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DEVELOPMENT OF AN EGG-WASHING AND GRADING MACHINE

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Abstract: *This work presents the design and construction and performance evaluation for an egg-washing and grading machine capable of efficiently washing and grading up to 1200 eggs per hour. The primary objective is to streamline the cleaning and grading of chicken eggs into standard grade sizes to encourage hygiene and uniformity in the egg production especially for smallholder poultry farms. The novelty of this machine lies in its compact, dual-functionality system combining washing and grading using low-cost microcontroller-based automation. The control system of the machine uses the Arduino Uno development board while load cells are used to estimate the weight of each egg before they are graded into categories using an array of servo motors and stepper motors for moving the eggs within the system. The eggs are washed by a soft nylon brush of 10cm which cleans the shells of the egg. The developed machine efficiently washes eggs to remove common stains, such as faces, blood, and feeds/sawdust residues adjudged to be the most common forms of stains on the shells of eggs. The combined washing and grading accuracy of the machine is evaluated to be 93.3% and an efficiency of 94% was also obtained. The egg washing and grading machine also achieved impressive performance metrics, with a combined washing and grading time of approximately 2.99 seconds per egg.*

Key words: Egg-grading; Egg-washing; Eggshell stain removal; Egg Grading Automation; Egg washing Automation

1. Introduction

The productivity of manual sorting of chicken eggs is less than 1000 eggs per hour, with the human sorter physically unable to detect many defects (including irregular shape, notch of the shell, and marbling) and not accurately identify the eggs by weight. To increase the profitability of chicken egg producers, eggs must be preserved and stored, and sorted eggs must be evaluated for exterior and interior quality. Any below-standard eggs must be removed (Pescatore et al 2011).
The washing of class A eggs is not allowed in the European Union (EU); however, it is permitted or even encouraged in Canada, Australia, Japan, and the United States of America (Patricia & Kenneth, 2017).
Egg washing can reduce the number of microorganisms on the egg's shell, given the number of countries that allow or demand table egg washing (Hutchison, 2003). A test by Kuhl (2005) proved that egg washing reduces shell-borne bacteria and Salmonella enteritis by 99.98%.
The most common type of chicken egg-washing machines in the 1940s before intensive research into egg washing consisted of a wire basket, which could contain 50-60 eggs. The basket was manually lowered into a rotating washing machine, where the eggs were submerged and agitated. The water used was typically heated to around 49 ºC as this was an immersion wash. A household, dish, laundry, or other detergent was added, and the eggs were washed for less than three minutes before the operator lifted the basket out of the water washing (Hutchison, 2003).
Chicken eggs are sorted based on internal (yolk quality, albumen height) and external (shell strength, cleanliness, size, shape) parameters using tools like candling and weighing. Methods include both manual

and automated approaches. Candling, using light to check internal defects, is a key non-destructive technique, while destructive methods (like broken-out analysis) help validate grading accuracy (Sparks, 2006; Vargas et al., 2018).

In egg weight determination, Asadi & Raoufat (2010) developed a machine vision system in combination with an artificial neural network (ANN) technique. The machine vision system comprises a charge-coupled device (CCD) camera to capture videos, a lighting system, and a mirror. From each sample, two images were captured and processed. Each feature needed from the image was calculated and fed to a multilayer perceptron (MLP) network with different training algorithms. They obtained a correlation coefficient 0.96 between the estimated and measured egg weight with a maximum absolute error of 2.3 g. By applying ANN to calculate the weight of an egg, eggs with small air cells were graded effectively, but poorly graded eggs that are older and have larger air cells were graded poorly.

Javadikia et al (2011) predicted egg weight using image processing (IP) and an adaptive neuro-fuzzy inference system (ANFIS) model. They measured the width and length of an egg by real-time image processing (IP), designed an ANFIS model, and extracted the best relationship between IP outputs and egg weight. They obtained the R-value and mean absolute error (MAE) for the actual and predicted egg weights as 0.9942 and 0.3285 g, respectively. The image processing technique was very effective for freshly laid eggs with small air cells but was also less accurate for eggs with large air cells. Also, the system developed produced less accurate results for eggs with stains on their shells.

Mahmoud et al (2015) designed an egg volume prediction system using a machine vision technique based on the Pappus theorem and ANN. In this study, a simple machine vision system was developed for egg volume estimation. The mathematical and ANN models were developed and validated. The results of model validation confirmed the good performance of the two methods. However, after the system's calibration, another experiment was performed, and the evaluation results demonstrated the superiority of the mathematical modelling system over the ANN model. This model generated was mathematical, and its implementation in a real-world system would reduce its accuracy and scalability.

