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DESIGN, DEVELOPMENT AND PERFORMANCE EVALUATION OF WEIGHT-BASED COCONUT GRADER

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ABSTRACT

Weight-based grading of coconut (*Cocos nucifera* L.) is essential for ensuring uniform quality, enhancing market value, and improving post-harvest management. This study aimed to design, develop, and evaluate an automated coconut grading system integrating a conveyor, load cell, pneumatic sorting unit, and programmable logic controller (PLC). Coconuts were classified into four grades based on weight: >600 g, 450-600 g, 350-450 g, and 250-350 g. Physical analysis showed high variability (average weight 551.76 ± 163.6 g; sphericity 0.641±0.06), supporting the need for automation. Performance was tested at feed rates of 100-200 kg h^{-1} and belt speeds of 0.26-0.37 m s^{-1}. Optimal efficiency (94.60%) was achieved at 150 kg h^{-1} and 0.26 m s^{-1}. Response Surface Methodology confirmed significant effects of operating parameters (R^2 = 0.968). The developed weight-based coconut grader can be effectively used in coconut procurement centers, farmer producer organizations, processing industries, wholesale markets, and export facilities for rapid and standardized grading. It enhances grading efficiency, reduces manual labor, ensures fair pricing, and supports improved post-harvest handling, packaging, and quality management across the coconut supply chain.
***Keyword* :** Coconut, Automated weight grading, Grading efficiency, Response Surface Methodology.

Introduction

The coconut (*Cocos nucifera*) or the tree of life is among the most significant tropical crops in the world. It is an integral part of the economies and cultures of most tropical countries, especially in such countries as India, Phillippines, Indonesia, Sri Lanka, and Thailand, the world production of coconut, 62.4 million tonnes in 2022 (Silpa *et al*., 2024). Indonesia, Philippines and India are the major coconuts producers and they make up more or less 72 percent of the global production. Indonesia leads in production with an approximate of 14.2 million tonnes in close follow up is the Philippines with an approximate of 14.7 million tonnes and India with an approximate of 20.7 million tonnes. Coconut production is a very important part of India economy, especially in the states of Kerala, Tamil Nadu, Karnataka and Andhra Pradesh which produce nearly 90 percent of the total coconuts in the country. Kerala has the highest concentration of coconut trees as compared to Tamil Nadu which is the largest producer of the same per hectare. In India, the overall plant area under coconut growing is approximately 2.08 million hectares which produces something about 24 billion nuts and an average productivity of 11,505 nuts per hectare (CDB, 2022). Coconut industry has been a major element in agricultural economy of most tropical nations (FAO, 2021).

The determination of dimensional properties of coconuts is crucial for various applications, particularly in the agricultural and food processing industries. The dimensional knowledge of coconut is priceless to design of deshelling, dehusking, grading, and sorting machines (Pandiselvam *et al*., 2020). With the current increase in demand of coconut products, the need to have efficient and accurate grading systems to provide quality control and satisfy market needs is as well increasing. The manual grading systems are labor intensive, time consuming and subject to inconsistency, which underscores the need to come up with automated grading systems (Abeza *et al*., 2019).

Most industries have automated grading technologies in order to address the increased accuracy and efficiency in the industry processes. Among them, weight-based graders have been already included in the list of the necessary equipment to increase the efficiency of operations and the quality of products (Ahammad *et al*., 2024). With the use of such technologies, the sorting process would be more accurate compared to traditional ways of grading, which are often based on measurements of dimensions. The purpose of the study is to design and test a weight-based coconut grader that will help resolve the issues related to manual coconuts graders. The system has the following components weight sensors, conveyor belt mechanism, pneumatic sorting devices to automatically sort the coconuts into four different weight categories. Through these technologies, the grader will increase the efficiency and precision of the coconut grading processes and it may be seen as a revolution of postharvest processing of coconuts in both small scale and large-scale productions. (Gaikwad *et al*., 2014; Selvan *et al*., 2022).

Materials and Methods

Dimensional properties

The dimensions of randomly selected coconuts were measured in terms of their longest axis (length, L), intermediate axis (breadth, B), and shortest axis (thickness, T). These measurements were taken using a digital vernier calliper (INSIZE, Chand Company, Delhi, India) with an accuracy of 0.001 mm, and the results were recorded in cm.

The arithmetic mean diameter (Da) is calculated as the average of the three dimensions of an object from following equation [1] (Mohsenin 2020). It provides a fundamental understanding of the overall diameter of the object, which can be useful in determining size-based sorting and grading operations.

$$D_a = \frac{(LBT)}{3} \quad [1]$$

The equivalent mean diameter (D_e, mm) is calculated by using the equation (Mohsenin 2020)

$$D_e = \left[\frac{(L(B+T)^2}{L}\right]^{\frac{1}{3}} \quad [2]$$

The square mean diameter (D_s, mm) is calculated by using the relationship (Mohsenin 2020),

$$D_s = \left(\frac{LB+BT+TL}{3}\right)^{\frac{1}{3}} \quad [3]$$

The geometric mean diameter (GMD) offers an overview of the coconut's overall structure. Generally, it is recognized as an equivalent diameter and has been investigated by several researchers (Pandiselvam *et al*. 2020). The GMD of coconut was determined using [4].

$$GMD = (LBT)^{\frac{1}{3}} \quad [4]$$

Surface area (Sa) refers to the total area of all the surfaces of a given object. Studying the fluidization of fruit, peeling, seasoning, and coating can be helped by knowing the surface area. These values were calculated and given in mm² using Equations [5].

