AI tools and Technologies for Productivity Enhancement in Sugar Industry

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ABSTRACT
The South Asian region, especially India, is a key player in global sugar production. India ranks among the top sugar producers. Over the years, India has improved its sugarcane farming with advanced technologies, making the industry productive, sustainable, and self-reliant. This independence, supported by industry connections and partnerships, helped it overcome challenges, including those caused by the COVID-19 pandemic. Furthermore, the industry engages in social responsibility activities that benefit stakeholders and align with the 2030 Sustainable Development Goals. This paper explores ways to improve sugarcane farming and productivity using new technologies in the sugarcane industry. The adoption of ICT and IoT has ushered in a new era for India's sugarcane industry, transforming it into a tech-enabled, self-reliant sector. These innovations have not only modernized traditional farming and processing methods but also laid the groundwork for a more resilient, eco-friendly, and profitable future. As technology continues to evolve, the industry is poised to reach new heights - benefiting millions of farmers and stakeholders across the country.

General Terms
Sugar Industry, Pattern Recognition, Internet of Things, Deep Learning.

Keywords
AI, Sugar production, GIS, Sugarcane, Productivity Enhancement, Data Analysis.

1. INTRODUCTION
India is a key sugar producer in South Asia, hitting record production levels recently due to strong research and development. With a long history of sugarcane farming, India has created new, region-specific technologies that have made it a global leader in sugar production. The sugar industry supports about 7 million farmers and many workers across more than 550 mills. Besides meeting the domestic demand of 27 million tons annually, the industry produces 370-400 million tons of cane and 27-30 million tons of sugar. It also makes jaggery, biofuels, bioelectricity, and chemicals. The industry exports 3,500 MW of power to the national grid, making it self-sufficient and a model for sustainable energy and production. Additionally, the Government of India aims to double farmers' incomes in five years, with special focus on sugarcane farmers [1].

To improve sugarcane farming, we need to:

- Develop cost-effective technologies.
- Transfer these technologies from the lab to the field.
- Educate farmers.
- Foster cooperation among stakeholders.

Efforts will focus on increasing sugarcane productivity and using resources efficiently through methods like intercropping, managing pests and diseases, biotechnology, and reducing losses after harvest.

Advances in biotechnology, such as genetically modified stress-resistant varieties, will play a key role. Success depends on the profitability and sustainability of the sugar industry. By using advanced technologies, cutting cultivation costs, and creating value-added products, farmers' incomes can increase [2].

Small-scale waste-to-resource technologies can also boost income, especially for farmers in India's subtropical regions. Sugarcane is the main source of sugar in India, producing around 359 million tons annually, with 75% processed by 526 sugar mills. As a C4 plant, sugarcane efficiently converts sunlight into biomass, making it valuable for sustainable farming. To maximize its potential, adopting modern, scientific, and mechanized farming practices is essential. Increasing productivity per area while lowering costs can boost profitability. This can be achieved through biotechnology, improved yield and disease-resistant varieties, and climate-resilient strains to counter climate change effects. Efforts to breed stress-tolerant varieties aim to enhance sugarcane's performance under environmental challenges, especially in subtropical regions [3].

2. ADOPTION AND DEVELOPMENT OF THE SUGARCANE VARIETIES
The sugar industry depends on having high-yield, high-sugar-content sugarcane varieties. To maximize sugar recovery, it's important to have a steady supply of quality sugarcane throughout the crushing season, which lasts from October to April. Choosing early and mid-late maturing varieties strategically helps increase sugar production, as the type of varieties directly affects recovery and productivity in any area [4].

Maintaining a mix of early and mid-late varieties allows for a longer crushing period with better sugar recovery. Studies show that a well-planned schedule for these varieties helps growers and mill operators optimize land use, planting, harvesting, and ratooning. This ensures a continuous supply of mature, high-quality cane, benefiting both farmers and sugar mills. Biotechnology has also created new elite varieties with higher sugar content, further improving sugar recovery rates [5].