Payam et al (2015) worked on measuring egg weight using image processing and the ANFIS model. This research attempted to measure the width and length of the egg by real-time image processing and then designed and optimised an ANFIS model to find the best relationship between image processing outputs and egg's weight. The correlation coefficient between the experimental value for the egg's weight and that predicted by the ANFIS model is 0.9942. This shows that the image processing and ANFIS model give a very accurate value for the mass of an egg. The system developed had lower accuracy of older eggs as a result of the growth of the air cell.

Jakhfer et al (2019) worked on the design and performance evaluation of an automatic egg sorting system based on computer vision using the minor and major axis, area and perimeter, shape factor, and shape index to generate an algorithm to calculate the egg's weight. The system used the ANFIS to train the machine to calculate the egg grades. The system was equipped with a programmable controller and frequency-controlled electric drive, which allows for the control of the electro-pneumatic actuators and the speed of transport conveyors. This makes the system more flexible and allows easy readjustment when changing production requirements. This work, however, did not grade the eggs based on eggshell quality cracks or the presence of dirt, which are important criteria for egg grading.

Bengua et al (2022) researched developing a salted egg grading system using machine vision. The electro-mechanical salted egg grading system saves time, reduces labour costs, and minimises egg breakage. The system can detect clean, dirty, well-pickled, and spoilt eggs with 96% and 93% accuracy for cleanliness and quality, respectively. Thus demonstrating its robustness in sorting and grading salted eggs. However, this system was designed for salted eggs with shells already peeled.

Most eggs in Nigeria come from smallholder farms using traditional or semi-intensive systems. Sorting and grading are rarely practiced, leading to poor pricing, wastage, and reduced market value. Research showed that sorting could increase revenue by up to 15% (Abanikannda & Leigh, 2010)

Recent global efforts have employed machine vision, ANNs, and image processing to detect defects and estimate egg weight. However, these systems often require pre-cleaned eggs and show reduced accuracy with older or stained eggs. Load cell-based systems, though less explored, offer improved reliability in such settings (Hao et al., 2009; Asadi & Raoufat, 2010; Jakhfer et al., 2019).

The objective of this work therefore is to design, fabricate, and evaluate the performance of a dual-functional machine capable of washing and grading chicken eggs based on their weight using weight sensors for use in small – medium holder farms in Nigeria. Its novelty is that the machine integrates egg washing and weight-based grading into a compact, low-cost solution using Arduino and load cell technology, making it suitable for smallholder poultry operations in Nigeria using locally sourced materials with a non-chemical washing approach, and a compact transmission-based mechanism not previously reported in literature.

BJET, 2026, Vol. 201(1), 133-144

2. Theoretical Analysis

Engineering properties of eggs used include an average egg length of 38.1 to 63.5 mm and breadth of 31.75 to 44.45 mm (USDA, 2023), (UNECE, 2010) which also covers the range of 53 to 63mm in length and 40 to 45mm in width used by Abanikannda et al., 2007; Narushin, 2005. These values informed tray size, spiral pitch, and load cell thresholds. Shell strength was also considered to avoid breakage during brushing (Brinsea, 2022).

2.1 Egg-Washing Chamber Design

2.1.1 Washer In-Let Tray Design

The tray's dimensions are such that it can accommodate the length of the largest category of chicken egg. The egg dimensions can vary based on the egg's weight, but a safe length and breadth for chicken eggs can be considered within the range of 38.1 to 63.5 mm in length and 31.75 to 45 mm in breadth [11]. Therefore, the washer inlet tray length (L) can be calculated for a maximum capacity of N eggs as in (1) by Singh & Heldman (2001).

$$L = N \times L_{nom} \qquad (1)$$

Also, the width of the tray is equal to the maximum safe breath of an egg, as given in (2) by Singh & Heldman (2001).

$$W = W_{nom} \qquad (2)$$

The shape index which informs the inner curvatuire of the the inlet tray to allow the ggs to roll into the washing chamber will be obtains using the egg given by Narushin & Romanov, (2002) as (3)

$$S_{idx} = 72 - 76\% \times (W_{nom}/(L_{nom} \times 100)) \quad (3)$$

The egg-washing chamber has a cylindrical washing shape with an internal spiral that serves as a guide rail for the eggs moving within the washing chamber. In designing the spiral rails, therefore, a safe length ($\boldsymbol{L_{nom}}$) of an egg of 63.5 mm and a safe width ($\boldsymbol{W_{nom}}$) of 45 mm was used.

