Integration of a Spring-Loaded Doneness Testing Mechanism into the Design of a Fully Automated Yam Cooking and Pounding Machine

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ABSTRACT:

The mechanisation of yam processing is essential for reducing labour intensity, improving product uniformity, and enabling large-scale adoption of yam-based foods. This study presents the design, experimental validation, and performance evaluation of an automated yam cooking and pounding machine. The research was driven by the need to eliminate the manual processes traditionally associated with yam preparation, while ensuring consistency in texture, doneness, and overall quality. A series of controlled tests were conducted to establish cooking times across different yam grades, temperature distribution during the cooking cycle, piercing force requirements for doneness evaluation, and the efficiency of the pounding mechanism. The doneness tests were performed using a fork-penetration method, with force recorded at five-minute intervals to determine the precise cooking point. Temperature profiling confirmed that thermodynamic equilibrium was reached at approximately 90 °C after five minutes, maintaining stability throughout cooking. The pounding mechanism achieved acceptable smoothness within five minutes, with particle sizes reducing to approximately 1 mm at completion. Comparative analysis with manual pounding demonstrated that the machine produced yam with comparable textural properties, while significantly reducing labour effort and variability. The results confirm that the proposed machine can reliably automate the traditionally labour-intensive process of yam cooking and pounding. This development establishes a foundation for future scaling, refinement of control logic, and broader adoption within the food processing sector

1 INTRODUCTION

Yam (*Dioscorea* spp.) is a major staple crop consumed in many parts of West Africa, Central Africa, the Caribbean, and Southeast Asia. It is commonly prepared by boiling and is further processed into products such as pounded yam, yam flour, or yam porridge. In these preparations, the cooking stage plays a critical role in determining both taste and texture, which directly influence consumer satisfaction and the efficiency of downstream processing steps.

Traditionally, the determination of yam doneness during boiling relies on manual probing using forks or knives. This method is inherently subjective, relying on human perception of softness, and often results in inconsistencies in cooking quality, especially when preparing large volumes or in mechanized food processing environments. As the demand for automated food processing technologies grows, the need for an objective, repeatable, and automated method of assessing yam doneness becomes increasingly critical.

In response to this need, this paper presents the design and development of a Cooked Yam Doneness Testing Machine. The machine is engineered to simulate the traditional probing technique but with a standardized mechanical process that removes human subjectivity. It uses a spring-loaded piercing mechanism designed to detect when the yam has softened sufficiently to be penetrated by a calibrated force. This mechanism is embedded within a cooking chamber and is monitored using an Arduino Uno microcontroller, temperature sensors, and limit switches that detect the state of the piercing arm.

The machine processes 2 kilograms of yam cut into 1-inch cubes within a closed cooking chamber. As the yam cooks, the piercing arm periodically applies downward force via a tension spring. When the yam is soft enough for the piercer to fully retract, indicating full penetration, a buzzer is triggered and the cooking time is logged through the Arduino interface. The device was tested across multiple yam textures, categorized as soft, medium, and hard, to establish cooking time profiles for integration into future automated cooking and pounding machines.

This work is intended not only as a standalone advancement in food processing automation but also as a foundational research tool to inform time-controlled systems in yam-based meal preparation technologies.

