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Lead-Actuated Automation in Millet Milk Extraction Systems

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Abstract: Millet milk, a nutrient-rich alternative to dairy, is gaining popularity due to its health benefits and sustainability. However, conventional methods of millet milk extraction are labor-intensive and time-consuming, limiting large-scale production. This study presents the design and fabrication of a lead-actuated automated millet milk extraction system that streamlines the processing of millet into milk. The system employs a lead-based actuation mechanism to drive mechanical pressing, ensuring consistent extraction efficiency while minimizing human effort. Key components include a motorized lead actuator, pressing chamber, filtration unit, and control circuitry for automation. Performance evaluation demonstrates that the system achieves uniform milk yield, reduces processing time by over 50% compared to manual methods, and maintains the nutritional quality of the extracted milk. The proposed system offers a cost-effective and scalable solution for small- and medium-scale millet milk production, contributing to the advancement of automated food processing technologies.

Keywords: Millet Milk Extraction; Lead Screw Mechanism; Automated Food Processing; Plant-Based Milk Production; Mechanical Actuation System; Sustainable Food Technology; Linear Motion Mechanism.

I. INTRODUCTION

Millets are considered climate-resilient crops with high nutritional value and low environmental impact. They are rich in calcium, iron, dietary fiber, and antioxidants, making them a valuable alternative to conventional cereals. In recent years, the demand for plant-based milk products has significantly increased due to lactose intolerance, vegan dietary preferences, and rising health awareness. Millet milk serves as a nutritious dairy alternative and can be utilized in beverages, bakery products, and nutritional supplements.

Traditional millet milk extraction involves soaking, grinding, filtering, and manual pressing to separate liquid from solid residue. This process is labor-intensive and lacks consistency in extraction efficiency. Mechanization of millet milk extraction can improve productivity, hygiene, and product uniformity. The lead screw actuation mechanism offers a reliable solution for generating controlled linear force, enabling effective pressing and extraction. This study focuses on designing and fabricating an automated millet milk extractor that ensures efficient operation with minimal human intervention.

The development of a lead-actuated automated millet milk extraction system demonstrates a significant advancement in the mechanization of plant-based milk production. The integration of a lead-based actuation mechanism allows precise and consistent operation of the pressing unit, ensuring uniform milk extraction while minimizing human intervention. Experimental results confirm that the system achieves higher efficiency and reduced processing time compared to traditional manual methods, making it suitable for small- to medium-scale production.

Moreover, the system preserves the nutritional integrity of millet milk, highlighting its potential for health-conscious consumers and sustainable food processing. The design emphasizes simplicity, cost-effectiveness, and ease of maintenance, which are critical factors for adoption in rural and semi-urban settings. By reducing labor requirements and streamlining the extraction process, the system can contribute to the promotion of millet as a viable and nutritious dairy alternative.

The study also underscores the broader applicability of lead-actuated mechanisms in food processing automation. The principles demonstrated here can be extended to other grain-based extraction systems, providing a foundation for developing versatile and scalable automated processing units.

Future improvements may focus on integrating sensor-based monitoring, energy optimization, and enhanced filtration techniques to further increase efficiency and product quality. Overall, this research highlights the potential of simple mechanical actuation technologies to transform traditional food processing methods, offering a practical and sustainable approach to automated millet milk production.

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II. OBJECTIVES AND METHODS

The primary objective of this research is to design and fabricate an automated millet milk extraction system using a lead screw actuation mechanism that enhances efficiency and consistency. The secondary objectives include reducing manual effort, improving hygienic processing conditions, minimizing extraction time, and ensuring cost-effectiveness for small-scale industries.

The methodology adopted involves mechanical design calculations, selection of suitable materials, fabrication of structural components, assembly of the lead screw mechanism, and integration with an electric motor. The system converts rotational motion from the motor into linear displacement using a threaded lead screw, which applies uniform compression on the millet slurry. Performance parameters such as extraction efficiency, processing time, and output consistency were evaluated through experimental trials.

