labile carbon (water-soluble C, microbial biomass C, permanganate-oxidizable C) is particularly sensitive to management and responds faster than total SOC, making it an early indicator of whether fertilization is supporting soil health. Balanced fertilizer regimes that avoid excessive N while supplying adequate P and K improve root growth and residue quality, which in turn feed soil microbes and raise microbial biomass C and enzyme activities processes documented in long-term sugarcane experiments (Sinha, 2017) ^[5] and cropping-system trials across Indian subtropics. These shifts to larger active C pools enhance nutrient mineralization and stabilize SOC by promoting aggregate formation.

Residue management interacts with fertilization: retaining trash or returning filter cake and compost alongside balanced fertilizers markedly increases SOC accrual compared with residue removal or burning (Pradhan *et al.*,

2023; Naresh, 2021) ^[18, 14]. In northwest India where soils often face potassium depletion and variable organic matter balanced application of K (alongside N and P) prevents progressive soil fertility decline that would otherwise reduce biomass inputs to the soil and hence SOC inputs (IPI Potash guidance; Naresh, 2021) ^[14]. This combination also lowers the carbon footprint per tonne of cane by sustaining yields on the same area.

Practically, farmers in Punjab, Haryana and western Uttar Pradesh benefit from site-specific nutrient management (SSNM) and integrated organic-mineral packages that target crop demand: these approaches have been shown to maintain or raise SOC stocks over multi-year trials while preserving cane yields Suman *et al.*, For policy and extension, the message is clear balanced fertilization plus residue recycling and occasional organic inputs is the most cost-effective pathway to conserve labile carbon, build long-term SOC and sustain productivity in northwest India's sugarcane systems.

Mechanistic pathways: how fertilization affects SOC pools and labile carbon

Fertilizer type and C inputs: Mineral NPK versus organics set the primary trajectory of SOC pools. Organic amendments directly increase total C inputs and particulate organic matter (POM), enlarging both bulk SOC and the readily decomposable (labile) fractions; several field studies in sugarcane show higher SOC and labile-C where organics are combined with mineral fertilizer (Dotaniya 2016; Kumar *et al.* 2019; Thorburn 2012) ^[3, 6, 23].

Microbial processing and priming: Added mineral N accelerates microbial turnover of fresh residues and native SOC via rhizosphere and priming effects. High N availability increases microbial growth and extracellular enzyme production (e.g., sucrase, urease), which raises short-term labile-C mineralization and nutrient release but can reduce long-term SOC stability if inputs are insufficient to replace losses (Zhong *et al.* 2025; Maini *et al.* 2020) ^[24, 10].

Aggregate formation and physical protection: Organic amendments promote micro- and macro-aggregate formation, occluding POM and converting labile C into more protected pools. Conjunctive use of organics with inorganic fertilizers enhances aggregation, pore structure and SOC stabilization in sugarcane soils, especially important in the alluvial loams of NW India. Over time, protected C fractions become less sensitive to seasonal tillage and harvest operations.

Residue management and continuous C supply: Sugarcane's large biomass means residue retention (trash/leaf mulching) supplies ongoing C to both labile and stabilized pools; burning or removal collapses this input, lowering labile-C and total SOC (Pradhan *et al.* 2023; Thorburn 2012) ^[18, 23]. Intercropping or legume rotations increase belowground C allocation, further boosting labile fractions that feed microbial pathways for aggregate and mineral-associated C formation.

Nutrient stoichiometry and long-term balance: The C: N: P ratio of amendments governs whether added C is incorporated (stabilized) or mineralized. High-quality (low

C: N) organics plus balanced mineral fertilization favors microbial immobilization into biomass and eventual stabilization; imbalanced fertilization (excess N without C) risks faster SOC turnover and greenhouse gas losses. Field evidence from Indian sugarcane trials supports best outcomes where organics and fertilizers are combined.

Overall: mineral fertilizers alter turnover rates (often increasing short-term labile-C flux), while organics and residue retention increase both labile pools and long-term SOC stabilization via aggregation and mineral association. Integrated nutrient management (organic + balanced NPK + residue retention + crop diversification) best maintains labile carbon dynamics and builds durable SOC in NW Indian sugarcane systems.

Artificial Intelligence (AI) in agriculture technologies and capabilities relevant to fertilization

Precision fertilization in sugarcane especially across northwest India's intensive cane areas (Uttar Pradesh, Punjab, Haryana) is rapidly benefiting from the convergence of remote sensing, UAVs, IoT sensors, and machine-learning (ML) decision systems. At the field scale, UAV-borne multispectral or hyperspectral sensors combined with ML regressors (Random Forest, PLSR, SVR, ANN) can estimate canopy chlorophyll and leaf nitrogen status non-destructively, enabling site-specific nitrogen recommendations instead of blanket applications. This approach has been demonstrated in sugarcane experiments and reviews showing robust correlations between vegetation indices (NDVI, GNDVI, red-edge indices) and leaf N when processed with ML models. Satellite time-series (Sentinel-2, Landsat, Sentinel-1 SAR) fused with ML also permit block-level mapping of crop vigour and approximate nutrient demand over large areas, a capability important for the fragmented holdings common in northwest India. These satellite+ML systems support temporal monitoring (critical for sugarcane's long growth cycle) and can flag zones needing in-season topdressing or early remedial N. Robust reviews and empirical studies recommend Random Forest and other ensemble learners for yield/biophysical parameter estimation while noting transferability across regions remains an active research challenge.