In India, several promising early and mid-late maturing varieties (e.g., CoS 8436) have been introduced, enhancing sugar recovery in both tropical and subtropical regions. Expanding these high-sugar-yielding varieties, especially in a 50:50 ratio of early to mid-late, can significantly boost sugar

production. Effective planning of these varieties, staggered planting, and optimized harvesting can lead to higher sugar yields and better incomes for farmers [6].

3. USE OF GOOD QUALITY PLANTING MATERIAL

Germination is crucial for high yield and quality in sugarcane. To optimize germination, choose healthy canes from irrigated fields with low disease or pest risk. Use 2–3 bud setts from the top of the cane, planted right after cutting, when soil moisture is above 15% and the temperature is between 16–32 °C. Good seed-cane quality depends on the size, thickness, food reserves, and health of the setts, as well as the age and condition of the crop [7].

Setts from crops with high nitrogen and water levels can improve germination by over 20% and enhance yield and sugar content. Since buds rely on the setts' food reserves until roots develop, keeping the setts moist is essential. Thick canes offer about 5% better germination than thin ones, and 2–3 bud setts provide better crop stands than single-bud setts [8].

For best results, treat the setts with carbendazim (0.1%) and, if moisture is low, temperatures are high, or planting is delayed, soak the setts in water and irrigate the field right after planting. These methods can boost germination rates by 30–40%, improving crop quality and yield [8].

4. RECENT TECHNOLOGIES FOR HIGHER PRODUCTIVITY

India, a top sugarcane-growing country with various climates, needs location-specific farming strategies for the best crop performance. Information and Communication Technology (ICT) is transforming sugarcane farming by providing customized, easy-to-use solutions that boost productivity, profitability, and sustainability [9].

One significant innovation is the GPS-based sugarcane crop area survey introduced by the Indian Sugar Mills Association (ISMA) in 2011. Using GPS for mapping has replaced labour-intensive surveys, reducing manual work and allowing for precise crop estimation with just one operator instead of a team. This technology also enables accurate, location-specific soil nutrient analysis, helping sugarcane growers manage their soil better [10].

Various mobile applications make field management easier and more efficient. For example, "Cane Advisor" by ICAR-Sugarcane Breeding Institute helps with nutrient management, while "IkshuKedar" from ICAR-IISR, Lucknow, assists farmers in scheduling irrigation based on crop needs, ensuring efficient water use. These ICT tools also help conserve resources by minimizing unnecessary interventions and optimizing inputs like water and nutrients. The Soil Moisture Indicator by ICAR-SBI, which won the National Water Award in 2019, is a great example of these advances, helping stakeholders conserve water [11].

In addition to managing resources, disease diagnostics have also improved. Apps like "CaneDES" from ICAR-IISR, Lucknow, and "Plantix" (developed by PEAT, Germany, in collaboration with ICRISAT and Andhra Pradesh's Acharya NG Ranga Agricultural University) allow farmers to identify and manage crop diseases or disorders efficiently, directly from their mobile devices [12].

ICT has made post-harvest activities like marketing and sales more efficient. The Sugarcane Information System (SIS) from the Government of Uttar Pradesh is an e-governance platform that improves the transparency of sugarcane transactions, removes middlemen, ensures accurate cane weighing, and reduces the need for farmers to travel. During the COVID-19 pandemic, these mobile solutions were very valuable as they supported operations despite movement restrictions and helped farmers become self-reliant [13].

With ICT innovations, India's sugar industry has evolved to meet traditional agricultural needs as well as modern demands for efficiency, sustainability, and resilience, even in tough times [14].

4.1 ICT for Sugarcane Agriculture

India's sugarcane industry is one of the largest in the world and has greatly benefited from Information and Communication Technology (ICT). ICT has changed many aspects of crop production, resource management, disease control, and post-harvest processes. Due to India's diverse climates, location-specific strategies are important, and ICT helps provide custom solutions that boost productivity, profitability, and sustainability for millions of farmers and stakeholders in this industry [15].

