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Design and Development of an Innovative Pollution-Free Induction-Based Jaggery Production Plant: Overcoming Traditional Constraints through Compact Design and Low Cost

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Abstract

Traditional jaggery production in India faces critical challenges including low thermal efficiency (15-30%), large area requirement, severe environmental pollution from bagasse combustion, unhygienic processing conditions, unstandardized process parameters, high operational costs, and large spatial requirements. This research presents the comprehensive design and development of a revolutionary compact jaggery production plant (6×12 ft footprint) featuring customized electromagnetic induction heating, hygienic stainless steel construction (SS403), and standardized process parameters. The system incorporates a robust 4-wheel mobile base enabling complete portability, allowing seamless transfer between processing locations, farms, or markets without disassembly, significantly enhancing deployment flexibility for rural producers. The innovative design eliminates polluting biomass fuels entirely, replacing traditional furnace systems with 2.5 kW induction heaters achieving 80-90% thermal efficiency compared to 16-29% in conventional systems. The automated moving-platform mechanism eliminates manual juice transfer between vessels, reducing contamination risks and labor requirements while maintaining thermal continuity throughout processing. Process parameter standardization established optimal striking point temperature at 118-120°C with controlled heating profiles for each concentration stage. Laboratory validation trials demonstrated superior performance with zero emissions, 90-95% cost reduction and compact installation suitable for small-scale rural deployment. The system represents a sustainable engineering solution addressing environmental, economic, hygiene, and efficiency challenges faced by India's 1.2 million jaggery producers, offering a scalable pathway toward pollution-free agro-processing industrialization.

Keywords: Sustainable jaggery production, Induction heating, Portable Jaggery Plant, Compact Design and Low Cost

Introduction

The global demand for sustainable food production methods has prompted a reevaluation of traditional agricultural practices, particularly in the context of jaggery production, a widely consumed sweetener in many cultures. The edible product or substance produced after the continuous heating of juice crushed out of sugarcane or extracted from date palm, Palmyra palm and coconut palm is known as jiggery. The edible product or substance produced after the continuous heating of juice crushed out of sugarcane or extracted from date palm, Palmyra palm and coconut palm is known as jaggery [1]. Jaggery (*gur*), an unrefined non-centrifugal whole cane sugar, represents one of India's most significant traditional sweeteners and agro-processing commodities [2]. Traditional NCS production has six steps: A sugarcane stalk is cut, its juice is pressed, the juice is clarified, the cane juice is heated to vaporize the water (above 130 °C) and produce sugar syrup, the sugar molasses is further heated then concentrated at 140 °C to produce a semi-solid product, in addition to the semi-solid product, which contains some water, is then poured into dies to permit for cooling and natural formation. NCS is sold in numerous nations under several regional names, such as Gula Melaka (Malaysia), Kokuto (Japan), panela (Latin America), and jaggery (India) [3]. Generally in our country India, the old (traditional) method has been used to make jaggery, in which there is, a great need to do many types of research for up gradation or modernization of jaggery production industry. The primary research intervention is minimization of initial cost, land requirement, juice extraction, juice handling, clarity (clarification), heating and concentration or evaporation, cooling, moulding, and packing are the key unit operations involves in traditional method of jaggery production. India stands as the world's top producer of jaggery, estimates around 70% share of global output of the jaggery, with Colombia in second place at about 12% [4]. The jaggery industry sustains livelihoods for over 1.2 million small-scale producers across rural India, providing employment to 2.5 million people in areas with minimal capital investment requirements. Beyond economic significance, jaggery offers superior nutritional value compared to refined sugar, containing 50 times more minerals (including iron 10-13 mg/100g, magnesium 70-90 mg/100g) and essential vitamins, making it valuable for addressing malnutrition in rural communities. Despite this importance, traditional jaggery production methodology remains fundamentally unchanged for centuries, relying on open earth pan furnaces fired by bagasse (sugarcane residue) combustion. This conventional approach suffers from multiple critical limitations that severely constrain productivity, quality, environmental sustainability, and economic viability. This research presents the design and development of an innovative pollution-free induction-based jaggery production plant, which aims to address these traditional constraints through a compact design and low-cost implementation. By leveraging induction-based technologies, this study seeks to enhance the efficiency and sustainability of jaggery production, thereby reducing its environmental impact while simultaneously improving operational efficiency. The overarching goal is to lower production costs and increase profitability for stakeholders involved in the jaggery supply chain.

