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Design and Evaluation of an ESP32-Based Automatic Cake Ingredient Dosing System Using Load Cell Control

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ABSTRACT

Purpose – This study designs and evaluates an ESP32-based automatic ingredient dosing system for a small bakery experiencing imprecise manual weighing.

Methods – A research and development approach produced two prototypes: an auger-based rice flour doser and a peristaltic-pump coconut milk doser. Both used load cells, HX711 modules, and single-speed on/off control with a 400 ms settling step. Manual and automatic dosing were compared over ten reported repetitions per condition using targets of 263 g flour and 492 mL coconut milk, the latter treated as 492 g under an assumed density of 1.0 g/mL.

Findings – Reported accuracy increased from 91.5% to 97.9% for flour and from 95.2% to 98.9% for coconut milk. Mean absolute errors decreased to 5.4 and 5.3 g, respectively. Automatic dosing averaged 24.9 s for flour and 19.7 s for coconut milk. All nine functional test items were completed successfully.

Research implications – The findings concern one recipe, enterprise, operator, and testing session. Manual and automatic timing covered different task boundaries, and calibration ended at 453 g, below the coconut milk target. Further calibration, equivalent timing comparisons, and longer-term testing are needed before generalizing performance.

Originality – The prototype combines solid and liquid dosing mechanisms within a shared load-cell feedback framework intended for small-scale bakery production.

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INTRODUCTION

Background of the Study

Micro, small, and medium enterprises (MSMEs) are the backbone of the Indonesian economy. Data from the Ministry of Cooperatives and SMEs indicate that the sector comprises about 64.2 million business units, contributes 61.07% of national Gross Domestic Product, and absorbs roughly 97% of the total workforce [1]. However, many food-sector MSMEs still face difficulties in production efficiency and quality consistency because they depend on imprecise manual methods. D'NAVYA, a bread and cake producer in Banyuwangi, experiences this problem directly. The mechanical "duck scale" used in its kitchen is graduated only in coarse steps (50 g, 100 g, 200 g), so it cannot represent the intermediate values that recipes frequently require, such as 72 g, 125 g, or 175 g. Weighing deviations of 20-30 g consequently occur and produce three practical effects: inconsistent product texture between batches, cakes that burn more easily when excess sugar triggers over-caramelisation, and unproductive weighing time of about 2-3 hours per day across 8-12 production batches. The owner also cannot observe the dosing process without being physically present in the kitchen.

The main challenge in designing an automatic solution lies in the diversity of the physical characteristics of cake raw materials. Wheat flour and rice flour are dry, cohesive, non-free-flowing powders that are difficult to move by gravity alone, whereas coconut milk is a viscous liquid. These two behaviors require different dosing mechanisms: an auger screw feeder for solid powders and a pump for liquids.

Literature Review

The ESP32 microcontroller is widely chosen as the control unit for automatic dosing systems because of its processing capability, flexible GPIO support, and built-in wireless connectivity relevant to Internet of Things applications. Cahyanto et al. [2] demonstrated that an ESP32 combined with a load cell and an HX711 module could dose chicken-feed mixtures incrementally with an average error of 0.13%. The load cell itself operates on the strain-gauge principle, converting the deformation caused by a load into an electrical signal that the HX711 module amplifies and converts into digital data [3], [4]. For mechanical actuation of non-free-flowing powders, auger-based dosing driven by stepper motors has been shown to provide controllable discharge, adequate torque, and acceptable repeatability for granular and powder products [5], [6], [7]. On/off control based on continuous load-cell feedback - comparing the actual weight with the target and stopping the actuator once the target is reached - has been applied successfully in several automatic weighing devices, among them an automatic peanut weigher that reported an average error of 2.19% [8] and a microcontroller-based granule weighing device operated through a human-machine interface [9]. For liquid dosing, pump-based systems controlled through motor drivers with weight or flow feedback have been used to deliver liquid to a target value with acceptable precision [10], [11], [12], [13].

Gap Analysis

Although many previous studies have applied load cells, HX711 modules, and microcontrollers to automatic weighing of a single material class - animal feed [2], peanuts [8], granulated food [5], sugar [10], or water [11] - few have integrated two different dosing mechanisms within one control framework: a solid channel using an auger screw feeder and a liquid channel using a pump. Traditional cake production requires both material types in the same recipe, so a device that handles only one of them solves only part of the operational problem faced by MSMEs such as D'NAVYA. The present study addresses that gap.

Rationale of the Study

Based on this gap, the study was designed to build two complementary ESP32-based automatic dosing prototypes: a flour doser using an auger screw feeder with a NEMA17 stepper motor and an A4988 driver, and a coconut milk doser using a peristaltic pump with an L298N driver. Both devices apply on/off control based on a 5 kg load cell and an HX711 module, with a short settling delay before

the final weight is verified. Dosing status is displayed in real time on a 16 × 2 I2C LCD and on a local web dashboard served by the ESP32 over its own Wi-Fi access point.

Purpose of the Study

This study aimed to design and build an ESP32-based automatic cake ingredient dosing system with a target deviation of approximately 5–10 g or mL from the recipe value, integrate its hardware and software, and evaluate dosing accuracy and time efficiency against the manual method used by UMKM D'NAVYA. Repeated trials were used to examine short-term performance under the tested operating conditions.