4.1.1 GPS-Based Crop Area Mapping and Monitoring

One significant advancement in precision agriculture for sugarcane is the GPS-based crop area survey, introduced by the Indian Sugar Mills Association (ISMA) and other agencies in 2011. This system reduces the need for labor-intensive surveys by providing accurate crop mapping with just one operator. In addition to estimating area, GPS technology helps track crop health, assess field conditions, and detect nutrient deficiencies. According to ISMA, GPS-based surveys allow real-time monitoring, which enables more accurate forecasting and planning for the sugar industry. These benefits are even greater when combined with Geographic Information System (GIS) mapping, which helps sugarcane mills and government agencies analyze spatial data to improve resource allocation and crop productivity [16].

4.1.2 Nutrient and Water Management through Mobile Applications

Several mobile applications designed for sugarcane farmers streamline nutrient and water management [17]:

4.1.2.1 Cane Advisor:

Developed by ICAR-Sugarcane Breeding Institute (ICAR-SBI) in Coimbatore, this easy-to-use app provides guidelines on nutrient management based on soil and crop conditions. By giving farmers timely information on the best nutrient requirements, the app helps improve crop health and yield [8].

4.1.2.2 IkshuKedar:

Created by ICAR-IISR in Lucknow, this app helps farmers schedule irrigation precisely according to crop water needs. By reducing water waste and ensuring timely irrigation, the app supports sustainable water use, which is especially important in areas with limited water resources. The app has been very successful in regions with scarce groundwater, reducing water usage while maintaining productivity [16].

4.1.2.3 Soil Moisture Indicator:

Developed by ICAR-SBI, this device measures soil moisture to help farmers avoid over-irrigation and improve water use efficiency. The Soil Moisture Indicator, which won the National Water Award in 2019, has been especially useful in water-scarce regions like Maharashtra and Karnataka. It advises farmers on when to irrigate, greatly reducing

unnecessary water usage [10].

4.1.2.4 Meetha Sona:
An interactive app by DSCL Sugars Ltd., Meetha Sona allows farmers to schedule irrigation and receive timely weather updates, pest control advice, and planting tips. This app helps farmers integrate various farming practices for the best results and provides a platform for them to connect with advisors [15].

4.1.3 Disease and Pest Management
ICT tools help improve disease and pest management, which is crucial for keeping sugarcane crops healthy:

4.1.3.1 CaneDES:
This diagnostic tool from ICAR-IISR, Lucknow, helps farmers identify diseases early and provides targeted solutions to control infections.

4.1.3.2 Plantix:
Developed by PEAT, Germany, in collaboration with ICRISAT and Acharya NG Ranga Agricultural University, India, Plantix is a popular app that uses AI to diagnose plant diseases from photos uploaded by farmers. This tool has been effective in India, providing immediate feedback on disease management, pest control, and nutrient deficiencies, which is important in areas where sugarcane diseases are common [9].

4.1.3.3 e-Pest Surveillance:
In Maharashtra, the Department of Agriculture, with help from the National e-Governance Plan in Agriculture (NeGPA), has implemented e-Pest Surveillance. Crop health specialists use mobile applications to monitor pests in sugarcane fields, allowing for quick responses to pest outbreaks [11].

4.1.4 Post-Harvest and Marketing Platforms
ICT has made post-harvest processes more efficient and transparent:

4.1.4.1 Sugarcane Information System (SIS):
Implemented by the Government of Uttar Pradesh, SIS is an e-governance platform that streamlines the sale, procurement, and marketing of sugarcane. It benefits farmers by ensuring transparency, eliminating middlemen, and simplifying the sale process. SIS also includes modules for weighing and payment, allowing farmers to track payments and check sale records online, reducing the need for frequent trips to mill offices [16].

4.1.4.2 Digital Payment Platforms:
With a high reliance on cash transactions in the sugarcane sector, digital payment platforms have become popular. For example, Unified Payments Interface (UPI) and mobile banking apps have facilitated faster payments from sugar mills to farmers, especially during the COVID-19 pandemic when in-person transactions were difficult [6].