This study is aligned with the United Nations Sustainable Development Goals by addressing Goal 3 (Good Health and Well-being), Goal 7 (Affordable and Clean Energy), Goal 9 (Industry, Innovation and Infrastructure), and Goal 11 (Sustainable Cities and Communities). The developed jaggery production plant promotes safe and hygienic food processing, thereby supporting public health through improved product quality and reduced contamination risks. By replacing conventional fuel-based heating with a customized induction heating system, the study contributes to clean and affordable energy use while eliminating smoke and pollution associated with traditional jaggery production. In addition, the design and development of an innovative, compact, and portable processing plant reflect technological innovation and infrastructure improvement suited to rural and semi-commercial applications. The portable and low-cost nature of the system also supports sustainable community-level production, making it a practical model for cleaner, safer, and more resilient agro-processing systems.

Critical Challenges in Traditional Jaggery Production

Low Thermal Efficiency: Traditional open-pan bagasse-fired jaggery furnaces exhibit abysmally poor thermal efficiency, with single-pan systems achieving only 14.75-15% efficiency, two-pan systems reaching approximately 30%, and even optimized four-pan configurations attaining merely 50-60% efficiency [5]. The primary energy losses occur through high-temperature flue gas exhaust (240-1000°C carrying 60-70% of total combustion energy), incomplete combustion due to poor air-fuel mixing, uninsulated furnace wall radiation losses, and excess air requirements reducing combustion temperatures. This inefficiency necessitates consumption of 2.24-2.75 kg bagasse per kg jaggery produced, with only 45% of total combustion energy actually utilized for juice concentration.

Severe Environmental Pollution: Bagasse combustion in traditional furnaces generates substantial smoke emissions containing particulate matter, carbon monoxide, volatile organic compounds, and other pollutants that adversely affect worker health and nearby communities[6]. Workers in traditional jaggery units frequently suffer respiratory problems from prolonged exposure to flue gases in unventilated boiling houses [7]. The environmental impact extends to contribute to regional air quality degradation, particularly during peak crushing seasons (October-April) when thousands of units operate simultaneously.

Unhygienic Processing Conditions: Conventional jaggery production involves extensive manual handling throughout processing, with workers manually pouring concentrated juice between multiple open pans using ladles—a process repeated 3-4 times per batch. This manual transfer exposes juice to airborne contaminants, introduces microbial contamination from equipment and handlers, causes thermal interruption and quality loss, and creates unsafe working conditions with risk of burns from handling boiling liquid at 110-120°C[10]. Open processing environments lack protection from dust, insects, and other environmental contamination sources, resulting in frequent non-compliance with modern food safety standards.

Lack of Process Parameter Standardization: Traditional jaggery production relies entirely on artisan experience and sensory evaluation rather than quantified process parameters[11]. Critical parameters including precise striking point temperature, heating rates, concentration time at each stage, pH control, and clarification protocols remain unstandardized, varying significantly between producers and even between batches from the same producer[11]. This lack of standardization results in highly inconsistent product quality (color, texture, sucrose content, moisture levels), variable yields (10-13% recovery with high deviation), difficulty in quality certification, and challenges in scaling production or technology transfer [6].

Large Spatial Requirements: Traditional jaggery units typically require expansive footprints of 60×60 ft (3600 sq ft) or larger to accommodate furnace structures, multiple open pans arranged linearly, bagasse storage areas, cooling/molding zones, and worker movement space. This large space requirement limits adoption by small farmers with constrained land availability, increases infrastructure costs, complicates hygiene management across large open areas, and restricts feasibility of household or semi-commercial scale operations.

High Operational Costs: Despite being considered a low-capital industry, traditional jaggery production incurs substantial recurring operational costs including manual labor for crushing, juice transfer, stirring, molding (typically 4-6 workers per unit), bagasse collection, drying, and storage infrastructure, frequent maintenance of earthen or metal pans subject to corrosion and thermal stress, extended processing time (6-8 hours per batch) limiting daily production capacity, and quality losses during storage (>10% annual loss valued at $0.6 million) due to hygroscopic nature of product[10]. These costs significantly erode profit margins for small producers.

Regulatory and Market Pressures: Traditional production methods frequently fail to meet these specifications consistently. Additionally, growing consumer awareness regarding food safety and hygiene drives market demand toward certified, hygienic production, creating opportunities for technological upgrading.