METHOD

Research Design

This study employed a Research and Development (R&D) approach because the objective was not only to analyze an existing phenomenon, but also to design, realise, and evaluate a functional prototype for direct use by a bakery-scale micro-enterprise [14], [15]. The process was organized into six operational stages: (1) problem identification through field observation and interviews with the business owner; (2) literature review on ESP32-based embedded systems, load-cell instrumentation, auger mechanisms, peristaltic pumps, and on/off dosing control [2], [3], [5], [6], [7], [8], [10], [11], [12], [16], [17], [18], [19]; (3) prototype design covering mechanical, electrical, and software architecture; (4) fabrication and integration of hardware and software; (5) calibration and performance testing; and (6) revision of the prototype based on test results. This orientation suits applied engineering research because design decisions can be validated iteratively against real operational needs rather than only under laboratory assumptions.

Research Site, Object, and Materials

The research was conducted at UMKM D'NAVYA in Pakistaji, Banyuwangi, East Java, Indonesia. The partner was selected purposively because its production still depended on manual weighing with a mechanical duck scale that could represent only coarse weight intervals, which caused recurring inaccuracy whenever a recipe value fell between the available scale marks. The object of the research was the dosing process for the two raw materials used most intensively in D'NAVYA's layer cake (*kue lapis*): rice flour as the solid ingredient and coconut milk as the liquid ingredient, with recipe targets of 263 g and 492 mL per batch, respectively. Because the coconut milk used by the partner has a density close to 1.0 g/mL, the volumetric target of 492 mL was treated throughout this study as a mass target of 492 g; this equivalence is an operational assumption and is revisited in the Limitations subsection. The two materials were chosen because they represent contrasting flow behavior: flour tends to bridge, compact, and continue discharging briefly after screw rotation stops, whereas coconut milk behaves as a fluid subject to pump pulsation and residual flow in the tube [16], [19]. Covering both in one system allowed the development to address the practical needs of small bakery production more completely.

Instruments and System Architecture

The research instruments consisted of two prototype units and supporting measurement equipment. The hardware configuration of both prototypes is summarized in Table 1, and the overall architecture is shown in Figure 1. The ESP32 was selected because it provides sufficient processing capability, GPIO flexibility, and integrated wireless communication for low-cost embedded control [2]. The load cell and HX711 combination was selected because it is widely applied in precision weighing systems and amplifies millivolt-scale strain-gauge output into digital data readable by the microcontroller [3], [4]. Supporting equipment included a set of calibration masses, measuring cups, wiring tools, a digital multimeter, and a stopwatch. The detailed electrical connections of the two devices are given in Figures 2 and 3.

Table 1. Hardware configuration of the two dosing prototypes

Subsystem	Device 1 - flour doser	Device 2 - coconut milk doser
Controller	ESP32 DevKit V1	ESP32 DevKit V1
Weight sensing	2 x load cell 5 kg (hopper and weighing platform) + HX711	1 x load cell 5 kg (weighing platform) + HX711
Actuator	Auger screw feeder driven by NEMA17 stepper motor	Peristaltic pump driven by DC motor
Driver	A4988 microstepping driver	L298N dual H-bridge driver
Material container	Aluminium hopper, 3 kg capacity	Food-grade reservoir with food-grade silicone tubing
User interface	16 × 2 I2C LCD, push-button, local web dashboard	16 × 2 I2C LCD, push-button, local web dashboard
Power supply	12 V DC adaptor with 5 V regulator	12 V DC adaptor with 5 V regulator

