Economic and Operational Viability of a Low-Cost Semi-Automated Egg Cleaning and Sorting System for Small-Scale Rural Salted Egg Producers in Malaysia

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ABSTRACT

Small-scale and rural salted egg producers in Malaysia continue to rely on manual cleaning and sorting methods that are labour-intensive, inconsistent, and prone to product damage, constraining productivity and limiting the ability to scale production to meet growing consumer demand. Fully automated cleaning and sorting machines exist commercially but require high initial investment (RM8,000 to RM15,000) and technical expertise for ongoing maintenance. These are unfavourable for most micro and small food enterprises operating in rural areas. Thus, this study evaluates the economic and operational viability of a low-cost, semi-automated egg cleaning and sorting system, deliberately designed without sensors or microcontrollers to keep fabrication cost low and maintenance requirements manageable for small-scale salted egg producers. The system integrates a rotary-brush and water-mist cleaning module with a counterweight-based sorting module that classifies eggs into three market-relevant grades. Performance was assessed over ten repeated trials of 100 eggs each for cleaning effectiveness and sorting accuracy, alongside throughput, egg-damage, and cost-benefit analysis benchmarked against manual processing and commercially available systems. The system achieved a cleaning effectiveness of 95.7%, a sorting accuracy of 98.0%, and a 56% reduction in processing time for a 100-egg batch (from 75 to 33 minutes). Nonetheless, an egg damage rate of 12%, concentrated at the sorting transfer point, was identified as the principal limitation. At a total fabrication cost of RM1,043, against an estimated RM21 in daily labour-cost savings relative to manual processing for a 300-egg/day operation, the system recovers its cost within approximately 50 working days. In conclusion, appropriately scaled, affordable automation can improve productivity while maintaining acceptable product quality for small-scale salted egg producers.

Keywords: Rural Livelihoods; Small-Scale Food Processing; Low-Cost Automation; Economic Viability; Salted Egg Production

I. INTRODUCTION

Salted eggs are a traditional delicacy widely consumed across Southeast Asia, including Malaysia, where stable demand and relatively low production costs have attracted a large base of small-scale and rural producers [1]. In salted egg production, cleaning and sorting determine hygiene and grading quality. For most producers, both processes are still performed manually. These labour-intensive, time-consuming, and inconsistent processes have become increasingly unreliable as batch sizes grow, resulting in slow processing speed, inconsistent accuracy, and higher rates of shell breakage, particularly among small and medium-scale producers [2].

Automation such as machine vision systems, load-cell sensing, or programmable controllers has been shown to improve sorting accuracy and reduce labour dependence in egg processing [3]. However, these types of systems are designed for industrial-scale operations, requiring substantial capital investment, typically between RM8,000 and RM15,000, as benchmarked in this study (see Section IV). Additionally, fully automated systems also depend on electricity and connectivity infrastructure, and appropriate technical support that is frequently unavailable in rural production settings [4]. As a result, small-scale producers are largely excluded from the productivity gains that automation offers [5].

Consequently, there is a need for an affordable, mechanically simple, and locally maintainable system that can still deliver substantial improvement over manual processing. Thus, this study focuses on designing, fabricating, and economically evaluating a semi-automated egg cleaning and sorting system built specifically around the cost and infrastructure constraints of small-scale rural salted egg producers.

A. Problem Statement

Manual cleaning and sorting remain common among small-scale producers as they involve minimal costs and can be performed without specialised skills. However, these manual methods are slow and labour-intensive [2], resulting in low productivity. The repetitive and time-consuming nature of the work also causes operator fatigue, which ultimately limits the profit that can be generated. Automated machines or systems exist commercially, but their cost and size make them more suitable for large-scale production. Furthermore, due to the advanced technologies involved, technical expertise is required for their ongoing maintenance. Therefore, a more affordable and technically simple alternative is needed to help small-scale producers improve productivity without depending on expensive, high-maintenance automated systems.

B. Research Objectives

This study aims to (i) design and fabricate a low-cost, semi-automated egg cleaning and sorting system suited to small-scale rural production conditions; (ii) evaluate the system's cleaning effectiveness, sorting accuracy, throughput, and egg-damage performance against manual processing; and (iii) assess the system's economic viability for rural producers through cost-benefit and payback-period analysis, benchmarked against commercially available automated alternatives.