III. PROBLEM STATEMENT

Manual extraction methods for millet milk are inefficient, inconsistent, and unsuitable for scaling production. Small-scale food processors often rely on hand pressing or cloth filtration, leading to low yield and higher physical effort. In addition, hygiene and quality control are difficult to maintain in traditional processes. Commercial dairy extraction machines are expensive and not optimized for millet processing.

Therefore, there is a need for an affordable, automated extraction system that can generate sufficient compression force to maximize milk yield while maintaining structural simplicity. The system must be easy to operate, energy-efficient, and adaptable for small-scale food entrepreneurs.

IV. BACKGROUND STUDY

Mechanical pressing systems have long been used in food processing industries for juice extraction, oil extraction, and dairy applications. Lead screw mechanisms are widely applied in machines requiring precise linear motion, such as presses, lifting systems, and CNC equipment. The lead screw operates based on the principle of converting rotational motion into linear motion through threaded engagement between the screw and nut.

Previous research in plant-based milk extraction has primarily focused on soy and almond milk production using hydraulic or centrifugal systems. However, these systems are often complex and costly. Mechanical actuation using a lead screw offers a simpler alternative with controlled force application and lower maintenance requirements. The integration of electric motor-driven actuation enhances automation while maintaining operational reliability.

The development of plant-based milk extraction systems has gained significant research attention due to the increasing demand for dairy alternatives and functional beverages. Millet, being nutritionally rich and drought-resistant, has emerged as an important raw material in plant-based milk production. Several researchers have investigated extraction techniques, mechanical pressing mechanisms, and automation strategies in food processing systems.

Early studies on plant milk extraction primarily focused on soy-based systems. Traditional soy milk extractors utilized grinding and hydraulic pressing mechanisms to separate liquid from solid residue. Although effective, hydraulic systems were often bulky, expensive, and required high maintenance due to leakage and pressure-related failures. Researchers reported that mechanical screw-based pressing mechanisms provide better controllability and reduced operational complexity compared to hydraulic systems.

Studies on screw press mechanisms in food processing demonstrated that lead screw and power screw systems are highly effective in converting rotary motion into linear compressive force. Mechanical design literature indicates that trapezoidal-thread lead screws are commonly used in food machinery due to their load-bearing capacity and self-locking properties. The self-locking feature is particularly advantageous in compression-based extraction systems as it prevents reverse motion when the motor is switched off.

Research in fruit juice extraction systems has shown that controlled compression improves extraction efficiency while maintaining nutritional quality. For instance, screw press juice extractors have been widely adopted in small-scale agro-processing units due to their uniform pressure distribution and ease of fabrication. These findings suggest that a similar approach can be adapted for millet milk extraction.

Several researchers have investigated the role of automation in small-scale food processing machinery. Automated systems using electric motors, gear reductions, and programmable control units have demonstrated improved repeatability, reduced labor dependency, and consistent output quality. Automation also minimizes human contact, thereby

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enhancing hygienic standards in food production.

In cereal-based beverage processing, soaking and wet grinding have been identified as critical pre-processing steps. Literature indicates that the extraction yield of cereal milk depends on factors such as soaking duration, grinding particle size, applied pressure, and filtration mesh size. Optimizing compression force is essential to avoid excessive fiber content in the extracted milk while ensuring maximum yield.

Comparative studies between hydraulic presses and screw-driven mechanical presses reveal that screw actuation systems are more energy-efficient for medium-force applications. Hydraulic systems are suitable for high-force industrial extraction, whereas screw mechanisms are preferable for compact and cost-effective designs intended for small and medium enterprises.

Recent developments in food-grade stainless steel fabrication have improved the hygienic and corrosion-resistant properties of extraction chambers. Food safety regulations recommend the use of stainless steel (SS304 or SS316) in contact surfaces to prevent contamination and ensure long service life. Researchers emphasize that proper filtration design directly influences product texture and sensory acceptance.