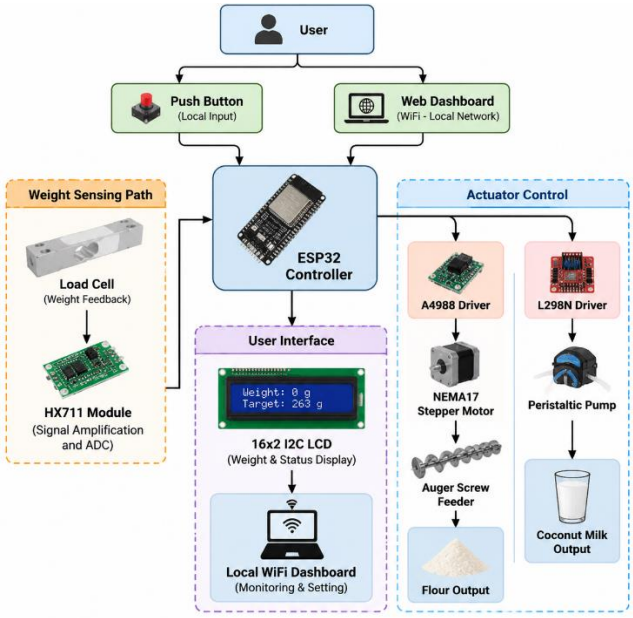


Figure 1. Block diagram of the ESP32-based automatic dosing system

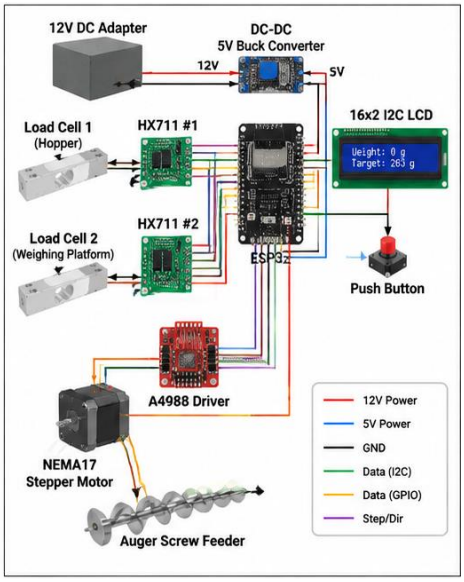


Figure 2. Electrical schematic of the flour dosing device

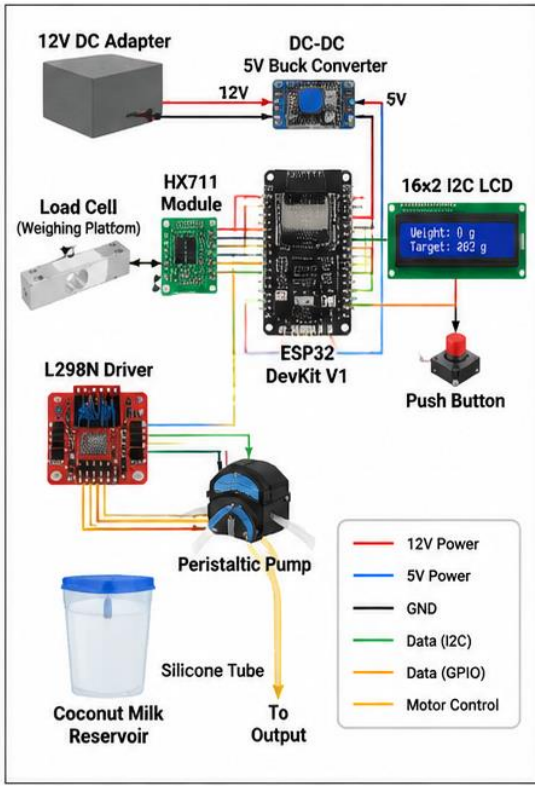


Figure 3. Electrical schematic of the coconut milk dosing device

Control Algorithm

Both prototypes operate under the same closed measurement loop. The operator selects a target value, the ESP32 reads real-time weight data from the load cell through the HX711 module, the controller activates the actuator, and the actuator is switched off once the measured value reaches the target. The control law is on/off (bang-bang) rather than proportional: the stepper motor and the pump run at a single fixed speed for the whole dosing cycle and are not slowed down as the target is approached. On/off logic was chosen deliberately because the primary design goal was a low-cost, easy-to-maintain solution for MSME operation; although simpler than PID or fuzzy control, it remains appropriate for discrete dosing tasks when the system is calibrated carefully and the resulting overshoot stays within production tolerance [11], [18].

After the actuator stops, the controller waits 400 ms before reading the load cell again and comparing the settled weight with the target. The specified completion criterion is a residual deviation within ±1 g; otherwise, the controller briefly pulses the actuator and repeats the verification step. The actuator operates at a single speed, so this sequence does not implement a reduced-speed approach to the target. Continued discharge after the stop command can produce overshoot. Figure 4 presents the control sequence.

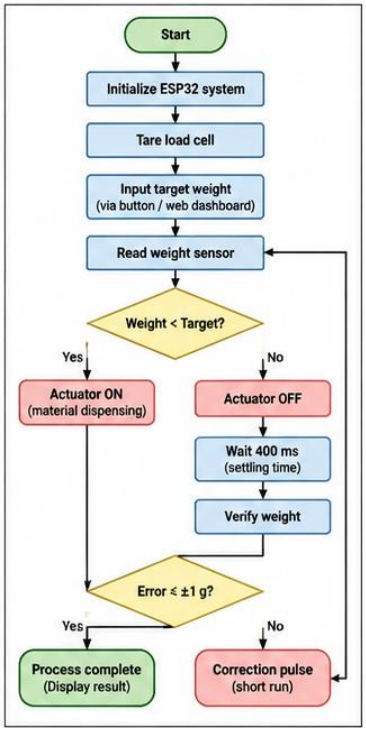


Figure 4. Flowchart of the on/off dosing algorithm with settling and verification

Calibration Procedure

Before the main experiment, each load cell was calibrated using ten reference masses from 41 to 453 g and a calibrated digital reference scale. The raw readings and reference masses were fitted by ordinary least squares using W_corrected = a × W_raw + b. The correction was implemented in the ESP32 firmware. The calibration range includes the 263 g flour target but does not include the 492 g coconut milk target or the sensor's full 5 kg capacity. Measurement performance beyond 453 g therefore requires further calibration verification.