C. Significance of the Study

This study is significant because it offers small-scale producers a practical way to improve productivity without the high cost of commercial automation. In addition, it helps preserve traditional food practices while making small-scale production more viable. The project also shows that simple mechanical engineering can solve problems usually handled by expensive automated systems. Unlike existing solutions that rely on sensors, microcontrollers, or machine vision, this system cleans and classifies eggs using purely mechanical means, making it more practical for small operations with limited resources. Furthermore, the modular design makes maintenance and future upgrades easier. Environmentally, the cleaning system uses controlled water-mist spraying rather than open washing, which is designed to reduce water usage compared to manual hand-washing. In addition, durable materials such as stainless steel and food-grade components are intended to extend the system's working life and reduce material waste over time. Finally, the design insights and engineering approach documented in this research may be useful for future student projects or academic work in affordable agri-tech.

II. LITERATURE REVIEW

Several automated egg sorting systems have been developed specifically for small-scale industry using locally available materials. Quilloy et al. [7] achieved 91% sorting accuracy using a microcontroller-based sorter, while Hernando et al. [9] reported an average sorting accuracy of 93.88% using an Arduino-based system with a load cell. Vision-based systems have reported comparable or higher performance, where Bengua et al. [3] achieved 96% detection accuracy for cleanliness and 93% for quality classification using a Raspberry Pi microcomputer, a camera module, and a servo-driven sorting arm. Meanwhile Akkoyun et al. [6] demonstrated a multi-flow, camera-based sorting line for real-time egg classification on an industrial roller conveyor. These systems confirm the technical feasibility of small-scale automated sorting, but all retain some reliance on sensors, cameras, or microcontrollers. These components add cost and maintenance complexity, as well as dependency on reliable electrical supply and technical support that is not universal in rural production environments [4]. This is on top of egg production costs of RM0.22 to RM0.36 per egg in West Malaysia and RM0.33 to RM0.40 per egg in East Malaysia [8].

Separately, eggshell breakage has been linked to mechanical shock and contact forces during handling and transfer within processing chains [10]. Eggshell strength under impact loading has been shown to depend strongly on the magnitude and location of impact [11]. Aggressive washing has similarly been shown to damage the eggshell cuticle, which protects against bacterial penetration [12], indicating that gentler, lower-pressure cleaning mechanisms, even at some cost to visible cleanliness, are preferable from both a food-safety and a shell-integrity standpoint.

Only a few studies have tested whether a pure mechanical design can achieve comparable sorting performance for small-scale or rural producers who cannot absorb the added cost and maintenance demands. Thus, this study evaluates that question directly, using the cleaning and sorting system described in the following sections.

III. METHODOLOGY

The system was developed in stages, starting with conceptual design using CAD tools, followed by material selection, fabrication, assembly, and integration. Materials were chosen based on cost, local availability, hygienic design and compliance with ISO 14159:2008, and halal compliance with MS 1500:2019. Testing and refinement were carried out iteratively throughout development.

A. System Description

The fabricated system consists of two mechanically linked modules operating without sensors, microcontrollers, or electronic control logic. The cleaning module uses a DC-gear-motor-driven rotary nylon brush combined with a low-pressure water-mist spray to remove surface dirt while minimising mechanical stress on the shell. The sorting module uses an AC-induction-motor-driven, counterweight-based tipping platform that classifies eggs by weight into three categories: Category A (<60 g), Category B (60-70 g), and Category C (>70 g). Total fabrication cost, based on the finalised Bill of Materials, was RM1,043, using stainless-steel, PVC, and nylon components selected for food-grade compliance, corrosion resistance, and local availability.

Figure 1. Fabricated semi-automated egg cleaning and sorting system (angled view).

B. Performance Evaluation

Cleaning effectiveness was assessed over ten trial runs of 100 eggs each (1,000 eggs total) through visual inspection for visible dirt or surface contamination. Sorting accuracy was assessed over a further ten runs of 100 pre-weighed and labelled eggs each (30 Category A, 50 Category B, 20 Category C), with outcomes compared against ground-truth labels using a confusion-matrix analysis. Throughput and egg-damage rate were evaluated by processing a continuous 100-egg batch and recording total processing time and the number of cracked eggs at three inspection points: before processing, during cleaning, and during sorting. Manual processing of an equivalent batch was timed under comparable conditions to serve as the baseline for comparison.

C. Economic Evaluation

Economic viability was assessed by comparing the time required for manual versus semi-automated processing, converting the time saved into labour-cost savings at a conservative local labour rate of RM10 per hour, and computing the payback period as the total fabrication cost divided by estimated daily labour-cost savings across three representative daily production scenarios (100, 300, and 500 eggs/day). The resulting cost, payback period, and return on investment were benchmarked against commercially available automated cleaning and sorting machines (RM8,000 to RM15,000).