2.1.2 Spiral Design

The spiral is made from plastic material with a pitch equal to the safe length of an egg (taken as 63.5 mm) multiplied by a safety factor. The internal diameter of the spiral (D_{smin}) is the sum of the diameter of the cylindrical nylon brush (D_{brush}) and the safe width of an egg (W_{nom}) multiplied by a factor of safety for allowance ($S.f$), as given in (4) by Singh & Heldman (2001)

$$D_{smin} = D_{brush} + (W_{nom} \times S.f) \quad (4)$$

Using a plastic of thickness T_s used to make the spiral, the outer diameter of the spiral is given as in (5) by Singh & Heldman (2001).

$$D_{smax} = T_s + D_{smin} \quad (5)$$

The external diameter (D_{smax}) of the spiral is equal to the internal diameter (D_{hmin}) of the hollow cylinder, which would serve as the body of the grading chamber, as given in (6) by Singh & Heldman (2001).

$$(D_{smax}) = (D_{hmin}) \quad (6)$$

The pitch of the spiral is such that it can accommodate the length of the eggs as they move on the internal surface of the hollow cylinder. Therefore, the pitch of the spiral is calculated using (7) by Shigley et al (2004).

$$P = L_{nom} \times S.f \quad (7)$$

The number of turns is denoted as N_s. This number of turns is assumed to be 1.5 to give sufficient distance for the egg to be washed properly. The length of the spiral L_s is given by (8) by Shigley et al (2004).

$$L_s = \pi D_{smax} \times N_s \quad (8)$$

2.1.3 Cylindrical washing chamber design

The cylinder for the washing chamber is also made from plastic with a thickness of 0.5 mm. The cylinder is hollow, with both of its ends covered. The spiral is attached to the internal surface of the hollow cylinder. Given that the number of turns is 1.5, the cylinder's length is twice the pitch (P) of the spiral, and clearance was added above and below the spiral to prevent the brush from rubbing on the surface of the cylinder. Therefore, the length of the cylinder for the washing chamber is given in (9) by Shigley et al (2004).

BJET, 2026, Vol. 201(1), 133-144

$$L_{hmin} = (2 \times P) + (2 \times clearnace) \quad (9)$$

2.1.4 Nylon fiber brush design

A cylindrical nylon fibre brush with a diameter (D_{brush}) is used. The shell strength of an egg is between 3 - 6kgf Altuntas & Sekeroglu, 2008. Therefore the fibre of the brush used should be generally very flexible and tends not to alter the overall dimensions or geometry of the part the length of the nylon brush. L_{brush} is equivalent to twice the pitch (P) of the spiral, as given in (10) by Singh & Heldman (2001).

$$(L_{brush}) = 2 \times P \quad (10)$$

DC motor is used to drive the cylindrical nylon brush, and the torque on the brush is given as in (11) by Khurmi & Gupta (2005).

$$T_{brush} = (F_{motor} \times D_{brush})/2 \quad (11)$$

The length of the bristles on the nylon brush is chosen to clean the egg's surface effectively without damaging it. A bristle length of 1 cm is chosen to be sufficient Narushin, 2005. Also, the density of the bristles is always chosen to be high enough to provide adequate cleaning force but not so high that it damages the eggs as the range for egg shell thickness is between 0.3 – 0.4mm Altuntas & Sekeroglu, 2008 a density of 10 bristles per cm is often suitable (FAO 2018).

2.2 Egg-Grading Chamber Design

2.2.1 Grader Plate Design

The grader plate is made of thermoset plastic because of its strength and rigidity in deflecting when loaded. The diameter of the plate is chosen to accommodate a maximum of six (6) eggs. The six (6) eggs are oriented 60° from each other on the plate, as shown in Figure 1. The radius of the plate was designed by adding the minimum radius required to carry six (6) safe-sized eggs with a safe space between all the eggs (CM), half the safe width of an egg (W2), and a clearance between the edges of the egg and the edge of the plate (CL) as shown in Figure 1 and Figure 2.

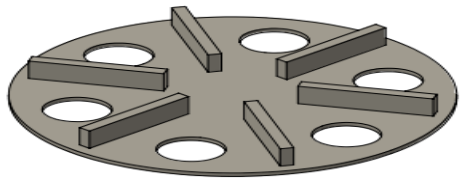


***Figure 1**. Grader Plate*

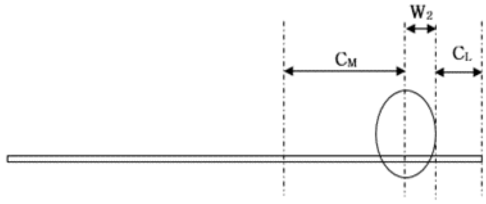


***Figure 2**. Sectional View of Grader Plate*

Therefore, the radius of the grader given in (12) by Khurmi & Gupta (2005).