Testing Procedure

Testing comprised three parts: accuracy testing, time-efficiency testing, and functional testing. Accuracy testing compared the existing manual method - a duck scale for flour and a measuring cup for coconut milk, operated by the partner's own staff - with the automatic method, using the layer-cake targets of 263 g rice flour and 492 g coconut milk. Each of the four conditions (flour manual, flour automatic, coconut milk manual, coconut milk automatic) was repeated ten times, giving n = 10 per condition and 40 dosing events in total. Time-efficiency testing recorded, for the same ten repetitions, the elapsed time from the start of the dosing action until the target was reached. Functional testing was carried out in stages on nine system items, from component initialization, sensor reading, and actuator control to LCD display, the automatic stopping mechanism, and low-material detection in the hopper.

For every repetition the researcher recorded the target value, the measured value read on an independent reference scale, the absolute error, the calculated accuracy, and the elapsed time on a standardized data-collection sheet. All repetitions were performed on the same day, by the same

operator, and with the same material batch, so the dispersion reported below reflects short-term repeatability rather than day-to-day or operator-to-operator reproducibility.

Data Analysis and Repeatability Reporting

Data were analyzed quantitatively and descriptively. For each trial i, the absolute error was defined as $e_i = |W_{target} - W_i|$, and the accuracy of the trial as $A_i = (1 - e_i / W_{target}) \times 100\%$. For each condition the mean measured value, the mean absolute error (MAE), and the mean accuracy were computed over the ten trials. Time saving was calculated as $(t_{manual} - t_{automatic}) / t_{manual} \times 100\%$ after converting both values to seconds.

Dispersion complements mean error when evaluating dosing repeatability. The analysis includes the sample standard deviation of the ten measured values, the coefficient of variation ($CV = s / mean \times 100\%$), and the observed minimum and maximum [20]. These measures help distinguish a systematic offset from variable dosing behavior.

To position the findings, the quantitative results were then compared with previous studies on load-cell-based weighing, screw-fed powder transfer, and pump-based liquid dosing. The comparison does not claim superiority on every metric, because the materials, target ranges, and industrial scales of those studies differ from the present case. It is used instead to locate this study within the literature and to identify which aspects of the prototype already meet practical expectations and which still require refinement.

Validity, Reliability, and Practical Acceptance Criteria

Because the study focused on prototype performance in a real production context, validity was interpreted in three forms. Design validity was pursued by matching each subsystem to the practical problem identified at UMKM D'NAVYA, namely the need to dose both solid and liquid ingredients more accurately and faster than the existing manual method. Measurement validity was strengthened through repeated calibration against an independent reference scale and through repeated trials, so that conclusions do not rest on one-off observations. Practical validity was judged by operational acceptability: a prototype is useful only if the achieved accuracy and speed are relevant to bakery work, not merely statistically improved. Reliability in this context refers to consistency across repeated runs, and is quantified by the standard deviation and coefficient of variation defined above.

Practical acceptance criteria were also formulated in advance to align the evaluation with MSME needs. A device was considered operationally acceptable when it satisfied four conditions simultaneously: (1) it completed the dosing task without repeated manual intervention; (2) the final dose stayed close enough to the recipe target to support consistent product quality, operationalized here as a mean absolute error of no more than 10 g; (3) the total dosing time was shorter than that of the existing manual method; and (4) the system architecture remained simple enough to be maintained locally. These criteria matter because MSME users typically prioritize robustness, simplicity, and affordability over maximum theoretical precision, and stating them in advance makes explicit how engineering success was judged.

Scope and Limitations of the Methodology

The study was limited to a maximum weighing capacity of 5 kg, a target deviation of approximately 5-10 g, a calibration range of 41-453 g, and testing conducted on site at UMKM D'NAVYA with ten repetitions per condition. System performance was not tested on raw materials other than rice flour and coconut milk, nor on recipes other than the layer cake.

RESULTS AND DISCUSSION

Implementation of the Prototypes

Both devices were built and operated in the partner's kitchen. The implemented flour doser (Figure 5) comprises a 3 kg aluminum hopper, an auger screw feeder, a NEMA17 stepper motor with an A4988 driver, two 5 kg load cells with HX711 modules, an ESP32, and a 16 × 2 I2C LCD. Initial testing showed that all modules communicated without interference and that the stepper motor rotated the auger screw steadily, so that flour reached the weighing container without clogging or bridging in the hopper throat. The implemented coconut milk doser (Figure 6) comprises a food-grade reservoir, a peristaltic pump with an L298N driver, one 5 kg load cell with an HX711 module, an ESP32, and a 16 × 2 I2C LCD; the pump delivered coconut milk continuously with no leakage at the hose connections throughout testing.

Hardware integration testing confirmed that every major component performed its intended function. The ESP32 acquired load-cell data through the HX711 module and drove the A4988 and L298N drivers correctly. In addition to the LCD, the ESP32 operated as a local Wi-Fi access point and web server; the resulting dashboard (Figure 7) allowed the operator to set the target weight, perform a tare operation, monitor the current weight, and observe dosing status without an internet connection, using periodic data requests to refresh the display. The implementation therefore integrated sensing, processing, actuation, and user interaction into a single automatic dosing platform.