IV. RESULTS AND DISCUSSION

A. Cleaning Effectiveness

Across 1,000 eggs processed over ten runs, 957 eggs were visually clean after processing, giving an overall cleaning effectiveness of 95.7% (Table 1). Per-run performance ranged narrowly between 93% and 98%, with no sudden decline across repeated operation, indicating stable and repeatable cleaning behaviour. Mean cleaning effectiveness across the ten runs was 95.7% (SD = 1.49%; 95% CI: 94.83-96.57%), indicating a narrow and statistically consistent spread of outcomes across repeated trials. Importantly, no cracking, chipping, or surface abrasion attributable to the cleaning module was observed in any run, confirming that the gentle rotary-brush and low-pressure water-mist design successfully prioritised shell integrity, consistent with prior evidence that aggressive washing damages the protective eggshell cuticle [12]. The 4.3% of eggs that retained residual dirt were predominantly those with heavier, dried, or embedded contamination, a limitation the design deliberately accepts in exchange for eggshell safety.

Table 1. Cleaning Effectiveness Results (10 Runs × 100 Eggs)

Run	Total Eggs	Visually Clean	Not Clean
1	100	96	4
2	100	95	5
3	100	98	2
4	100	97	3
5	100	95	5
6	100	96	4
7	100	94	6
8	100	93	7
9	100	96	4

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10	100	97	3
Total	**1000**	**957**	**43**

B. Sorting Accuracy

Sorting accuracy across the ten evaluation runs averaged 98.0%, with 980 of 1,000 eggs correctly classified into their labelled weight category (Table 2). Individual-run accuracy ranged from 96% to 100%, and misclassifications were concentrated among eggs with weights close to the category boundaries, a pattern consistent with the discrete-threshold behaviour of the weight- and load-cell-based systems reviewed in [7], [9]. Mean sorting accuracy was 98.0% (SD = 1.16%; 95% CI: 97.33-98.67%), confirming that this performance was consistent and not driven by a small number of unusually strong runs. This performance is comparable to, and in some cases exceeds, reported accuracies for more complex vision-based systems (93-98%), while relying on no sensors or electronics, underscoring that mechanical simplicity need not come at the cost of grading reliability for this application.

Table 2. Sorting Accuracy Results (10 Runs × 100 Eggs)

Run	Total Eggs	Correctly Sorted	Misclassified	Accuracy (%)
1	100	99	1	99
2	100	97	3	97
3	100	98	2	98
4	100	100	0	100
5	100	96	4	96
6	100	98	2	98
7	100	97	3	97
8	100	99	1	99
9	100	98	2	98
10	100	98	2	98
Total	**1000**	**980**	**20**	**98**

C. Throughput, Egg Damage, and Reliability

Processing a 100-egg batch required 75 minutes manually versus 33 minutes with the fabricated system, a time saving of 42 minutes, or a 56% reduction (Table 3). This gain is attributable to the continuous, integrated flow of the cleaning and sorting stages, which removes the repeated manual scrubbing, weighing, and decision-making steps that dominate manual processing time. Egg damage, however, was recorded at 12% overall, concentrated entirely at the sorting stage; no cracking occurred during or before the cleaning stage. Damage was traced to impact and drop-height effects at the transfer point between the sorting plate and output track, consistent with the literature linking eggshell breakage to mechanical shock and contact-force events during handling and transfer [10], [11]. This egg-damage rate represents the principal limitation of the current design and the clearest target for the next iteration, with practical mitigations identified, including reduced drop height, smoother rolling transitions, and cushioned contact surfaces at the sorting exit.

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Table 3. Throughput and Egg Damage Summary (100-Egg Batch)

Metric	**Manual**	**Semi-Automated System**
Processing time (min)	75	33
Time reduction	—	56% (42 min saved)
Egg damage rate	5–10% (typical, manual)	12%

D. Economic Viability for Rural Producers

At a conservative local labour rate of RM10/hour, the 0.7-hour time saving per 100 eggs translates to RM7.00 in labour-cost savings per 100 eggs. For a medium-scale operation processing 300 eggs/day, this equates to RM21.00 in daily labour-cost savings relative to manual processing. Against the total fabrication cost of RM1,043, the system reaches payback in approximately 50 working days, at which point 100% of the initial investment is recovered and all subsequent operation represents net economic gain (Table 4). For benchmarking purposes, the system's total cost was compared with commercially available egg cleaning and sorting machines, which typically cost between RM8,000 and RM15,000 and often require additional technical support and maintenance. Although commercial systems offer higher levels of automation, their high capital cost makes them unsuitable for many small-scale producers. In comparison, the proposed system, at RM1,043, offers a significantly lower-cost alternative that achieves meaningful labour and time savings while maintaining acceptable performance.