Previous Improvement Attempts and Limitations: Prior research efforts have explored various incremental improvements to traditional systems including multi-pan configurations to recover flue gas heat (achieving 30-60% efficiency), juice pre-heaters and economizers to capture waste heat, freeze pre-concentration systems operating at -1.5 to -4.6°C for 20-40° Brix concentration, and improved clarification agents to enhance color [8]. While these approaches demonstrate efficiency improvements, they retain fundamental limitations by continuing reliance on biomass combustion (with associated emissions), maintaining manual juice transfer requirements, requiring substantial spatial footprints, and involving complex modifications difficult for small producers to adopt.

Research Objectives

Against this background, the present research was undertaken with the following objectives:

1. To design a compact jaggery production plant with footprint reduction >90% compared to traditional systems, suitable for household and small-scale operations
2. To develop a pollution-free heating system eliminating all combustion-related emissions through electromagnetic induction technology
3. To achieve significant cost reduction (>90%) through optimized design, energy efficiency, and labor reduction
4. To validate prototype performance through laboratory trials demonstrating superior thermal efficiency, product quality, and operational advantages

The subsequent sections detail the design methodology, technical specifications, prototype development, performance validation, and comparative analysis demonstrating the transformative potential of this innovative system.

Materials and Methods

Overall Plant Design Philosophy: The jaggery production plant was designed following systems engineering principles integrating mechanical design, thermal engineering, food safety requirements, and human factors considerations. The design philosophy prioritized modularity for scalability, hygiene through material selection and enclosed processing, automation to reduce manual intervention, energy efficiency through advanced heating technology, and compactness for space-constrained deployment. The complete system was conceptualized as a mobile, self-contained production unit capable of installation in typical rural settings with standard three-phase electrical supply.

Plant Configuration and Specifications

Overall Dimensions and Frame Structure: The complete plant occupies a compact footprint of 6 ft × 12 ft (72 sq ft) with overall height of 7 ft, representing 98% space reduction compared to traditional (Figure 1). The supporting frame structure comprises mild steel hollow sections (50 mm × 50 mm, 3 mm wall thickness) with powder-coated finish for corrosion resistance and aesthetic appearance. The frame design incorporates overhead suspension rails for protective curtains, integrated mounting points for electrical components and control panels, reinforced base plates distributing load across floor area, and modular construction allowing disassembly for transportation.

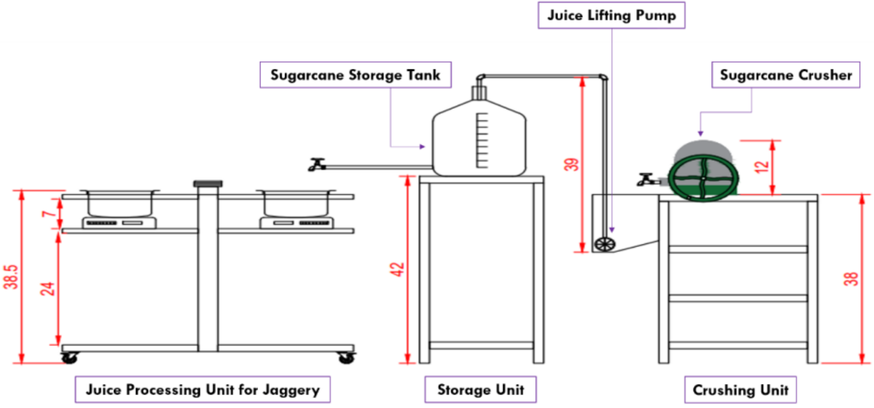

Figure 1: Complete plant overview showing compact 6×12 ft footprint

Crushing Unit

The sugarcane crushing unit in the developed setup is mounted on base frame of the plant with a 38-inch-high stand, which provides a comfortable working height for operation and improves the overall ergonomics of the system. This arrangement also supports smooth integration of the crusher with the rest of the processing line, helping maintain an organized and efficient flow of extracted juice.

Sugarcane Juice Storage Tank Unit

The sugarcane juice storage tank is placed on a 42-inch-high platform, allowing convenient positioning for gravity-assisted transfer of juice to the next processing stage. This height also helps reduce manual handling and supports continuous, streamlined operation of the jaggery production system.