4.1.4.3 Online Crop Advisory Services:
The Krishi Vigyan Kendra (KVK) network, managed by ICAR, provides online advisory services to sugarcane farmers across various states. Through video conferences and WhatsApp groups, KVK experts offer guidance on pest control, irrigation, and crop management, helping farmers stay updated on best practices and resolve issues quickly [16].

4.1.5 Energy and Biofuel Production: ICT's Role in Sugar Complex Operations
India's sugar industry has evolved into a versatile sector that produces sugar, biofuels, bio-CNG, bioelectricity, and biomanure. ICT tools help manage these diverse operations efficiently:

4.1.5.1 Smart Monitoring Systems for Bioelectricity Production:
With ICT, sugar mills can monitor and optimize bioelectricity generation from bagasse, a by-product of sugarcane. Remote monitoring systems track energy output, helping facilities manage production efficiently and meet energy demands. The surplus energy generated is sold to the national grid, making the industry more self-sustaining [18].

4.1.5.2 Bioethanol Production Tracking:
ICT tools also help monitor bioethanol production. Real-time data analysis allows facilities to adjust production to meet the growing demand for green energy sources, supporting India's initiatives toward cleaner fuels [4].

4.1.6 COVID-19 and ICT's Role in Ensuring Business Continuity
During the COVID-19 pandemic, ICT was extremely valuable as it allowed remote support and minimized disruptions in sugarcane farming. Mobile apps enabled farmers to schedule irrigation, diagnose diseases, and receive advisory services, even with movement restrictions. The quick adoption of digital solutions showed the sector's resilience and paved the way for a more self-reliant, ICT-enabled future [12]

4.2 IoT in Sugar Industry
IoT (Internet of Things) has great potential to boost productivity in the sugar industry. By connecting devices, sensors, and machines, IoT can gather real-time data and automate processes in sugarcane farming, production, and processing. Here's how IoT can drive efficiency, sustainability, and yield improvement in the sugar industry:

4.2.1 Precision Agriculture and Crop Monitoring
4.2.1.1 Soil and Climate Monitoring:
IoT sensors can monitor real-time soil moisture, temperature, humidity, and nutrient levels. This helps farmers optimize planting, watering, and fertilization schedules based on the exact needs of the soil [].

4.2.1.2 Weather Stations:
On-field weather stations with IoT capabilities can forecast weather and predict environmental changes. This data helps farmers plan irrigation and harvest, protecting crops from extreme weather and avoiding resource wastage [10].

4.2.1.3 Disease and Pest Detection:
Smart cameras and sensors can monitor for pests and diseases in real-time, identifying outbreaks before they spread. Early detection and treatment reduce yield loss and lower the costs associated with large-scale pest management [8].

4.2.2 Smart Irrigation and Water Management
4.2.2.1 Automated Irrigation Systems:
IoT-enabled irrigation systems, like drip irrigation, can detect moisture levels and water the crops based on real-time needs. This saves water and ensures crops get the right amount of hydration. This approach is especially useful in areas with limited water and can improve yields by preventing under- or over-watering [20].

4.2.2.2 Soil Moisture Sensors:
Using IoT moisture sensors in sugarcane fields ensures efficient water use by activating irrigation systems only when soil moisture is below optimal levels. These sensors can help reduce water usage by up to 50%, which is crucial for sustainable water management in sugarcane farms [12].

4.2.3 Efficient Nutrient and Fertilizer Application

4.2.3.1 Real-Time Nutrient Analysis:

IoT sensors can monitor the soil's nutrient levels and determine when extra fertilizers are needed. This precise approach reduces overuse of fertilizers, lowers costs, and prevents environmental damage [6].

4.2.3.2 Fertilizer Application Systems:

Automated nutrient dispersal systems can apply fertilizers only when needed, based on data from IoT sensors. This ensures crops receive optimal nutrients throughout their growth cycles [13].