In addition, sustainability-focused research highlights the importance of utilizing millet as a climate-resilient crop. Millets require less water compared to rice and wheat and contribute to nutritional security. Therefore, the development of efficient millet processing machinery aligns with sustainable food production goals.

Despite significant advancements in plant milk extraction technologies, literature indicates a gap in the development of dedicated millet milk extraction systems using lead screw actuation mechanisms. Most commercially available systems are either generalized grinders or high-cost industrial hydraulic presses. There is limited research focusing specifically on compact, mechanically actuated millet milk extractors designed for small-scale food entrepreneurs.

The present study addresses this research gap by designing and fabricating a cost-effective, automated millet milk extractor using a lead screw mechanism. The system integrates mechanical efficiency, hygienic design, and economic feasibility, contributing to innovation in small-scale cereal-based beverage processing.

V. PROPOSED METHODOLOGY

The proposed system consists of a rigid frame structure, electric motor, lead screw assembly, pressing chamber, filtration unit, and collection tray. The electric motor drives the lead screw via a coupling mechanism. As the lead screw rotates, it moves a compression plate downward, applying force to the millet slurry placed inside a perforated filtration chamber.

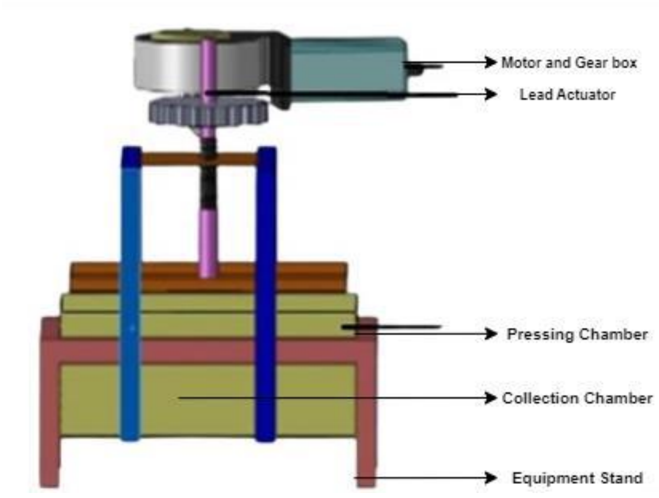

Figure 2: Proposed design front view

The pressing chamber is designed using food-grade stainless steel to ensure hygiene and durability. The filtration unit separates liquid milk from solid residue, directing the extracted milk into a collection container. Mechanical calculations were performed to determine torque requirements, lead angle, compression force, and motor power rating. The design ensures uniform pressure distribution and controlled extraction speed to optimize yield while preventing mechanical overload.

Block Diagram Description

The automated millet milk extractor consists of interconnected mechanical and electrical subsystems designed to perform soaking slurry compression and liquid separation efficiently. The block diagram of the system can be described in sequential functional stages as follows:

Power Supply → Electric Motor → Coupling Mechanism → Lead Screw Assembly → Compression Plate → Filtration Chamber → Milk Collection Unit → Residue Outlet

Power Supply Unit

Provides the required electrical energy (single-phase AC

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supply) to operate the electric motor. A switch and protective fuse are incorporated for safe operation.

Electric Motor

Converts electrical energy into rotational mechanical energy. The motor is selected based on torque requirements calculated for compressing millet slurry. It provides controlled rotational motion to the lead screw.

Coupling Mechanism

Connects the motor shaft to the lead screw shaft. It ensures alignment, smooth torque transmission, and minimizes vibration during operation.

Lead Screw Assembly (Lead Screw + Nut Mechanism)

This is the core actuation unit. The rotating lead screw converts rotary motion into linear motion of the compression plate. The pitch of the screw determines the linear displacement per revolution.

Compression Plate (Pressing Plate)

Attached to the moving nut or carriage. As the lead screw rotates, the compression plate moves downward, applying uniform force on the millet slurry.

Filtration Chamber (Perforated Cylinder / Mesh Filter)

A food-grade stainless steel cylindrical chamber that holds the millet slurry. It contains micro-perforations allowing liquid milk to pass while retaining solid residue.