$$R_g = C_M + W_2 + C_L \quad (12)$$

Where C_M is obtained from the relationship between the circumference of a circle and its radius, as given in (13) by Shigley et al (2004).

$$C_M = \frac{(6 \times l_{nom}) + (6 \times 5)}{2 \times \pi} \quad (13)$$

Half the maximum width of an egg is also given in (14) as by Narushin (2005),

$$W_2 = \frac{W_{nom}}{2} \quad (14)$$

CL is the clearance between the edge of the eggs and the plate. For an accurate reading of the weight of the egg by the weight sensor, the deflection on the grader plate due to the egg's weight must be minimal. Hence, the plate deflection, when loaded, is analysed as a cantilever loading. The mathematical relationship to determine the deflection of a cantilever when loaded is therefore applied to the plate. The maximum deflection β of a cantilever is given in (15) by Beer, et al (2012) ;

$$\beta = \frac{Pa^2(3R_g - a)}{6EI} \quad (15)$$

BJET, 2026, Vol. 201(1), 133-144

p = Load (Nominal weight of the egg), a = Length from a fixed position to where the load is acting on, R_g = Radius of the grader plate, E = Modulus of elasticity and, I = Moment of Inertia.

The Modulus of elasticity for thermoplastic materials is given as 6.4×10^5 MPa and the Moment of Inertia for a circular plate of Mass (M) and Radius (R) are given in (16) by Beer et al (2012):

$$I = \frac{M{R_g}^2}{2} \qquad (16)$$

A circular groove was made on the plate to hold them in place and ensure the eggs were secure. This also provides the contact point for the load cells and the eggs.

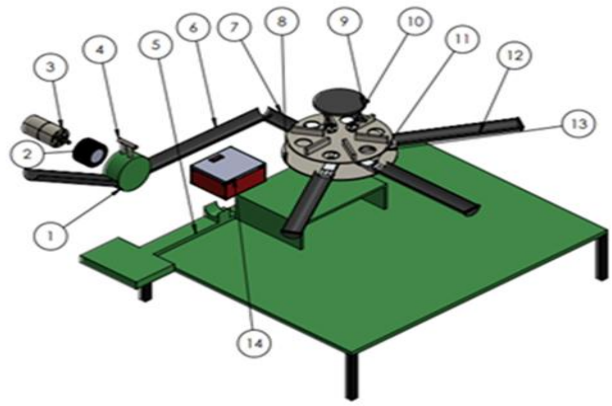
2.2.2 Egg Grading System Design

The eggs are graded based on their weight rather than the size of the shell. The load cells were calibrated to determine the weight of the eggs. The load cells were programmed for the below weight categories as the range of egg weights is between 45 – 70g (Jakhfer et al., 2019 and USDA, 2000):

i. AA: from 63g above were classified as large (L)
ii. A: from 53g to 63g were classified as medium (M)
iii. B: from 53g and below were classified as small (S)

3.1 Machine Operation

The machine operates such that when eggs are placed on the inlet tray of the washer, they are made to roll due to the inclination of the tray into the washing chamber. The eggs are then washed automatically by the action of the moving bush and water. After the eggs are washed, they move onto the conveyor tray between the washer and the grader plate, where they are picked at regular intervals and placed on the grader plate by the grader's arm. The weight of each egg on the grader plate is measured by the load cells located directly under each perforation of the grader plate. The load cells are programmed with the weight range of all the eggs, starting from small to large. Figure 3 shows the conceptual design of the machine, while Figure 4 shows the developed egg washing and grading machine, and Figure 5 shows the machine during the grading process. Appendix A shows the engineering drawing of the machine.



ITEM NO.	PART NAME	QTY.
1	Washing Chamber Outside Cylinder	1
2	Nylon Fiber Brush	1
3	DC Motor	1
4	Water Inlet Pipes	2
5	Egg Sorting and Grading Frame	1
6	Conveying Tray from the Washer	1
7	Inlet Tray for the Grader	1
8	Load Cell Plate	1
9	Selector Plate	1
10	Servo-motors	3
11	Load Cells	3
12	Egg Collectors	3
13	Egg Rotating Plate	1
14	Control box	1

***Figure** 3. Conceptual Design of the Machine*

***Figure** 4. Developed Egg Washing and Grading Machine*

***Figure 5.** Developed Egg Washing and Grading Machine while Grading*

3 Performance Evaluation Overview

The machine's performance was evaluated in three phases: the washing unit, the grading unit, and the combined operation of both. For the washing section, the effectiveness, speed, potential egg damage, and adherence to best practices like drying and water temperature control were assessed. Room-temperature water was used, and a fan aided in drying the eggs post-wash.