4.2.4 Crop Health Monitoring

4.2.4.1 Drones with IoT Capabilities:

Drones with cameras and sensors can quickly scan large sugarcane fields to monitor crop health, identify stress signs, and spot nutrient deficiencies. IoT drones can send this data to a central system, helping farmers take timely action for crop management [6].

4.2.4.2 Image Analysis and AI Integration:

When combined with AI, IoT-based image analysis can classify various crop health metrics, identifying specific nutrient deficiencies or disease symptoms. This data enables more precise application of fertilizers and pesticides, reducing crop loss and increasing productivity [8].

4.2.5 Improving Harvest Efficiency

4.2.5.1 GPS and Location-Based Tracking:

IoT-enabled GPS devices can track the harvest schedule for each field section, ensuring sugarcane is harvested at peak maturity. This maximizes sugar content and reduces crop loss due to delayed harvesting [21].

4.2.5.2 Yield Estimation with Predictive Analytics:

Using IoT sensors and historical data, predictive analytics can accurately estimate yield size. This information is crucial for resource planning, storage, and logistics management, enabling sugar mills to be better prepared for incoming supply and optimizing production schedules [22].

4.2.6 Supply Chain and Transportation Management

4.2.6.1 Fleet Management with IoT:

GPS and IoT sensors on vehicles can track the real-time movement of harvested sugarcane, ensuring timely transport from the field to the mill. This reduces spoilage, which is important for maintaining sugar quality [9].

4.2.6.2 Cold Chain Management for Perishable Products:

IoT sensors monitor temperature and humidity during transportation and storage. This is vital for maintaining the quality of sugar by-products like molasses and other perishable items [14-18].

4.2.7 Smart Processing and Energy Management at Sugar Mills

4.2.7.1 Factory Process Monitoring:

IoT sensors in sugar mills can track every stage of the sugar-making process, from juice extraction to crystallization. Real-time data allows operators to make instant adjustments, improving production efficiency and reducing waste [22].

4.2.7.2 Energy Optimization:

IoT sensors can monitor energy use within mills, identifying inefficiencies and helping to optimize energy usage. Since sugar production uses a lot of energy, IoT-based energy management systems can significantly lower operational costs [23].

4.2.7.3 Biogas and Bioethanol Production:

Bagasse (sugarcane residue) is used to produce biogas and bioethanol. IoT sensors can monitor the fermentation and distillation processes, ensuring these by-products are efficiently converted into energy, which can be used in mill operations or sold to the national grid [24].

4.2.8 Predictive Maintenance of Machinery

4.2.8.1 IoT-Enabled Predictive Maintenance:

IoT sensors on processing machinery can detect wear and tear before a breakdown happens, reducing downtime and repair costs. Predictive maintenance extends equipment lifespan and ensures continuous production during peak seasons [11].

4.2.9 Post-Harvest and Marketing Solutions

4.2.9.1 Transparent Farmer Payments:

IoT-integrated data on crop yields and sugarcane quality ensures fair and prompt payments to farmers, enabling real-time transaction updates through mobile platforms. This transparency eliminates middlemen and guarantees fair compensation [24].

4.2.9.2 Digital Marketplaces for Sales:

Through IoT data, sugar mills and farmers can monitor sugar inventory levels and connect with buyers in digital marketplaces, potentially even setting prices based on real-time demand [24].

4.2.10 Environmental Sustainability and Waste Management

4.2.10.1 Monitoring Greenhouse Gases (GHG):

IoT sensors in processing facilities can track emissions, helping mills reduce their carbon footprint by optimizing processes to minimize GHG output [18].

4.2.10.2 Wastewater Management:

IoT-based water quality sensors can monitor and treat wastewater from sugar mills before it's released into the environment. This system helps the industry meet environmental regulations, reducing fines and promoting sustainable practices [22-24].

4.3 Benefits of IoT for Productivity and Profitability

4.3.1 • Enhanced Yield and Quality:

IoT-driven precision agriculture optimizes resources, improves crop health, and enhances yield quality, leading to higher profitability for farmers [12].

4.3.2 Reduction in Operational Costs:

Real-time monitoring and automation lower labor costs, water and fertilizer usage, and energy consumption [23].