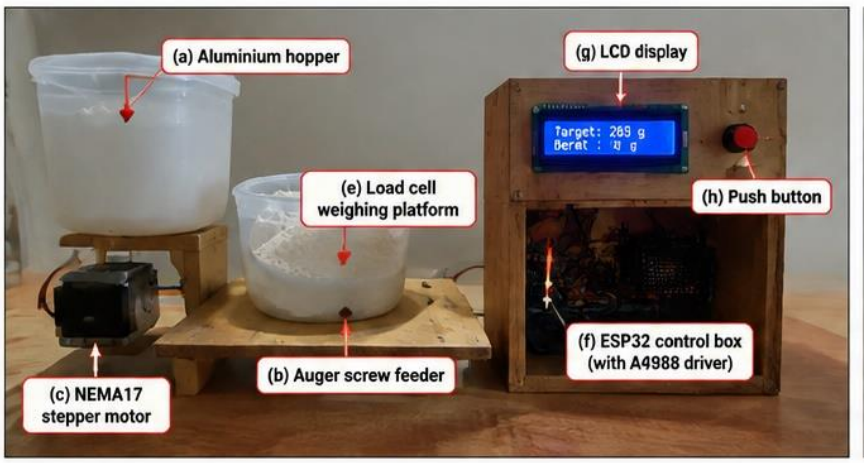


Figure 5. Implemented flour dosing device (Device 1)

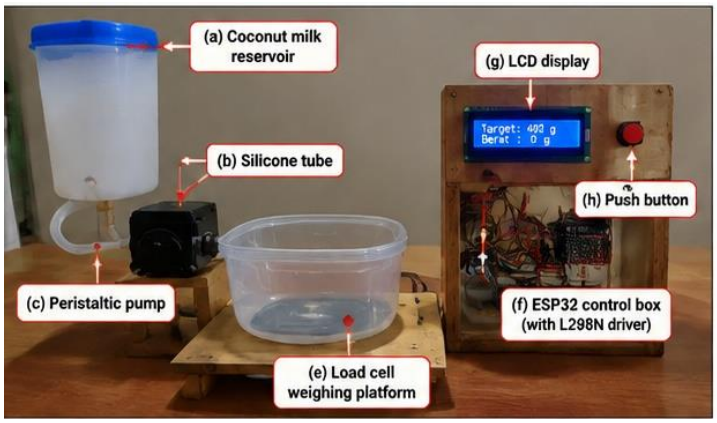


Figure 6. Implemented coconut milk dosing device (Device 2)

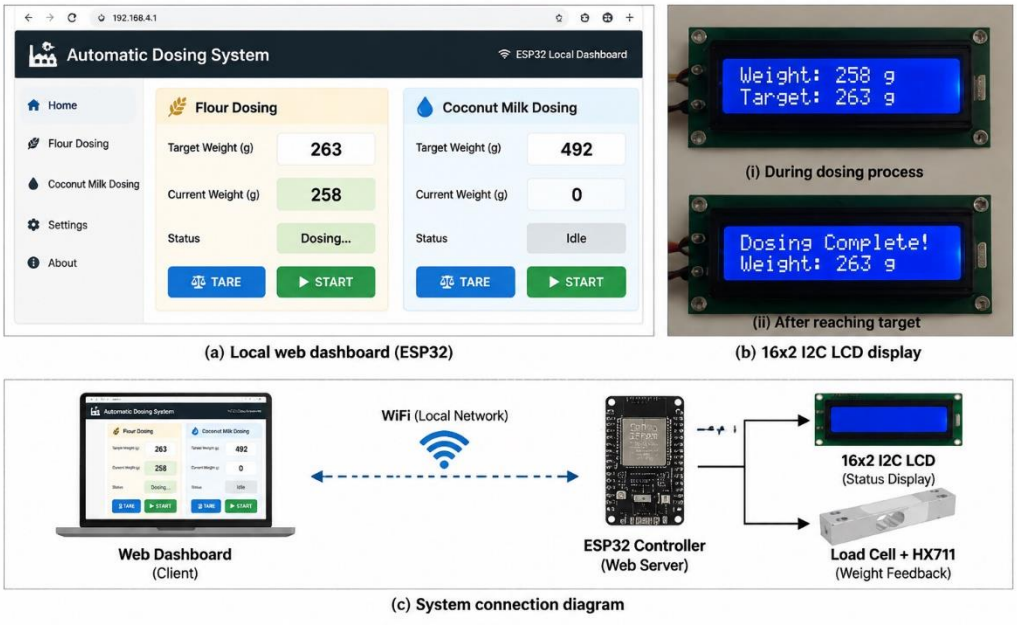


Figure 7. Local web dashboard and LCD display during operation

Load Cell Calibration

Table 2 reports calibration measurements for ten reference masses. Absolute deviations ranged from 0.01 to 2.02 g, with a mean of 0.92 g. Ordinary least-squares regression of reference mass on measured mass gave W_corrected = 1.0034025 × W_raw − 1.3295226, with R^2 = 0.9999 over the calibrated range. The correction was implemented in the ESP32 firmware. Figure 8 presents the calibration curve and residuals.