To determine the appropriate sample size, Cochran (1963) formula for an unknown population given as in equation (17) below is used;

$$n = \frac{Z^2 pq}{e^2} \quad (17)$$

Where the value of Z is determined from statistical tables which contain the area under the normal curve. For a 95% confidence level used, the Z value is approximately 1.96 (Mascha & Vetter, 2018). p is the estimated proportion of an attribute that is present in the population. A p-value of 0.5 is often chosen as a conservative estimate which will yield the maximum required sample size (Mascha & Vetter, 2018) as in (18) below;

$$q = 1 - p \quad (18)$$

e is the desired level of precision. This was chosen as 0.05 to achieve high accuracy for the results and a ±0.035 margin of error (Mascha & Vetter, 2018) as in (19) below;

$$n = \frac{(1.96)^2 * 0.5 * 0.5}{(0.05)^2} = 384.1 \quad (19)$$

Given that the minimum sample size as calculated above to be used for the performance evaluation is 384.16 eggs, the result is approximated to 400 and divided into 40 tests groups with 10 eggs per sample to make the performance evaluation easier to manage and more accurate.

3.1 Washing Speed Test

The washing speed was measured to estimate how long it takes the machine to wash a single egg and to determine its capacity per unit time. Fourty tests were conducted, each involving 10 eggs, where the time from when the eggs were manually loaded until the end of washing was recorded. To ensure test precision, the timer was started simultaneously with the machine, and fresh water was used for each test without reuse. These controlled steps ensured that the washing process met immersion time standards for egg safety.

3.2 Damage After Washing Test

This test focused on determining whether the washing process caused any external shell damage to the eggs. Prior to washing, each egg was inspected for pre-existing cracks, and care was taken in handling to prevent new cracks from unrelated mishandling. Each test group contained 10 eggs, totaling 40 samples. After each wash, eggs were examined, and any shell damage was recorded. Only ungraded and previously unwashed eggs were used to minimize the influence of micro-cracks from earlier procedures.

3.3 Washing Effectiveness Test

The machine's effectiveness in removing various types of stains from egg shells was evaluated. Eggs with different stains such as dry/fresh faeces, blood, decolorization stains, and foreign materials were sourced from different poultry farms to reflect diverse real-world conditions. After visually inspecting each egg before and after washing, the level of cleanliness was assessed. Cracked eggs were excluded to avoid contaminating other eggs during the wash, and the washing chamber was rinsed between tests to maintain consistency.

3.4 Grading Accuracy Test

The accuracy of the grading section was tested by comparing machine-based egg classification with digital scale measurements. Each of the 40 test samples contained 10 eggs, categorized into small, medium, and large sizes after weighing. After grading by the machine, the assigned categories were recorded and compared with the scale-based classifications. Randomized egg selection and avoidance of repeated measurements ensured the reliability of the data collected.

3.5 Grading Speed Test

This test assessed how quickly the machine could classify eggs. Fourty tests were conducted using 10 eggs per trial, timed from the moment all eggs were placed on the inlet tray to the end of grading. To eliminate time variance from sequential loading, all eggs were placed before activating the machine. Additionally, eggs used for this test were not washed to prevent any handling-related inconsistencies.

3.6 Damage After Grading Test

To evaluate the potential for egg damage during the grading process, each of the 40 samples used in the speed test was examined for cracks before and after grading. Eggs with existing damage were excluded. This test aimed to determine the safety of the grading process in handling eggs delicately, ensuring that shell integrity was not compromised by machine mechanisms.

3.7 Combined Washing and Grading Test

A comprehensive performance test was carried out to evaluate how the machine functioned when washing and grading eggs in a single operation. A total of 40 samples, each with 10 eggs of varying sizes and stains, were used. Each sample was pre-inspected for cracks and weighed, then placed into the machine. The total operation time and the number of correctly graded eggs were recorded, helping assess the machine's efficiency and throughput under combined use.

3.8 Damage from Combined Operation

Following the combined washing and grading, eggs were visually inspected to identify any shell cracks caused during the process. The test employed the same 40 samples used in the combined performance test. The eggs were checked both before and after processing to ensure accuracy in identifying newly formed cracks. This data is useful in refining the machine's design to minimize damage in future use.