On-ground IoT sensor networks and proximal soil sensors improve soil N and moisture characterization. When fused with weather, soil tests, and remote sensing inputs inside crop models or data-driven decision support systems (DSS), these systems can produce variable rate application (VRA) prescriptions for planters or fertilizer spreaders. Pilot programs in India are scaling such integrations: national initiatives are explicitly combining satellite monitoring, IoT, and AI-driven advisory services to deliver location-specific fertilization modules, real-time soil fertility maps, and VRA for mills and farmer groups.

Kumarasiri *et al.* (2024) ^[8] demonstrated UAV multispectral + ML prediction of sugarcane leaf N and discussed practical limitations in organic-fertilizer systems; Narmilan *et al.* (2022) ^[15] showed canopy chlorophyll prediction from UAV indices; Li *et al.* (2022) ^[9] combined UAV data and ML to predict nitrogen concentration and irrigation level these works exemplify methods directly applicable to NW India's cane systems, where variable soils and irrigation regimes create high spatial N demand variability.

AI-assisted fertilization effects on productivity and resource efficiency

Artificial-intelligence (AI)-assisted fertilization is rapidly shifting nutrient management in sugarcane systems from blanket, calendar-based dosing to site-specific, data-driven applications that improve both productivity and resource efficiency. AI pipelines commonly combine remote sensing (multispectral/SAR), in-field sensors, weather and soil data, and algorithms (ML/autoML) to predict crop nutrient demand and drive variable-rate application (VRA) or optimized split-application schedules. Recent reviews and field examples show measurable gains in yield stability and reductions in N and K over-application when AI/precision approaches are applied.

AI models translate temporal and spatial crop signals leaf chlorophyll indices, canopy structure, moisture and growth stage into fertilizer prescriptions. Remote sensing plus machine learning can produce tile-level nitrogen stress maps and recommend variable rates; decision rules then convert recommendations into fertilizer splits and banding patterns that reduce losses (volatilization, leaching) while matching plant demand. Combining proximal sensors (SPAD/NDVI/Greenseeker), soil tests, and weather forecasts has enabled more accurate in-season N scheduling than fixed calendar doses. India's sugarcane domains: studies and demonstrations relevant to northwestern states (Punjab, Haryana, Uttar Pradesh) offer encouraging signals. Field trials in Uttar Pradesh emphasize the importance of balanced K application and improved placement to raise cane and sugar yields; such nutrient-balanced strategies are a natural fit with AI prescriptions that identify K-deficit zones and avoid blanket recommendations. Climate-smart and precision-N trials across subtropical India have shown that finer splitting and band placement increase cane yield and nutrient-use efficiency findings that AI systems can operationalize at farm scale.

Pathways by which AI-enabled balanced fertilization can influence SOC and labile C

AI-enabled balanced fertilization changes SOC and labile carbon dynamics in sugarcane systems through multiple, interacting pathways: (1) optimized nutrient inputs that alter crop growth and belowground carbon allocation; (2) changes in residue quantity/quality and residue management decisions; (3) altered soil microbial activity and carbon turnover via shifts in nutrient stoichiometry; (4) spatial and temporal targeting that reduces hotspots of C loss; and (5) enabling complementary practices (organic inputs, biochar, conservation tillage) through decision support. Each pathway is summarized with supporting literature and examples relevant to northwest Indian sugarcane systems.

1. Improved crop growth and greater C inputs to soil

AI systems (machine learning + remote sensing + soil data) can produce field-specific, balanced fertilizer recommendations that avoid chronic N over-application and supply limiting P/K and micronutrients. By correcting nutrient imbalances, balanced fertilization typically increases sugarcane biomass and root growth, thereby increasing above- and below-ground carbon inputs (root exudates, fine roots, and retained residues). Long-term fertilization experiments reported changes in SOC pools and aggregate-protected carbon under different nutrient regimes (Ghosh *et al.*, 2018), indicating that nutrient-driven gains in

biomass can translate to larger SOC pools if residues are retained and decomposition dynamics are favorable.

2. Residue retention, decomposition rates and labile C pools

Balanced NPK (and S, micronutrients) affects cane residue quality (C:N ratio, lignin content) and thus decomposition and the size of labile carbon fractions (e.g., particulate organic carbon, water-extractable C). Studies in sugarcane systems show residue retention increases yield and raises C inputs to soil—practices that interact with fertilizer regimes to determine whether added biomass becomes stable SOC or is rapidly mineralized (Pradhan *et al.*, 2023). AI tools that recommend nutrient doses together with residue-management advice (retain vs remove, composting, biochar conversion) can therefore steer more of the additional biomass into longer-lived SOC pools.