Table 2. Load cell calibration results against reference masses

Trial	Reference weight (g)	Measured weight (g)	Deviation (g)
1	41	43.01	+2.01
2	77	79.02	+2.02
3	133	132.01	-0.99
4	163	163.05	+0.05
5	216	218.02	+2.02
6	258	257.01	-0.99
7	301	301.01	+0.01
8	327	328.01	+1.01
9	405	405.05	+0.05
10	453	453.01	+0.01
Mean absolute deviation			0.92

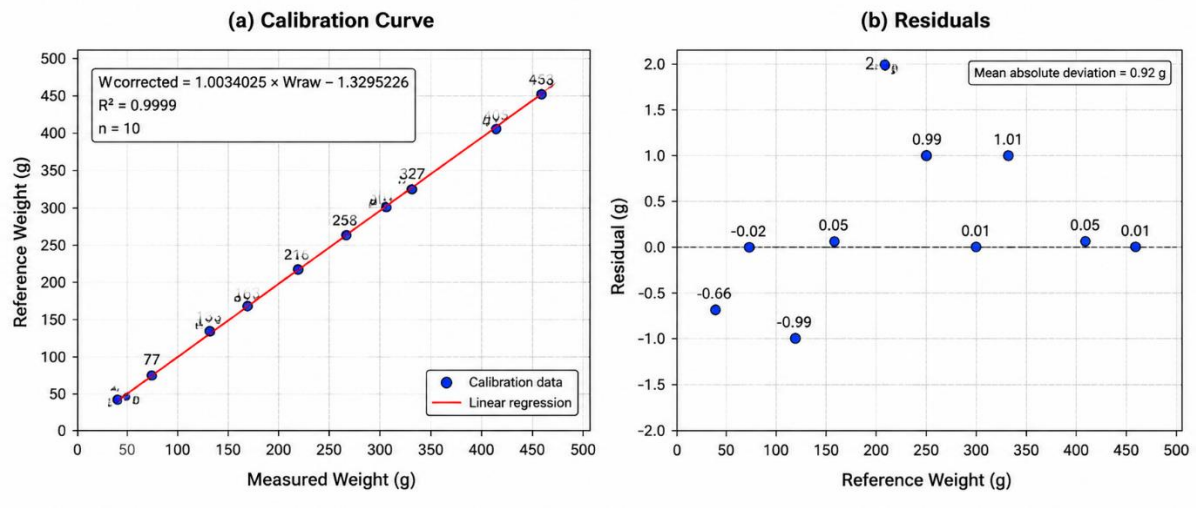


Figure 8. Load cell calibration curve and residuals

Dosing Accuracy and Repeatability

Dosing was repeated ten times per condition for rice flour and coconut milk. Figure 9 visualizes the reported measurements. For rice flour against the 263 g target, the manual method produced measured values between 233 g and 295 g, with a mean absolute error of 22.4 g and a mean accuracy of 91.5%. The automatic method narrowed the measured range to 255-272 g, reduced the mean absolute error to 5.4 g, and raised mean accuracy to 97.9%. The pattern for coconut milk against the 492 g target was similar: manual dosing produced 458-520 g with a mean absolute error of 23.4 g and an accuracy of 95.2%, whereas automatic dosing produced 485-502 g with a mean absolute error of 5.3 g and an accuracy of 98.9%. In both materials the spread of measured values narrowed by roughly a factor of three, from a 62 g span under the manual method to a 17 g span under automatic dosing, which indicates that the improvement lies in consistency and not only in the average. The trial-by-trial dispersion of the four conditions is visualized in Figure 9.

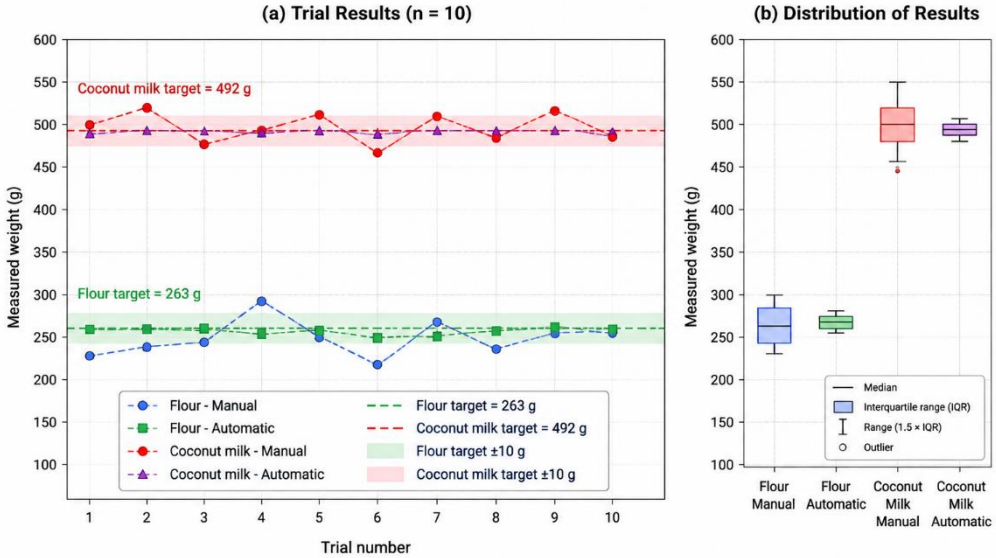


Figure 9. Dispersion of realised dosing values across ten repetitions for manual and automatic methods. The horizontal lines indicate recipe targets and the shaded areas show the acceptance range (±10 g).