3.9 Shelf Life Test

This test investigated how machine washing affects the longevity of eggs in storage. A total of 140 eggs (70 washed and 70 unwashed) were grouped and stored under refrigerated conditions (2–4°C), with mixed batches tested at intervals over 56 days. Each batch contained both washed and unwashed eggs, sealed in pulp packaging and checked for spoilage after 2, 14, 21, 28, 35, 42, and 56 days. Eggs were pre-inspected for cracks to ensure spoilage results were due to washing impact and not pre-existing damage.

4. Result and Discussion

4.1 Washing Speed Test

The results of the washing speed test are graphically represented in Figure 6. The average washing time for the ten eggs per sample is 23.9 seconds, approximately 2.39 seconds per egg. Considering that the eggs are wet-washed, the washing time of 2.39 seconds is below the maximum acceptable time for an immersion wash of 3 minutes given by Mike & Sparks (2005). Also, for a washing time of 2.39 seconds per egg, approximately 1506 eggs can be washed in 1 hour.

Figure 6. *Washing Time Test*

4.2 Washing Damage Test

The results of the washing damage test are graphically represented in Figure 7. A one-sample independent t-test was used for the result obtained in Figure 7, with the null hypothesis that the mean quality of the eggs in the sample was undamaged and the alternate hypothesis that the mean quality of the eggs in the sample was damaged. The statistical averages obtained are given in Table I.

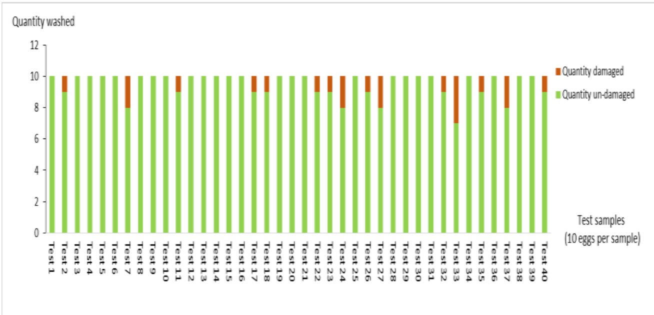


Figure 7. *Damage after Washing Test*

Table 1: *One Sample T-Test Results For Washing Damage*

Statistical Measures	Values
Mean	0.9475
Variance	0.0499
Observations	400
Hypothesised Mean	1 (undamaged)
Df	400
t Stat	6.6571
P(T<=t) one-tail	4.62E-11
t Critical one-tail	1.6487

The null hypothesis will be rejected if the t-value (t Stat) exceeds the one-tailed t-critical value (6.6571) and/or the obtained p-value is less than the alpha significance level (0.05). From Table I, the null hypothesis is accepted, and the alternate hypothesis is rejected. This suggests that the mean condition of the eggs is significantly similar to the hypothesised mean value of undamaged eggs. Also, from the 40 tests with ten eggs per sample (totalling 400 evaluated), 21 eggs were damaged with cracks on their shell after washing. The 379 eggs that were graded without damage from the test represent a washing efficiency of 94.8% for the machine.

4.3 Stain Removal after Washing Test

The stain removal result after the washing test is graphically represented in Figure 8. The machine efficiently removes faces (dry and pre-wet cases), sawdust and feed stains. These categories of stains on the eggshell are the most common types of eggshell stains that affect the external grade quality of eggs. For the permanent de-coloration stains, the machine was unable to remove these stains. These stains often arise from the chicken's genetics, feed quality, and breed types. Also, for other stains (consisting of inks, mud, etc., which are not commonly found in poultries), the machine is only partially effective in removing such stains.

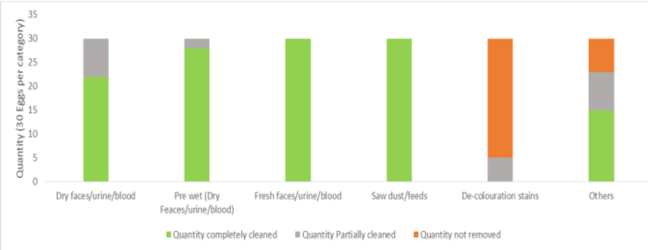


***Figure 8**. Stain Removal after Washing Test*

4.4 Grader Accuracy and Repeatability Test

The results of the grader accuracy test are graphically presented in Figure 9. From the 240 eggs categorised, a total of 226 eggs were graded accurately, and 14 were graded wrongly. This represents an accuracy of 94.17%. The variation between the weight recorded by the weighing scale and the load cells is due to the weighing scale having a higher sensitivity than the load cells, hence the approximations. This result is close to the 95% grading accuracy using machine vision obtained by Mahmoud et al (2013) and higher than that of the study by Bengua et al (2022), whose grading system has 93% accuracy for grading salted eggs.