2 LITERATURE REVIEW

Very few studies to date provide real-time monitoring of yam doneness during cooking; most rely on post-process evaluation using mechanical and thermal analysis. Instrumental assessments such as Texture Profile Analysis (TPA) have been applied to *pounded yam* to capture textural attributes, including hardness, cohesiveness, adhesiveness, and springiness, which correlate well with sensory panel evaluations (Otegbayo et al., 2007). These, however, are conducted after cooking and pounding, offering no in-process indication of readiness. Likewise, mechanical testing of yam tissues, measuring penetration and compressive strengths, gumminess, rupture energy, and bio-yield strain, provides useful design baselines for actuator sizing (Nwadike et al, 2018). Thermal characterisation using Differential Scanning Calorimetry (DSC) and Rapid Visco Analyzer (RVA) methods has quantified gelatinisation transition temperatures in various *Dioscorea* species, with onset (To), peak (Tp), and conclusion (Tc) temperatures typically spanning ~71–85 °C and enthalpies of ~16–25 J g^{-1}, highlighting cultivar-specific thermal behaviour (Chukwu et al., 2021; MDPI, 2022). This again reflects material properties rather than dynamic signals. In other food systems, however, in-pot real-time techniques have been explored: ultrasonic monitoring can detect starch gelatinisation by measuring changes in acoustic velocity and attenuation during heating (Lehmann, Kudryashov & Buckin, 2004), while acoustic velocity and attenuation changes have been used to monitor gel network formation in dairy colloids (Kudryashov et al., 2000). Additionally, electrical impedance methods have been used in potatoes to infer changes in cell integrity and water mobility during cooking, and reflective cycling-based thermo-sensing, commonly found in intelligent rice cookers, infers doneness from plateau profiles (e.g., fuzzy-logic control) (Fuentes et al., 2014). However, none of these approaches have been demonstrated on yam to provide direct, real-time texture or doneness feedback. Standard laboratory and field protocols still depend on post-cooking instrumental or sensory evaluations. Accordingly, a critical knowledge gap exists: there is presently no in-process, real-time method for detecting yam doneness that is both practical for automation and responsive to variability across yam cultivars. Addressing this, the current research intends to develop such a sensory-based mechanism, using calibrated mechanical resistance thresholds, to inform a fully automated cook-and-pound machine.

3 METHODOLOGY

The Cooked Yam Doneness Testing Machine was developed as a research-grade device capable of objectively determining the exact cooking time of yam using a mechanical-texture-based approach. Its design integrates mechanical, thermal, and electronic subsystems within a stainless steel cooking chamber to simulate real boiling conditions. The primary objective was to detect yam doneness using a calibrated spring-loaded piercing mechanism that reflects the resistance of yam tuber to penetration. The machine’s operation is fully automated and monitored via an Arduino-based control system.

3.1 *Mechanical Design and Material Selection*

The core mechanical system consists of a vertical piercer assembly, mounted concentrically above a stainless steel boiling chamber. The machine is designed to accommodate 5 kg of yam, uniformly cut into 1-inch cubes, ensuring even exposure to thermal energy and mechanical force. The piercing assembly is fabricated from AISI 304 stainless steel for corrosion resistance, hygiene, and durability in high-temperature environments. All moving parts in contact with food or steam are fabricated from stainless steel or food-safe high-temperature polymers.

The piercing rod is aligned vertically and guided through a sealed shaft mounted on the chamber lid. The base of the rod connects to a tension spring and a lever arm, which interfaces with limit switches for positional feedback. The piercer head is blunt-edged (non-cutting) and cylindrical to replicate the surface contact of a human finger or fork and to avoid premature puncture of partially cooked yam

3.2 *Spring and Piercing System Design*

The core design logic is that yam doneness corresponds to its yield resistance. The piercing force required to penetrate yam tissue reduces as cooking progresses. The spring is selected to apply a constant restoring force, which initially cannot pierce the yam, but over time becomes sufficient to cause full penetration once the tissue softens.

Table 1. Spring Design Parameters

Parameter	*Value*
Spring Type	Tension Spring
Wire Diameter,	0.75 mm = 0.00075 m
Mean Coil Diameter, D	10 mm = 0.01 m
Free Length, l_f	30 mm = 0.03 m
Number of Active Coils, n	30
Modulus of Rigidity, G (Stainless Steel)	77×10^9 Pa

Using the formula for spring constant k of a helical spring

$$k = \frac{Gd^4}{8D^3n} = \frac{77 \times 10^9 \times 0.00075^4}{8 \times 0.03^3 \times 30} = 1.01N/mm$$

Assuming a full compression travel of 10 mm during the test:

$$F = kx = 1.01 \times 10 = 10.1N$$

The spring exerts a piercing force of approximately 10.1 N, calibrated empirically as sufficient to pierce fully cooked yam but insufficient for undercooked yam.

This value is based on multiple physical trials and verified against manual fork-based tests. The diameter of the piercer and spring stiffness were tuned iteratively to ensure that premature piercing does not occur.