The present results extend this evidence by showing that the same directional benefit is achievable at a small fraction of the capital cost typically associated with automation, provided the design accepts a purely mechanical, sensor-free architecture. For a rural household producer, a sub-two-month payback period and reduced daily labour burden represent a materially significant improvement in income potential and time availability for other livelihood activities, directly addressing the productivity and market-access constraints identified in the problem statement.

The present economic evaluation focused on labour-cost savings as the primary driver of payback, since labour represents the largest recurring cost difference between manual and semi-automated processing. Other operating costs were not separately quantified: water consumption is minimal, as the cleaning module uses a low-pressure mist spray rather than continuous washing; electricity consumption is limited to two small motors (a DC gear motor and an AC induction motor) operating intermittently; and, because the system uses no sensors or electronic components, maintenance is expected to involve only routine mechanical upkeep (e.g., brush replacement, lubrication) rather than specialised servicing or training. A full accounting of these costs, along with sensitivity and break-even analysis across production volumes, is identified as a direction for future work rather than included in the present evaluation.

Table 4. Economic Comparison Summary

Item	**Proposed System**	**Commercial Automated System**
Capital cost (RM)	1,043	8,000–15,000
Daily labour saving (300 eggs/day)	RM21.00	Higher, but not economically accessible to most small producers
Estimated payback period	~50 working days	Not typically achievable for small-scale producers

Technical/infrastructure requirement	None (purely mechanical)	Sensors, electronics, technical support

Taken together, the system met its performance and economic targets, with the sorting-stage egg damage rate as the main limitation. Due to its localised nature, this issue is likely fixable without affecting the cost advantage the system offers.

E. Limitations of the Study

This study has several limitations. The experimental evaluation, while consistent across ten repeated runs, was based on a relatively small sample (1,000 eggs per metric) and did not systematically vary egg size, shell quality, dirt level, or moisture content, factors that could affect performance under different rural production conditions. The reported 12% egg damage rate at the sorting-stage transfer point represents a real material cost that was not quantified in the present economic evaluation, since a reliable per-unit value for raw duck eggs at the point of processing was not available; the payback period reported in Section IV.D should therefore be read as based on labour-cost savings alone, and may be longer once material losses from damaged eggs are accounted for. The economic evaluation also did not separately quantify water, electricity, maintenance, or training costs, as discussed above. Finally, this study benchmarked the proposed system against manual processing and against cost figures reported for commercial automated systems in the literature, rather than against a standardized, direct performance comparison with a commercial or existing semi-automated system under identical test conditions. Future work should expand the experimental sample across varied production conditions, apply statistical significance testing between manual and automated performance, quantify the material cost of egg damage, and conduct direct comparative trials against existing commercial systems using standardized performance indicators.

V. CONCLUSION

This study designed, fabricated, and economically evaluated a low-cost, semi-automated egg cleaning and sorting system for small-scale rural salted egg producers in Malaysia. The system achieved a cleaning effectiveness of 95.7%, a sorting accuracy of 98.0%, and a 56% reduction in processing time relative to manual handling. The fabrication cost is RM1,043, which can be recovered within approximately 50 working days under a medium-scale production scenario. The 12% egg damage rate identified at the sorting transfer point represents the main limitation, which is localised to a specific point in the design. This can likely be addressed through reduced drop height, smoother transfer geometry, and cushioned contact surfaces in future iterations. In conclusion, these results show that low-cost, mechanically simple automation can meaningfully improve productivity for small-scale producers without the capital, infrastructure, or technical support demands of commercial automated systems. Future work should extend the evaluation to longer-duration field trials under real production conditions and assess the system's applicability to other small-scale egg- and produce-handling contexts.

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DECLARATIONS

Ethical Approval: This study did not involve human participants or animal subjects requiring ethical approval; it involved the design, fabrication, and mechanical/economic performance testing of a food-processing prototype using raw duck eggs as processing material.

Conflict of Interest: The authors declare no conflict of interest.

Data Availability: The experimental datasets generated during the current study are available from the corresponding author upon reasonable request.

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