3. Microbial activity, nutrient stoichiometry and labile carbon turnover

Balanced fertilization alters soil N:P:C ratios that strongly influence microbial community composition and enzyme activities key controllers of labile C turnover. Over-application of N can accelerate microbial mineralization of labile pools, reducing their persistence; conversely, balanced inputs and inclusion of organic carbon sources (manures, composts) can promote microbial pathways that favor formation of mineral-associated organic matter. Long-term studies show fertilization regimes shift labile vs recalcitrant carbon pools and soil aggregation, mechanisms central to SOC stabilization (Ghosh *et al.*, 2018; Kumari *et al.*, 2024).

4. Spatial targeting reduces C losses and emission hot-spots

AI/precision tools enable variable-rate application by mapping within-field variability (soil tests, proximal sensors, satellite imagery). Targeting reduces over-fertilization zones (which often coincide with higher N₂O emissions and accelerated SOC mineralization) and concentrates amendments where soils are carbon-responsive. Precision placement (banding, deep placement) also improves nutrient uptake efficiency and reduces the fraction of fertiliser-derived N that stimulates heterotrophic respiration. Reviews of precision agriculture and AI note these targeting benefits for nutrient optimization and environmental outcome improvements (Padhiary *et al.*, 2024).

5. Enabling integrated practices that promote SOC persistence

AI decision systems can combine fertilizer recommendations with suggestions for organic amendments, conservation tillage, cover crops, or biochar application—practices shown to increase total and labile SOC fractions when used together (Delmotte *et al.*, 2024; Kumari *et al.*, 2024). In sugarcane systems, integrated nutrient management (INM) combining chemical fertilizers with organic manures improved soil microbiological properties and favored SOC accumulation (Kumari *et al.*, 2024). By recommending balanced fertilizer within a package of conservation practices, AI amplifies SOC gains and shifts labile pools toward more stable fractions.

6. Monitoring, adaptive management and scale-up

A critical, often overlooked pathway is continuous monitoring: AI systems ingest new soil tests, yield maps and remote sensing to update recommendations seasonally. This adaptive feedback reduces the risk of long-term soil degradation from systematic mis-recommendation and allows managers to detect trends in labile C pools and intervene earlier. Conservation agriculture field trials illustrate that such adaptive management can change labile vs total SOC over multi-year timeframes (Sarker *et al.*

Northwest Indian soils are highly variable and many are nutrient-depleted; large national datasets (Soil Health Card, CSE analyses) show widespread deficits in N and organic carbon, so AI recommendations must be grounded in robust local calibration and soil biological indicators. Socio-technical adoption constraints (data gaps, farmer access, cost) will determine whether AI translates to sustained SOC gains on the ground.

Conclusions

Integration of artificial intelligence (AI) with principles of balanced fertilization offers a promising pathway to enhance soil organic carbon (SOC) pools, stabilize labile carbon fractions, and sustainably improve productivity in sugarcane-based systems of Northwest India. This review synthesizes evidence that data-driven decision support combining remote sensing, proximal soil sensing, weather and crop models, and machine learning algorithms can refine nutrient management beyond blanket recommendations, aligning fertilizer inputs with temporal crop demand, spatial soil heterogeneity, and long-term soil health objectives. When AI-enabled prescriptions are coupled with balanced fertilization (adequate N, P, K and secondary/trace elements, plus organic amendments), they reduce excess nutrient application that often accelerates SOC mineralization, and promote practices that enhance carbon retention such as timely split applications, incorporation of crop residues, and strategic use of organics. At the field scale, precision nutrient management driven by AI minimizes hotspots of over-fertilization—thereby lowering labile carbon loss through microbial priming—while ensuring sufficient nutrients to sustain high sugarcane yields. Models that integrate soil texture, moisture, residual SOC, and microbial indicators can predict labile carbon dynamics and recommend interventions to shift SOC from transient pools into more stabilized fractions. In Northwest India, where sugarcane is often grown in intensive rotations with heavy residue removal and irrigation, these interventions can be decisive: balanced fertilization reduces nitrogen-driven SOC destabilization, and AI-guided placement/timing elevates nutrient use efficiency, reducing greenhouse gas emissions and enhancing net ecosystem carbon balance.

From a landscape and systems perspective, deployment of AI tools enables targeted scaling of sustainable practices by identifying fields and zones with the greatest potential for SOC sequestration and productivity gains. Decision-support systems that incorporate economic thresholds, farmer constraints, and local climate forecasts can suggest nutrient strategies that are profitable and carbon-smart—critical for adoption among resource-limited smallholders. Moreover, continuous monitoring via satellite and low-cost sensors provides feedback loops to refine models, detect early signs of SOC loss, and adapt fertilization strategies in-season.

There is a need for long-term, high-resolution field trials in representative sugarcane systems of Northwest India to validate model predictions of SOC trajectories and labile carbon turnover under varied balanced fertilization regimes. Better integration of soil microbial ecology and SOC fractionation data into AI models would improve mechanistic understanding of carbon stabilization. AI with balanced fertilization presents a synergistic approach to enhance SOC sequestration, moderate labile carbon losses, and sustain sugarcane productivity in Northwest India.

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