3.3 *Power requirement of the pounding system*

To estimate power requirements, we begin by modelling yam's mechanical resistance during pounding. Boiled yam behaves like a viscoelastic-soft solid, with behaviour similar to soft dough or fibrous mash, especially during transition into a sticky, cohesive paste.

Experimental studies on rheology of cooked yam indicate the following average properties:

- Shear strength (yield shear stress), τ_y : 2–10 kPa for τ_y partially cooked yam, rising to 21–32 kPa when fully softened and cohesive (sticky stage) (Nwadike et al, 2018)
- Effective consistency coefficient K for yam pastes ranges from 30–60 Pa·s^n
- We will conservatively use τ_y = 25kPa to model average shear resistance during operation.

Table 2. Pounding Chamber Parameters

Parameters	*Value*
Pounding Hammer length l	0.125m
Pounding Hammer width w	0.03m
Pounding chamber D	0.3m
Speed of pounding	800rpm

Contact area of hammers $A_c = 2wl = 2 \times 0.125 \times 0.03 = 0.0075m^2$

Shear force required to pound $F_p = \tau_y A_c = 25000 \times 0.0075 = 187.5N$

Torque required for pounding $T = F_p l = 187.7 \times 0.125 = 23.4N.m$

Power of motor required $P_m = \frac{2\pi N}{60}.T = \frac{2\pi \times 800}{60}.23.4 = 1963W \approx 2kW$

Therefore, a **2.0 kW single-phase AC motor** was selected to provide sufficient torque under high-viscosity conditions.

3.4 *Power requirement of the cooking system*

Unlike open-pot boiling, pressure-based cooking enhances heat transfer by maintaining moist, saturated conditions and suppressing temperature fluctuations. From empirical analysis and literature survey on sealed cooking systems, the chamber typically stabilizes around **90–95 °C** during cooking, depending on steam retention and initial loading conditions.

To estimate the energy required to heat the yam and water from room temperature (25 °C) to 90 °C under sealed conditions

$$Q = (m_w \cdot c_w + m_y \cdot c_y) \cdot \Delta T$$

Table 3. Thermal properties of water and yam

Parameter	***Value***
Mass of water m_w	0.3kg
of Yam m_y	2kg
Specific heat capacity of Mass water c_w	4.2kJ/kgK
Specific heat capacity of yam c_y	3.2kJ/kgK (Nwadike et al, 2018)
Insulation thickness t_c	0.02m
Height of chamber h	0.3m

$$Q = (0.3 \cdot 4.18 + 2 \cdot 3.2) \cdot (90 - 25) = 523.51kJ$$

To achieve this heating in maximum **25 minutes (1500 seconds)**:

$$P_h = \frac{Q}{t} = \frac{523510}{1500} = 349Watts$$

Considering the heat loss, a **2 cm air gap** acts as thermal insulation. Air's low thermal conductivity (~0.026 W/m·K) significantly reduces steady-state heat loss.

$$Q_{loss} = \frac{kA\Delta T}{t_c}$$

Where, $A_c = \pi Dh + \frac{\pi D^2}{2} = \pi \times 0.3 \times 0.3 + \frac{\pi \times 0.3^2}{2} = 0.424m^2$

$$Q_{loss} = \frac{kA\Delta T}{t_c} = \frac{0.023 \times 0.424 \times 65}{0.02} = 31.7Watts$$

Total heating power required = $\frac{P_h + Q_{loss}}{\eta} = \frac{349+3\ \ .7}{0.8} = 475watts$

A **0.5 kW electric coil heater** was selected to provide margin for heat loss and rapid temperature recovery.

3.5 *Control System Design and Automation Logic*

The control subsystem of the automated yam cooking and pounding machine was designed around an **Arduino-based microcontroller**, programmed to execute the full cooking-to-pounding sequence with minimal user intervention. This control unit orchestrated all process stages via digital and analog I/O channels, enabling responsive automation based on real-time sensory inputs.