4.3.3 Increased Industry Sustainability:

By conserving resources and reducing environmental impact, IoT makes sugarcane cultivation more sustainable [22].

4.3.4 Improved Decision-Making with Data Analytics:

Data collected by IoT devices helps make informed decisions, aiding sugar mills in forecasting demand, managing supplies, and predicting future trends [25].

Integrating IoT with sugarcane farming and processing can greatly boost the sugar industry's productivity, ensuring India meets domestic and global demands in a sustainable way.

5. DISCUSSION AND CONCLUSION

The use of Information and Communication Technology (ICT) and the Internet of Things (IoT) in India's sugarcane industry has brought significant improvements in efficiency, sustainability, and profitability. From the beginning stages of crop production to the final stages of post-harvest processing, these technologies have modernized traditional practices and created new opportunities for the industry.

ICT tools like mobile apps and IoT devices have made precision agriculture possible by providing real-time data on soil moisture, climate conditions, and crop health. For example, apps like "Cane Advisor" and "IkshuKedar" offer guidelines on nutrient management and irrigation scheduling, ensuring crops get the best care based on exact soil and climate conditions. IoT sensors monitor real-time soil nutrient levels and moisture, allowing for precise fertilization and irrigation, reducing resource waste, and improving crop yield and quality.

ICT tools have made great progress in diagnosing diseases and managing pests. Tools like "CaneDES" and "Plantix" use AI to diagnose plant diseases from photos uploaded by farmers, providing immediate solutions to manage crop health. IoT-based surveillance systems monitor pests in real-time, enabling early detection and reducing the costs and losses associated with large-scale pest outbreaks.

ICT has improved post-harvest activities such as marketing, sales, and transportation. The Sugarcane Information System (SIS) in Uttar Pradesh ensures transparent and efficient transactions, removing middlemen and simplifying the sale process. Digital payment platforms like UPI and mobile banking apps have made transactions faster and more reliable, especially during the COVID-19 pandemic when in-person interactions were limited.

ICT and IoT tools play a crucial role in managing resources and promoting sustainability. The Soil Moisture Indicator and other IoT sensors help conserve water by monitoring soil moisture and guiding irrigation practices. These technologies are particularly useful in water-scarce regions, reducing water usage while maintaining productivity. Additionally, IoT-enabled smart monitoring systems for bioelectricity production, biogas, and bioethanol generation from bagasse help optimize energy use and reduce the industry's carbon footprint.

IoT sensors in sugar mills monitor every stage of the sugar-making process, from juice extraction to crystallization. Real-time data allows operators to make instant adjustments, improving production efficiency and reducing waste. Predictive maintenance of machinery using IoT sensors detects wear and tear before breakdowns happen, minimizing downtime and repair costs, and ensuring continuous production during peak seasons.

Digital marketplaces and IoT-enabled platforms have improved market access for farmers. By monitoring sugar inventory levels and connecting with buyers in digital marketplaces, farmers and mills can set prices based on real-time demand. Transparent payments to farmers through IoT-integrated data ensure fair and prompt compensation, removing middlemen and building trust.

The data collected by IoT devices helps make informed decisions for sugar mills and farmers. Predictive analytics using this data helps estimate yield sizes, plan resources, manage supplies, and forecast future trends. This data-driven approach enhances overall productivity and prepares the industry to meet both domestic and global demands sustainably.

ICT and IoT tools help achieve environmental sustainability by monitoring greenhouse gas emissions and managing wastewater. IoT sensors track emissions, helping mills optimize processes to reduce GHG output. Water quality sensors monitor and treat wastewater, ensuring compliance with environmental regulations and promoting sustainable practices.

In conclusion, the integration of ICT and IoT in sugarcane farming has transformed India's sugar industry into a modern, self-sustained sector capable of meeting national and global standards. With continued innovation and adoption of these technologies, the industry is set to achieve greater heights in efficiency, sustainability, and profitability, ensuring a brighter future for millions of farmers and stakeholders.

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