Figure 9. Dispersion of measured dosing values across ten repetitions per condition

Dosing Time Efficiency

Table 3 summarizes the reported dosing times. Manual flour dosing averaged 15.0 min per batch, compared with 24.9 s for automatic dosing, corresponding to a reduction of approximately 97.2%. Coconut milk dosing averaged 12.0 min manually and 19.7 s automatically, a reduction of approximately 97.3%. The manual duration included fetching and zeroing the scale, scooping, checking, and correcting the amount, whereas the automatic duration represents the machine cycle. These differences in timing boundaries should be considered when interpreting the comparison.

Table 3. Summary of dosing time efficiency

Device	Manual time (mean)	Automatic time (mean)	Time saving (%)
Flour doser	15.0 min	24.9 s	97.2
Coconut milk doser	12.0 min	19.7 s	97.3

Functional Testing

Functional testing covered nine system items, from component initialization to the automatic stopping mechanism and the detection of insufficient material in the hopper. All nine items operated as designed (Table 4).

Table 4. Summary of system functional test results

No	Test item	Expected behavior	Result
1	Initialization of ESP32 and all components	All modules detected at start-up	Successful
2	16 × 2 I2C LCD display	Target, current weight, and status shown correctly	Successful
3	Hopper and platform load cell reading (Device 1)	Stable readings from both sensors	Successful
4	Load cell - HX711 - ESP32 communication	Continuous data acquisition without dropout	Successful
5	NEMA17 stepper motor and A4988 driver	Steady auger rotation under load	Successful
6	Peristaltic pump and L298N driver	Continuous liquid delivery without leakage	Successful
7	Push-button input	Start, tare, and reset commands registered	Successful
8	Automatic stop when target weight is reached	Actuator stops, settling and verification executed	Successful
9	Detection of insufficient material in the hopper	Warning displayed and dosing halted	Successful

Discussion

Reported accuracy increased from 91.5% to 97.9% for flour and from 95.2% to 98.9% for coconut milk. The narrower observed ranges suggest improved consistency under the tested conditions. Load-cell feedback transfers the stopping decision from the operator to the controller, reducing reliance on visual estimation. Calibration also supports measurement accuracy, although the 0.92 g mean deviation in Table 2 describes the listed calibration readings and should not be interpreted as a complete uncertainty estimate for the corrected dosing system.

The flour result can be read from the perspective of powder-flow behavior. Rice flour is not an ideal free-flowing material: it is cohesive, prone to compaction, and continues to move after the motor

stops because of screw inertia and material already in the discharge channel. Even so, the prototype reduced the mean absolute error from 22.4 g to 5.4 g, which suggests that the auger configuration produced a more controllable discharge than manual scooping. Xu et al. [6] reported that screw geometry strongly influences flow uniformity in wheat flour handling and that more stable feed behavior translates directly into dosing accuracy; the present study is consistent with that view in a practical MSME setting, since a screw far simpler than an industrial variable-pitch design still produced a measurable improvement. The coconut milk doser achieved the higher accuracy of the two, at 98.9%. This is plausible because liquids generally exhibit more predictable transport behavior than cohesive powders, even though peristaltic pumps introduce pulsation and a short residual flow at the end of a cycle [16], [19], [21]. Within the target range used by the recipe, the peristaltic mechanism evidently provided sufficiently stable displacement. Taken together, the two results show that the same measurement principle and controller platform can serve two quite different ingredient-flow profiles, which matters because a food production line rarely handles only one material type.

The reported time reductions exceeded 97% for both materials. However, manual timing included preparation and adjustment activities, while automatic timing represented the machine cycle. The findings therefore support a reduction in the recorded task durations, but an equivalent start-to-finish protocol is needed to quantify the operational time saving precisely. Both devices achieved reported mean absolute errors below the predefined 10 g acceptance threshold and completed the tested functional tasks.

All nine functional test items were completed successfully, supporting basic integration of sensing, control, actuation, and the user interface. This result demonstrates functional feasibility under the test conditions. It does not establish long-term measurement reliability or robustness to vibration, environmental changes, and machine wear. Repeated measurements across days, operators, and material batches are needed to assess those properties.

Single-speed on/off control simplifies implementation but may permit overshoot when material continues to flow after the stop command [11]. The approximately 5 g mean absolute errors indicate that the dosing results did not match the stated ±1 g completion criterion. The exact stopping and correction behavior therefore requires clarification. Future work could compare the present approach with staged dosing, using rapid filling followed by slower final adjustment [18].