The machine's control and data acquisition are handled by an **Arduino Uno**. It continuously monitors:

- **Temperature** of the cooking water using a **DS18B20 digital sensor**.
- **Piercer state** using **a limit switch** at predefined position.
- **Time tracking** via internal Arduino timer from heating start to doneness signal.

Sensor Logic:

- At system start, the piercer rests against the yam and compresses the spring.
- As yam softens, spring force becomes sufficient to drive the piercer downward.
- When the **piercer fully retracts**, the limit switch is activated.
- This state triggers:
  - A **buzzer alert**.
  - A **timer stop** and cooking duration log via the **serial monitor**.
  - After 1 minute, the controller starts the motor through the relay for the pounding to begin and run for 5 minutes.
- This logic can be seen visually in the Fig 1 below.

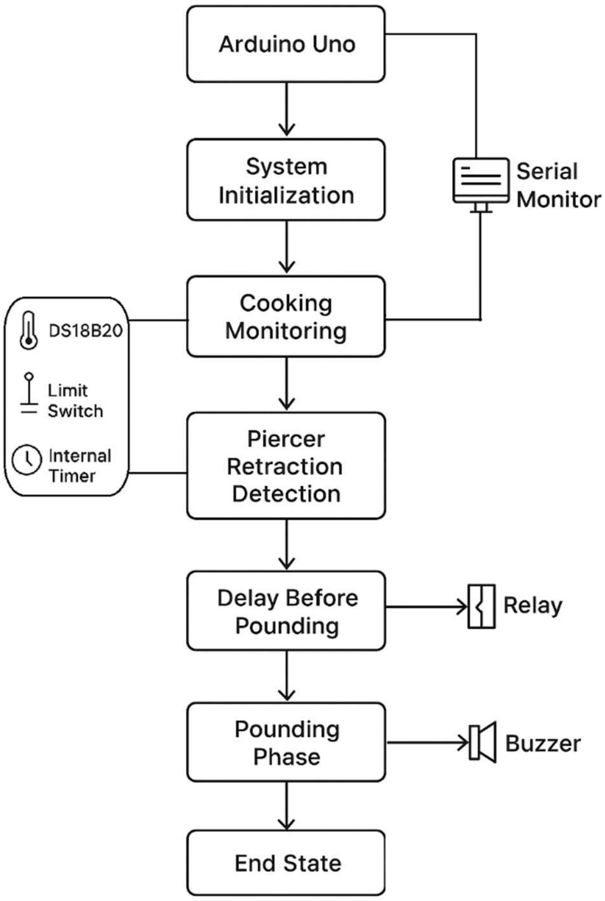

Fig 1. Sensor Logic for the Automated yam cooking and pounding machine.

This method offers real-time data without relying on fixed-duration cooking cycles.

4 RESULTS, DISCUSSION, AND PERFORMANCE EVALUATION

4.1 *Temperature Profile of the Cooking Process*

Temperature monitoring was conducted to establish the heating profile of 0.5 kg water during the cooking process. The objective was to confirm attainment of thermal equilibrium and identify the stability of the cooking medium. Temperatures were recorded every minute for the first 10 minutes, then every 5 minutes thereafter.

Table 4: Temperature Profile of Water During Cooking

Time (min)	*Average Temp across tests (°C)*
0	25
1	45
2	65
3	78
4	86
5	90
10	90
15	90
20	90

The temperature profile obtained and shown in Table 4 demonstrated a ramp-up to approximately 90 °C within five minutes of heating 0.5 kg of water, followed by equilibrium stability. This behavior is thermodynamically consistent with water-based cooking systems under controlled input energy, wherein the steady-state temperature hovers slightly below the boiling point due to heat transfer losses and convective dynamics around the yam cubes. The thermal uniformity observed ensures that starch gelatinisation progresses predictably. This equilibrium forms the baseline thermal condition under which yam doneness was evaluated.

4.2 *Piercing Force Evaluation*

This test aimed to quantify the force required to pierce yam samples during cooking. Since real-time force logging was not possible with the machine, the test was replicated using a calibrated fork and suspended weights. Force was measured every 5 minutes until doneness was detected and the values were recorded on Table 5. Three yam grades were tested.