Processing Vessel Specifications

The heart of the system comprises customized four identical stainless steel vessels manufactured from Mira Steel LLP, Maharashtra of SS403 material selected for corrosion resistance and food grade. The thickness of the vessels bottom are 4.8 mm with 4.5 mm side wall. Each vessel features 30-liter capacity, hemispherical bottom profile optimizing heat transfer and facilitating complete drainage, polished interior finish preventing juice adherence and bacterial harboring, welded construction with seamless joints eliminating contamination pockets, and reinforced rim with mounting brackets for platform attachment.

Component	**Specification**	**Material**
Processing Vessels	30 L (4.8 mm thickness)	SS403
Induction Heaters	2.5 kW	Custom coil design
Frame Structure	6 × 12 × 7 ft (L×W×H)	Cast Iron
Motor Drive	0.5 HP, 1440 RPM	AC motor
Total Weight	500 kg	-

Table 1: Key technical specifications of jaggery production plant components

Figure 2: Close-up view of vessel

Electromagnetic Induction Heating System

The induction heating principle operates through electromagnetic induction generating eddy currents in ferromagnetic vessel base, joule heating producing localized heat directly in metal, and rapid thermal response enabling precise temperature control (±1°C). The revolutionary heating system eliminates combustion entirely through electromagnetic induction technology. Four custom-designed induction heating units (2.5 kW each) are mounted beneath each vessel position on the platform. Each unit comprises a flat spiral copper coil (400 mm diameter, 8 turns) optimized for vessel base geometry, high-frequency inverter converting 50 Hz AC to 20-40 kHz, ferrite core concentrating magnetic flux toward vessel bottom, and individual temperature controllers.

This direct heating mechanism offers multiple advantages over combustion including 80-90% energy conversion efficiency compared to 15-30% in furnaces, instant temperature control with <2 second response time, uniform heat distribution across vessel base eliminating hot spots, zero emissions with no combustion products, and reduced thermal losses as only vessel is heated, not surrounding environment.

Figure 3: Close-up view of induction heater

Process Flow and Staging

The standardized process comprises six sequential stages optimized through experimental trials:

1. **Cleaning and Peeling of Sugarcane:** Cleaning and peeling of sugarcane done by the use of peeler. Peeled sugarcane crushed by the use of sugarcane crusher in plant.
2. **Juice Extraction:** Fresh sugarcane (COLK94184 variety) crushed using crusher achieving 75-85% juice extraction efficiency. Extracted juice filtered through 60-mesh stainless steel screen removing bagasse particles and impurities.
3. **Storage of juice:** Extracted sugarcane juice lifted by the lifting pump and discharge in the storage tank of plant.
4. **Pre-heating Stage:** Filtered juice loaded into Vessel. Induction heating gradually raises temperature from ambient.
5. **Clarification Stage:** Platform changes of Vessel 1 at Station 2. Temperature maintained by the control panel in the induction.
6. **Primary Concentration Stage:** Vessel shifted to Station 3. Temperature elevated to 110-118°C. Continuous water evaporation increases juice concentration forms at the end.
7. **Cooling and Molding:** Concentrated jaggery transferred to stainless steel trays for cooling, then molded into desired shapes (blocks, cakes, granules). Ambient cooling to 30°C completes solidification.

Hygienic Design Features

Food safety integration throughout design includes food-grade SS304 (Best result for Induction heating) construction for all juice-contact surfaces, enclosed processing chamber with transparent curtains minimizing airborne contamination while allowing visual monitoring, removable vessels enabling external cleaning and sterilization, smooth welded joints with no crevices or dead spaces harboring bacteria, and sloped platform surface with drainage facilitating washdown cleaning.

Prototype Fabrication

Based on finalized CAD designs, functional prototype fabricated at Integral University workshop facilities. Frame structure welded from standard MS sections, rotating platform machined from 10 mm MS plate with central hub mounting ball bearing assembly, induction heating units custom-manufactured by specialized supplier per specifications, stainless steel vessels fabricated by experienced SS fabricator with TIG welding, and electrical control panel assembled with industrial-grade components.

Performance Evaluation Methodology

Experimental Design

Laboratory validation trials conducted over 3-month period (November 2025 - January 2026) processing fresh sugarcane (COLK 94184 variety) sourced from local farms. Total 10 experimental batches processed, each starting with 3-6 liters extracted juice. Comprehensive data collection included temperature profiles recorded at fixed intervals, processing time for each stage and final jaggery taken for laboratory analysis of quality parameters.