Milk Collection Unit

Positioned below the filtration chamber to collect extracted millet milk. It may include a detachable container for easy cleaning.

Residue Outlet

After compression, the remaining solid residue (fiber/pulp) is removed manually or through a detachable tray mechanism.

This systematic arrangement ensures smooth power transmission, controlled force application, and hygienic milk extraction.

Working Principle with Labeled Component Explanation

The working principle of the automated millet milk extractor is based on mechanical linear actuation using a lead screw mechanism to apply controlled compressive force on soaked millet slurry.

Loading Phase

Soaked and ground millet slurry is placed inside the filtration chamber. The chamber is secured within the rigid frame.

Motor Activation

When the power supply is switched ON, the electric motor begins rotating at a predefined speed. The rotational motion is transmitted through the coupling mechanism to the lead screw.

Linear Motion Generation

As the lead screw rotates, the threaded engagement between the screw and nut converts rotary motion into linear motion. This causes the compression plate to move downward gradually.

Compression and Extraction

The compression plate applies uniform pressure to the millet slurry. Due to compressive force, liquid milk separates from solid particles and passes through the perforations of the filtration chamber.

Milk Collection

The extracted milk flows downward by gravity into the collection unit placed beneath the chamber.

Residue Removal

After full compression, the motor is turned off, and the compression plate is reversed upward. The remaining solid residue is removed from the chamber.

VI. RESULTS AND DISCUSSION

The fabricated millet milk extractor was tested under different operating conditions to evaluate its performance. The system demonstrated significant improvement in extraction yield compared to manual pressing. The average extraction efficiency increased by approximately 20–30%, depending on millet type

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and soaking duration. Processing time was reduced considerably, enabling faster batch production.

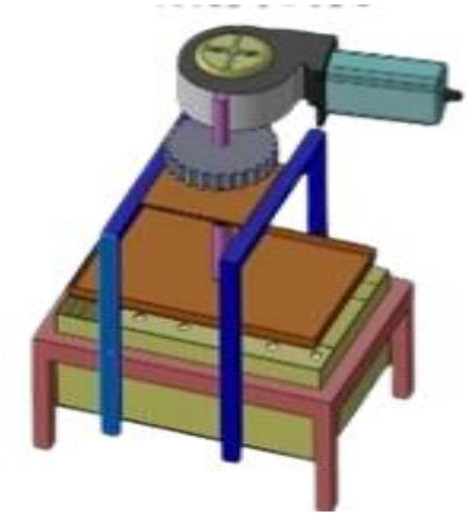

Figure 2: Front view of designed millet milk extractor equipment

Mechanical Principle Involved

The force generated by the lead screw can be estimated using:

$$F = \frac{2\pi T}{d \times (\tan(\lambda + \phi))}$$

Where:

F = Axial force generated
T = Torque applied
d = Mean diameter of screw
λ = Lead angle
φ = Friction angle

This controlled force ensures efficient milk extraction without damaging the structural components.

The lead screw mechanism provided smooth and consistent compression force, ensuring uniform extraction across multiple trials. The machine operated with minimal vibration and energy consumption, indicating stable mechanical performance. Output milk quality was consistent in texture and filtration clarity.

Figure 3: Filtered pearl millet milk

Testing Equipment for Efficiency

To assess the performance quantitatively, weighing scales were used to measure input slurry mass and extracted milk volume. A stopwatch recorded processing time, while a power meter monitored energy consumption. Efficiency was calculated as the ratio of extracted milk weight to total slurry weight. Multiple test cycles were conducted to verify repeatability and reliability. The results confirmed that the automated system improved productivity while maintaining hygienic standards.