Table 5**:** Piercing Force with Time for Different Yam Grades

Time (min)	***Firm Yam (N)***	***Medium Yam (N)***	***Soft Yam (N)***
0	45.2	41.5	35.7
5	38.7	32.9	25.2
10	29.5	21.7	12.4
15	18.3	10.9	2.8
20	9.8	3.0	—
22	3.5	—	—

Piercing force decreased progressively with cooking time, confirming the softening trend of yam tissues. Doneness corresponded to forces below ~3 N, at which point the spring-loaded piercing mechanism was consistently activated. Firm yams required the longest cooking time to reach this threshold, in agreement with the cooking time results.

4.3 *Testing Procedure for Doneness*

The objective of this test was to determine the average cooking time for different yam grades using the designed test machine. The doneness detection mechanism was based on the spring-loaded piercing system, which activates once resistance drops below a calibrated threshold. Each yam grade (firm, medium, and soft) was tested in three replicates, with 2 kg of yam samples cut into 1 inch cubes and steam boiled in 0.5 kg of water.

Table 6: Cooking Time for Different Yam Grades

Yam Grade	*TestA (min)*	*TestB (min)*	*TestC 3 (min)*	*Average (min)*
Firm	22	21	23	22.0
Medium	18	19	18	18.3
Soft	15	14	15	14.7

The results shown in Table 6 indicates a clear correlation between yam texture and cooking time. Firmer yams consistently required longer durations (average 22 min), while softer varieties reached doneness in under 15 min. These results validate the system's ability to distinguish doneness across yam grades.

4.4 *Pounding Mechanism Test*

This test evaluated the machine's pounding functionality by quantifying yam smoothness over time. Smoothness was measured as the size of the largest visible particle after different pounding durations. A maximum test duration of 5 minutes was used. Quadratic decay of particle size was assumed, with a target of ~1 mm at 5 minutes.

Table 7: Particle Size Reduction with Pounding Time

Time (min)	***Firm Yam (mm)***	***Medium Yam (mm)***	***Soft Yam (mm)***
1	8.0	6.5	5.0
2	5.5	4.0	3.0
3	3.2	2.5	2.0
4	1.8	1.4	1.2
5	1.0	1.0	1.0

The results shown in Table 7 demonstrate consistent reduction in yam particle size across all grades, achieving acceptable smoothness (<1 mm) within 5 minutes. Soft yams achieved faster reduction, while firm yams required nearly the full 5 minutes.

4.5 Comparative Analysis with Manual Method

The final evaluation compared the machine's performance with conventional manual yam cooking and pounding. Parameters of interest were total preparation time, physical effort, and uniformity of output.

Table 8: Machine vs. Manual Method Comparison

Parameter	***Machine***	***Manual***
Average Cooking Time (min)	18 (grade-dependent)	20–25 (subjective)
Pounding Duration (min)	5	8–15
Effort Required	Low (automated)	High (manual pestle)
Output Uniformity	High (≤1 mm)	Medium (2–5 mm particles)

The direct comparison with manual cooking and pounding shown in Table 8 revealed that while the traditional approach produces acceptable results, it is time-intensive and prone to inconsistencies. Manual cooking often exceeds the minimum required time, particularly for hard-textured yams, leading to nutrient losses and variable textural outcomes. Similarly, manual pounding is heavily operator-dependent, with smoothness varying according to effort and endurance. The automated device, on the other hand, achieved consistent doneness detection and smooth pounding in a shorter duration. This suggests that mechanization not only improves efficiency but also standardizes product quality

5 CONCLUSION AND FUTURE WORK

5.1 *Conclusion.*

The development and evaluation of the automated yam cooking and pounding machine have demonstrated the technical feasibility of fully mechanizing a traditional food preparation process that has long relied on manual labour. Through systematic testing, the work established reliable cooking times, thermal behaviour, piercing force requirements, and effective pounding durations across different yam grades. The incorporation of a spring-loaded doneness tester was particularly crucial, as it enabled the accurate determination of cooking completion, thereby eliminating guesswork and ensuring repeatability.