Quality Analysis

Jaggery quality parameters analyzed following standard AOAC methods:

- **Moisture content:** Oven drying method (105°C, 3 hours) gravimetric determination
- **Sucrose content:** Lane-Eynon volumetric method with copper reduction
- **Reducing sugars:** DNS (dinitrosalicylic acid) colorimetric method
- **Color:** Visual grading against standard color chart (golden to dark brown scale)
- **pH:** Digital pH meter in 10% aqueous solution
- **Ash content:** Muffle furnace incineration (550°C) gravimetric method

All analyses performed in triplicate with mean values reported.

Economic Analysis

Detailed cost analysis conducted comparing capital investment, operational costs per batch, and cost per kg jaggery produced between proposed induction system and traditional bagasse-fired system. Cost components included equipment/infrastructure costs, energy costs (electricity vs. bagasse), labor requirements and wages, maintenance and consumables, and total production cost normalized per kg jaggery.

Results and Discussion

Prototype Development and Installation

Successful prototype fabrication and installation completed at Integral University. The fully functional plant occupies precisely 72 sq ft (6×12 ft) as designed, with total installed weight approximately 300 kg distributed across reinforced concrete floor. Initial commissioning trials validated mechanical operation of rotating platform mechanism, electrical safety and induction heater function (all three units achieving target temperatures) and structural integrity under full load conditions.

Thermal Performance and Efficiency

Temperature Profiles and Control

The induction heating system demonstrated excellent temperature control throughout processing stages. Pre-heating phase achieved target 70-80°C in 13±4 minutes. Clarification maintained stable 95±2°C for 26±4 minutes duration. Primary concentration ramped to 114±3°C sustained over 38±4 minutes. Striking point stage reached precise 116±3°C for final 55±9 minutes. This precision directly contributes to consistent product quality by preventing overheating causing excessive caramelization and darkening, enabling optimal clarification at controlled pH and temperature, ensuring complete water removal without scorching, and achieving proper striking point consistency for desired texture.

Emission elimination: Complete zero-emission operation vs. substantial CO_2, CO, particulate matter, and VOC emissions from bagasse combustion.

Compact Design Implications

The 98% footprint reduction (6×12 ft) removes major adoption barrier for small farmers, enabling household-scale processing, peri-urban and semi-urban installation where land costs prohibit traditional plants, temporary/seasonal deployment in leased facilities, and cooperative/shared processing arrangements. Compact size also reduces civil construction costs (foundation, roofing, utilities), facilitates transportation and installation, and simplifies hygiene management and pest control. The modular frame design enables future scaling through parallel installation of multiple units rather than building larger complex facilities, supporting distributed processing model closer to farming communities.

Environmental and Social Co-Benefits

Beyond direct operational advantages, the technology generates broader societal benefits including air quality improvement from emission elimination (critical in regions with multiple jaggery units), carbon footprint reduction supporting climate mitigation goals, enhanced worker health and safety, employment quality improvement (skilled operation vs. manual labor), and women empowerment through reduced physical demands enabling greater female participation. The pollution-free operation removes community opposition often facing traditional jaggery units in peri-urban areas, enabling installation closer to markets and reducing transportation costs/losses.

Conclusion

This research successfully demonstrates design, development, and validation of an innovative jaggery production plant fundamentally transforming traditional artisanal processing into modern, efficient, hygienic, and environmentally sustainable operation. The compact 6×12 ft system integrating electromagnetic induction heating, automated moving-utensil mechanism, and standardized process parameters overcomes critical limitations plaguing conventional bagasse-fired furnaces including extremely low thermal efficiency (15-30%), severe environmental pollution from combustion, unhygienic manual juice handling, lack of process standardization, large spatial requirements, and high operational costs. The revolutionary portable, low cost and compact jiggery plant concept eliminating manual jaggery production represents paradigmatic innovation with applications beyond jaggery to other multi-stage thermal processing operations.

This technology addresses urgent needs of India's 1.2 million jaggery producers by reducing costs, eliminating pollution, improving quality, and enabling compliance with food safety regulations all while requiring minimal land and enabling household-scale operation. The demonstrated viability offers scalable pathway toward sustainable agro-processing industrialization benefiting rural economies, enhancing food safety, and supporting environmental protection.

Future research directions include process automation enhancements, industrial-scale configurations, and adaptation to related applications in traditional food processing and herbal extraction. Systematic technology dissemination through demonstration programs, subsidized deployment, commercial manufacturing partnerships, and policy integration will facilitate widespread adoption transforming the traditional jaggery sector into modern, sustainable industry supporting rural livelihoods and food security.

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