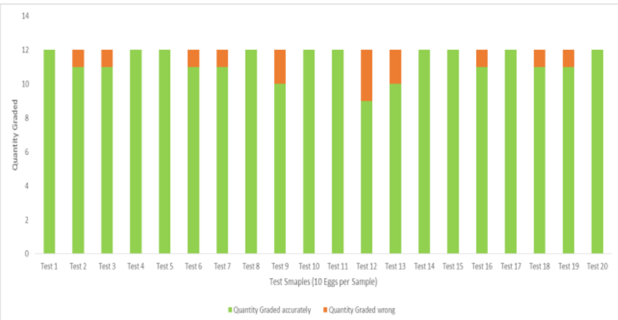


***Figure 9.** Grading Accuracy and Repeatability Test*

4.5 Grading Speed Test

The results of the grading speed test are graphically represented in Figure 10. The average grading speed of the grader is 28.4 for the 40 test samples. Since each test sample consists of ten eggs, it takes the grader 2.84 seconds on average to grade an egg. These averages can be scaled to imply that the machine can grade approximately 1267 eggs per hour. The grading capacity of 1267 is slightly lower than the 1426 obtained by Erwin et al (2018), who also designed a single-feed egg sorter using machine vision for grading table eggs in the Philippines.

***Figure 10.** Grading Speed Test*

4.6 Grading Damage Test

The results of the damage from grading are graphically presented in Figure 11. A one-sample independent t-test was used for the results obtained in Figure 11, with the null hypothesis that the mean quality of the eggs in the sample is undamaged and the alternate hypothesis that the mean quality of the eggs in the sample is damaged. The statistical averages in Table II were obtained.

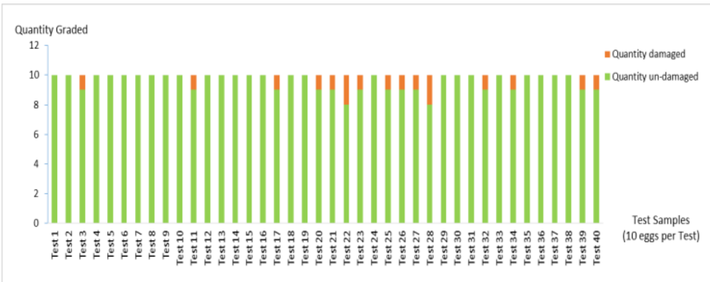


***Figure 11.** Grading Damage Tes*

Table 2: *One Sample T-Test Results for Damage from Grading*

Statistical Measures	Values
Mean	0.9575
Variance	0.0408
Observations	400
Hypothesised Mean	1 (undamaged)
Df	400
t Stat	7.2903
P(T<=t) one-tail	8.34E-13
t Critical one-tail	1.6487

The null hypothesis will be rejected if the t-value (t Stat) exceeds the one-tail t-critical value (7.2903) and/or the obtained p-value is less than the alpha significance level (0.05). Hence, the null hypothesis is accepted in Table II, and the alternate hypothesis is rejected. This shows that there is evidence to suggest that the mean condition of the eggs is close to the hypothesised mean, which means that damages are insignificant. Also, from the total of 400 eggs graded, 17 were damaged during grading, and 383 were undamaged. The 383 undamaged eggs represent a grading efficiency of 95.75%. The efficiency of grading eggs at 95.75 % for the machine is slightly lower than the 97% obtained by Erwin et al (2018) .

4.7 Combined Washing and Grading Speed and Accuracy Test

The combined washing and grading test results are graphically presented in Figure 12. From the graphical representation of the test results for the combined washing and grading of eggs, the average time taken to wash and grade a sample (10 eggs per sample) is 32.63 seconds. This washing time averages 3.26 seconds per egg. At a combined washing and grading time of 3.26 seconds per egg, 1104.3 eggs can be washed and graded per hour. Also, from the total of 350 eggs graded, 326 were graded accurately, and 24 had errors or damages. The error arises from dirt on the eggs weighted using the weighing scale, which was removed during washing and not factored in the final grading by the washing.

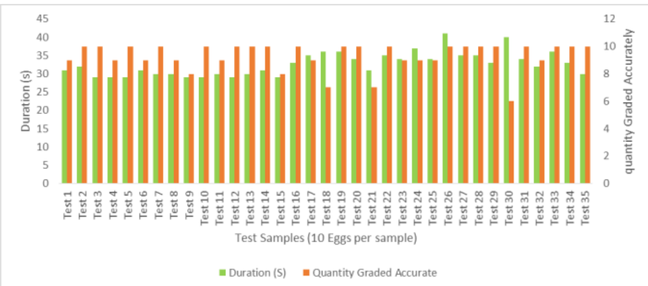


Figure 12. *Combined Washing and Grading Accuracy Test*

4.8 Damaged Eggs from Combined Egg Washing and Grading Test

The results of the damages for the combined washing and grading test are presented in Figure 13. A one-sample independent t-test was used for the results obtained in Figure 13, with the null hypothesis that the mean quality of the eggs in the sample is undamaged and the alternate hypothesis that the mean quality of the eggs in the sample is damaged. The statistical averages in Table III were obtained.