Parallel validation was also conducted using a Chinese-manufactured yam pounding machine. This product, while already capable of handling the pounding process, lacked the capacity for full automation in cooking and timing control. By integrating the experimental results from this study into the Chinese product via time-based programming, the device was successfully adapted to operate as a fully automated system. The outcomes confirmed the robustness and applicability of the experimental findings across different machine designs.

5.2 *Current Stage of Development*

At present, the project has progressed beyond experimental validation to international collaboration. The results from the spring tester experiments were used to develop a time-based cooking program, which was successfully tested on a Chinese-manufactured yam pounding machine with in-built cooking capacity. The trial confirmed that the experimental findings could be directly translated into a commercially viable system, providing a critical bridge between research and market application.

Following this validation, discussions have been initiated with the Chinese manufacturer to integrate the new developments into their machine design. The company is presently working on a redesigned model that incorporates the cooking–pounding automation in line with the experimental data. Furthermore, negotiations are ongoing to secure sole selling rights for this new version of the machine, ensuring both commercial advantage and protection of intellectual contribution.

5.3 *Future Work*

The next phase of the project will focus on refining and scaling the system for broader use. Immediate tasks include:

- **Optimization of the Control System:** Transitioning from purely time-based programming to a hybrid model that integrates real-time sensing (temperature and texture) for even greater accuracy.
- **Design Improvements:** Enhancing energy efficiency, user safety, and interface design to meet both domestic and industrial requirements.
- **Pilot Production:** Collaborating with the Chinese manufacturer to produce limited units for consumer trials and market testing.
- **Commercialization Strategy:** Establishing licensing agreements, distribution networks, and customer support structures to prepare for large-scale rollout.

In the longer term, the system can be expanded to accommodate related food processing applications, leveraging the same automation principles. The project has therefore laid a strong foundation not only for transforming yam preparation but also for modernizing broader African food processing systems.

6 REFERENCES

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7 APPENDIX

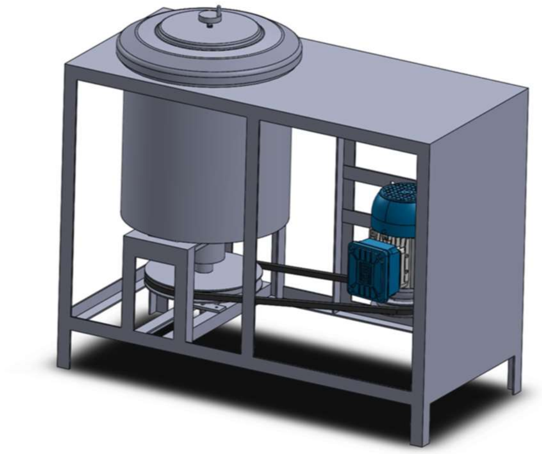

Fig A1. Isometric view of the Automated Yam Cooking and Pounding machine.

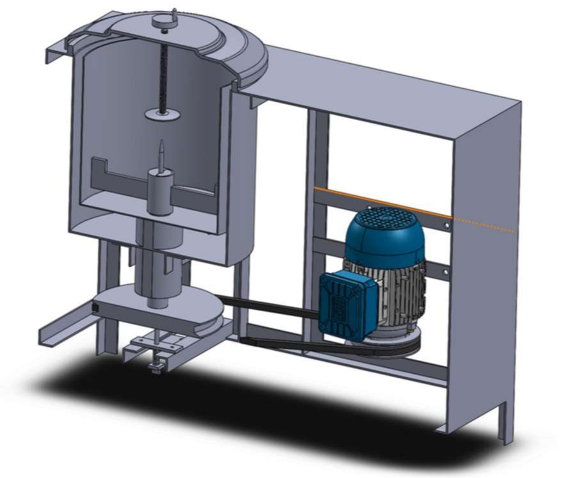

Fig A2. Section view of the Automated Yam Cooking and Pounding machine. [Interior Spring mechanism].

Fig A3. First fabricated model of the Automated Yam cooking and pounding machine with integrated spring doneness tester.

Fig A4. First implemented model using research data from fabricated model.

Fig A5. Sample from the Chinese Company (Dongguan Dragon) implementing data from the research obtained from previous models,.