Finally, the study illustrates the relevance of affordable embedded technology to food-process standardization. Product quality in bakery work depends heavily on formula repeatability: too much flour thickens the batter, while too little or too much coconut milk changes texture, taste intensity, and moisture retention. Experienced workers compensate intuitively, but intuition is difficult to standardise when staff change or production volume grows. By embedding the target value in the process itself, the prototype does not merely accelerate weighing; it externalises recipe discipline into the machine, which is strategically useful for MSMEs moving from person-dependent toward process-dependent production. The choice of ESP32 supports that trajectory, since the same platform can later carry data logging, wireless monitoring, recipe management, and preventive-maintenance alerts [22]. The present prototype is thus best interpreted as a low-cost hardware base for gradual digital upgrading rather than a finished product.

Implications

For UMKM D'NAVYA, more consistent dosing may reduce variation in recipe composition and preparation time. These potential benefits require direct assessment because product texture, taste, rejection rates, and daily labor savings were not measured in this study. The case nevertheless illustrates how a locally maintainable embedded system can address a specific production constraint in a small food business.

Research Contribution

Two numerical comparisons can be drawn against studies that report error on a comparable basis. The mean relative error of the automatic devices in this study was 2.1% for flour (5.4 g against a 263

g target) and 1.1% for coconut milk (5.3 g against a 492 g target). This is close to the 2.19% average error reported by Nasution et al. [8] for a load-cell-based automatic peanut weigher using on/off control, which supports the view that on/off control is a reasonably reliable approach for small-scale food dosing. It remains higher than the 0.13% reported by Cahyanto et al. [2] for an automatic chicken-feed doser; that study applied incremental dosing, which permits gradual correction as the target is approached, whereas the present design uses a single-speed on/off cycle and therefore absorbs more overshoot. Other load-cell weighing devices in the literature [5], [9] are described qualitatively here rather than compared numerically, because their reported metrics are defined on different targets and material classes and a direct numerical comparison would be misleading.

Beyond these figures, the contribution of this study is at the level of system integration. Many previous works demonstrate the technical feasibility of individual subsystems - load-cell weighing, auger transport, or pump control - but fewer examine how those subsystems behave together within the workflow of a small food producer. Here the controller, sensor, mechanical feeder, pump, display, and operating procedure were evaluated as a coordinated production aid rather than as isolated elements, and two ingredient types with contrasting flow behavior were addressed within a single control framework and tested in situ. For small enterprises this systems view matters, because practical failure usually arises not from one unusable component but from poor coordination between components, unclear operator interaction, or a mismatch between machine speed and material behavior.

Limitations

The study involved one enterprise, one recipe, and two materials, so the results support prototype feasibility rather than a general performance claim for powders and liquids. The sensor capacity was 5 kg, but calibration covered only 41–453 g. The 492 g coconut milk target was above that calibration range. The conversion from 492 mL to 492 g assumed a density of approximately 1.0 g/mL without a batch-specific density measurement. The prototype also lacked a reduced-speed final-dosing stage, cloud-based monitoring, and automated recipe storage.

A second set of limitations concerns the evidence base itself. The study emphasised comparative operational testing rather than statistical modelling of measurement uncertainty or long-term endurance testing, and no inferential test was applied to the difference between manual and automatic performance. The ten repetitions were sufficient to observe short-term repeatability at the pilot stage, but they were collected on one day with one operator and one material batch, and therefore do not establish reproducibility across days, operators, batches, humidity levels, or states of machine wear. For powders in particular, ambient moisture and packing density alter flow behavior, while for liquids the elasticity of the tubing and the effect of repeated compression may change displacement consistency over time [17]. These constraints do not diminish the practical value of the results, but they define the boundary within which the conclusions apply.

Suggestions

Further research is recommended in five directions: testing the system on a wider range of raw materials and target values, including targets near the upper end of the 5 kg capacity; implementing a two-speed or incremental dosing strategy so that overshoot is prevented rather than absorbed; adding an automatic calibration routine or a periodic calibration reminder; extending the existing local dashboard into cloud-based monitoring with batch data logging, for example through a platform such as ThingSpeak, so that the owner can supervise production remotely; and conducting endurance testing across multiple days, operators, and material batches to establish reproducibility as well as short-term repeatability.

CONCLUSION

The ESP32-based cake ingredient dosing system was implemented as a flour doser with an auger screw feeder and a coconut milk doser with a peristaltic pump. Both used load-cell feedback, an HX711 module, and single-speed on/off control with a 400 ms settling step. Across ten reported repetitions per condition, accuracy increased from 91.5% to 97.9% for flour and from 95.2% to 98.9% for coconut milk, while the observed range narrowed from 62 to 17 g for each material. Automatic dosing averaged 24.9 s for flour and 19.7 s for coconut milk, and all nine functional test items were completed successfully. These findings support preliminary operational feasibility. Further work should clarify the completion criterion, validate the full working weight range, compare equivalent timing intervals, and assess repeatability across multiple sessions and material batches.

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AUTHOR CONTRIBUTION STATEMENT

TAA designed the study, built and tested the prototypes, collected and analyzed the data, and wrote the initial manuscript. ESH and AH provided methodological guidance, reviewed the system design, and performed critical revisions of the manuscript.

AI DISCLOSURE STATEMENT

ChatGPT (OpenAI) was used during copyediting for language, formatting, and consistency checks. The authors remain responsible for the study design, data, analysis, interpretation, and final manuscript.

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