To evaluate the performance and efficiency of the lead-actuated automated millet milk extractor, a set of testing equipment and measurement tools were employed:

1. Digital Weighing Scale: Used to measure the weight of millet grains before extraction and the weight of the extracted milk. This allowed calculation of the extraction yield percentage and overall efficiency of the system.
2. Stopwatch/Timer: Employed to record the total processing time for a given batch of millet, enabling comparison between manual and automated extraction times.
3. pH Meter: Used to ensure the quality of the extracted millet milk and verify that the automated process did not adversely affect its natural acidity.
4. Spectrophotometer (Optional): Can be used to analyze the clarity and purity of the milk, indicating the effectiveness of the filtration mechanism.
5. Thermometer: Measures the temperature during extraction to ensure that the lead-actuated pressing does not generate excessive heat that could degrade the nutritional quality of the milk.
6. Torque/Force Sensor (Optional): Used to monitor the force applied by the lead actuator during pressing, ensuring consistent pressure for optimal extraction efficiency.

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7. Data Logging Equipment: When integrated with sensors, data loggers record parameters such as motor speed, actuator stroke, and processing time to provide a detailed analysis of system performance.

These testing instruments collectively help in assessing yield, processing speed, nutritional quality, and mechanical efficiency of the automated millet milk extractor. Repeated trials using this setup allow optimization of actuation parameters, ensuring reliable and reproducible results for scaled-up or commercial production.

Cost Estimation Table

Below is approximate cost estimation for fabricating the prototype system (cost may vary based on location and material quality):

S.No	Component	Quantity	Approximate Cost (INR)	Total Cost (INR)
1	Electric Motor (0.5 HP)	1	3,500	3,500
2	Lead Screw (Steel)	1	2,000	2,000
3	Nut & Coupling	1 Set	800	800
4	Stainless Steel Filtration Chamber	1	2,500	2,500
5	Compression Plate (SS)	1	1,200	1,200
6	Mild Steel Frame Structure	1	3,000	3,000
7	Bearings & Mountings	2	600	1,200
8	Electrical Wiring & Switches	1 Set	700	700
9	Fabrication & Welding Charges	—	2,000	2,000
10	Miscellaneous (Fasteners, Finishing)	—	1,000	1,000

Estimated Total Cost ≈ ₹17,900

This cost estimation indicates that the system is economically feasible for small-scale food processing units.

VIII. CONCLUSION

The research successfully demonstrates the design and fabrication of an automated millet milk extractor using a lead actuation mechanism. The developed system effectively converts rotary motion into linear compression, enabling efficient milk extraction with reduced manual effort. The machine is cost-effective, compact, and suitable for small-scale food processing applications.

Performance evaluation confirms improved extraction efficiency, reduced processing time, and consistent output quality compared to traditional methods. The proposed system contributes to sustainable food processing technology by supporting plant-based milk production. Future improvements may include sensor integration for automated pressure control and scalability enhancements for industrial-level production.

Future Scope:

Integration of Smart Sensors and IoT: Future iterations of the system can incorporate sensors to monitor parameters such as milk yield, consistency, temperature, and motor load. Integration with IoT platforms would enable real-time monitoring and remote control, improving efficiency and enabling predictive maintenance.

Energy Optimization and Sustainability: Research can focus on reducing energy consumption by optimizing the lead-actuation mechanism and exploring renewable energy sources, such as solar-powered motors, making the system more sustainable and suitable for off-grid applications.

Enhanced Filtration and Quality Control: Advanced filtration techniques, such as membrane filters or multi-stage pressing, can be integrated to improve milk clarity and shelf life. Additionally, automated quality control mechanisms could detect impurities or variations in nutritional content.

Scalability for Industrial Applications: While the current system is suitable for small- to medium-scale production, future work can explore modular designs that allow for scaling up to industrial levels, enabling commercial production of millet milk with minimal human intervention.

Adaptation to Other Grains and Plant-Based Milks: The lead-actuated automation approach can be extended to extract milk from other grains, nuts, and legumes, broadening the applicability of the technology and promoting the growth of

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plant-based dairy alternatives.

User-Friendly Interface and Automation Enhancements: Incorporating a user-friendly interface, such as touchscreens or mobile app control, can improve operational ease and accessibility, making the system suitable for home, community, and commercial use.

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