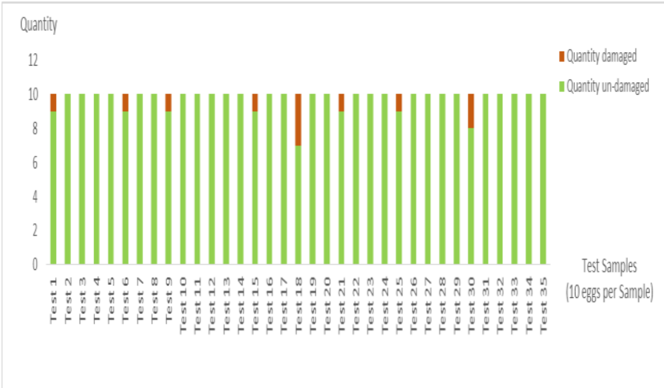


Figure 13. *Damages from Combined Washing and Grading Accuracy Test*

Table 3*: One-Sample t-Test Results for Damages from Combined Washing and Grading Test*

Statistical Measures	Values
Mean	0.9686
Variance	0.0305
Observations	350
Hypothesised Mean	1 (undamaged)
Df	350
t Stat	8.3366
P(T<=t) one-tail	8.85E-16
t Critical one-tail	1.6492

The null hypothesis will be rejected if the t-value (t Stat) exceeds the one-tailed t-critical value (8.3366) and/or the obtained p-value is less than the alpha significance level (0.05). Therefore, the null hypothesis is accepted, and the alternate hypothesis is rejected. Hence, evidence suggests that the mean condition of the eggs is close to the hypothesised mean, which is undamaged. Also, of the 350 washed and graded eggs, 24 were damaged or graded wrongly. The 326 eggs that were undamaged and graded correctly represent 93.14%. Therefore, the efficiency of washing and grading the eggs without damage or errors is 93.14%.

4.9 Washing and Grading on Egg Shelf-Life Test

The results of the effect of washing on the shelf life of the washed and unwashed eggs are graphically presented in Figure 14. Here, test samples consisting of 10 washed and 10 unwashed eggs were stored under similar conditions for 2 to 56 days. From Fig. 14, the washed and unwashed eggs stored for 2 days, 14 days, 21 days, 35 days, and 42 days retained their freshness when checked. However, the eggs for the washed and unwashed samples at 49 and 56 days had some spoilages. This means the eggs washed by the machine can also retain their qualities for up to 42 days, as can the unwashed eggs. 42 days (6 weeks) is often the recommended safe consumption period for refrigerated eggs (between 2 °C and 4 °C). After this, they are unsafe to consume or sell as graded eggs Yu-Chi et al (2016). The eggs start to go bad after 42 days due to age and excessive moisture on the egg's surface, leading to the growth of bacteria, as reported by Hanita et al (2003).

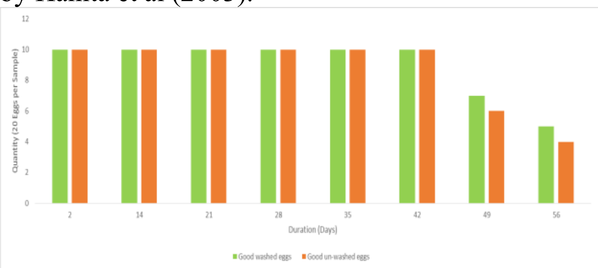


Figure 14. *Shelf Life Test Result for Washed and Unwashed Eggs*

5. Conclusion

The developed egg washing machine's average washing time per egg is 2.39 seconds. The washing time is below the maximum acceptable time for an immersion wash of 3 minutes. Also, the egg washing machine was highly effective in removing common types of egg stains that affect the external quality of eggs but ineffective in removing de-coloration stains that do not affect the egg grade. The machine's efficiency when simultaneously washing and grading eggs was evaluated to be 93.14%. The grading component of the machine also has a high accuracy of 94.17% in categorising eggs into their correct weight categories and an efficiency of 98. The shelf-life study shows that the washed eggs maintained quality for more than 42 days before they started to go bad.

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