$$SA = \pi(GND)^2 \quad [5]$$

Sphericity (φ) is a dimensionless parameter that quantifies the extent to which the shape of a commodity deviates from that of a perfect sphere. A sphericity value approaching unity indicates a higher degree of spherical symmetry (Nadiya Jan *et al*. 2019). According to Sahay & Singh, (1996) sphericity is mathematically defined as the ratio of the diameter of a sphere with the same volume as the solid to the diameter of the smallest circumscribed sphere that can fully enclose the solid. The sphericity of coconut was computed using Equation [6].

$$\Phi = \frac{(LBT)^{\frac{1}{3}}}{L} \quad [6]$$

Design and Development of weight-based coconut grader

The weight-based coconut grader's components were chosen based on a number of criteria, including long-term serviceability, cost-effectiveness, ease of assembly, mechanical durability, and regional availability. Figure 1a, b presents the 3D drawings showing various perspective views of the coconut grader. The all dimensions and components demonstrated in Figure 2 and 3 respectively.

Main Frame

The frame of the coconut grader was engineered using 14-gauge square steel pipes. The structural frame was designed to provide adequate strength, rigidity, and stability during continuous operation. The use of mild steel ensured high load-bearing capacity to withstand the weight of coconuts, grading components, motor assembly, and associated mechanical vibrations.

Feed Hopper

A temporary storage unit holds the material before it is graded, allowing for uninterrupted operation. it was made of a 2 mm thick iron sheet. The rectangular frustum feed hopper was having a top opening of 66 cm (length) × 78 cm (width), a bottom opening of 20 cm (Figure 2).

Power requirement

Power (P) is functionally connected to torque (T) and angular velocity (ω), as expressed by the following relationship reported by Khan *et al*. (2026).

$$P = T \times \omega \qquad [7]$$

Belt calculations

The belt–pulley system was designed to transmit the required power from the motor gearbox assembly to the conveyor drive pulley at the desired speed without slippage. The power to be transmitted by the system is 0.75 kW. The diameter of the driving pulley (D_1) is 0.10 m, while the driven pulley (D_2) has a diameter of 0.30 m. The driving pulley operates at a speed of 70 rpm. The centre distance (C) between the two pulleys is maintained at 1.90 m. The coefficient of friction (μ) between the belt and pulley surface is 0.30. The groove half angle (α) is 18°.

Belt speed

Belt speed was calculated to ensure appropriate operating velocity for efficient power transmission without excessive slip or wear.

$$V = \frac{\pi DN}{60} \qquad [8]$$

Where V is belt speed (meter per second); D is pulley diameter (m), and N is pulley speed (rpm).

$$V = \frac{\pi \times 0.10 \times 70}{60}$$

V = 0.37 m/sec

Power transmitted by belt

The power transmitted by the belt was calculated to verify that the belt drive can safely deliver the required mechanical power to the conveyor system.

$$P = (T_1 - T_2) \times V \qquad [9]$$

Where T_1 is tight-side belt tension (N) and T_2 is slack-side belt tension (N).

Ratio of belt tensions

The ratio of belt tensions was calculated to evaluate the frictional grip between the belt and pulley and to prevent belt slippage during operation.

$$\frac{T_1}{T_2} = e^{\mu\theta} \text{ or } \ln\frac{T_1}{T_2} = \mu\theta \qquad [10]$$

Where: μ is coefficient of friction (0.25 – 0.35 for rubber flat belt) and θ is angle of contact (rad).

Effective tension

Effective belt tension was calculated to determine the net force responsible for transmitting power through the belt.

$$T_1 - T_2 = \frac{P}{V} \qquad [11]$$

Where, T_1 = tight-side belt tension (N), T_2 = slack-side belt tension (N), and V is belt speed ($m.s^{-1}$).

$$T_1 - T_2 = \frac{750}{0.37}$$

$$T_1 - T_2 = 2027\ N \qquad [13]$$

Angle of contact

The angle of contact was calculated because it directly influences frictional force and the power-transmitting capacity of the belt.

$$\theta = \pi - 2\,Sin^{-1}\left(\frac{D_2 - D_1}{2C}\right) \qquad [13]$$

$$\theta = \pi - 2\,Sin^{-1}\left(\frac{0.30 - 0.10}{2 \times 190}\right)$$

$$\theta = 3.14 \text{ radian}$$

Using the $\theta = 3.14$ radian in the equation

$$\ln\frac{T_1}{T_2} = 0.30 \times 3.14$$

$$\ln\frac{T_1}{T_2} = 0.942$$

$$\frac{T_1}{T_2} = e^{0.942}$$

$$T_1 = 2.56 \times T_2$$

T_1 value using in the equation [12].

$$T_1 - T_2 = 2027\ N$$

$$2.56T_2 - T_2 = 2027\ N$$

$$1.56T_2 = 2027\ N$$

$$T_2 = \frac{2027}{1.56} = 1299.35\ \text{N}$$

Therefore, $T_1 = 2027 + T_2$

$$T_1 = 3326.35\ \text{N} \quad \text{so } T_{max} = 3326.35\ N$$

The belt stress was determined using the following formula

$$\sigma = \frac{T_{max}}{B \times t} \qquad [14]$$

$$\sigma = \frac{3326.35}{20 \times 0.50}$$

$$\sigma = 332.63\ N.cm^{-2}$$

Belt length

The belt length was calculated to ensure proper belt fit and adequate provision for tensioning and alignment.

$$L = 2C + \frac{\pi}{2}(D_1 + D_2) + \frac{(D_2 - D_1)^2}{4C} \quad [15]$$

Where, L is length of belt (m), C is the centre distance between pulleys (m), D_1 and D_2 are the diameter of driving pulley (m) and driven pulley.

$$L = 2 \times 1.90 + \frac{\pi}{2}(0.10 + 0.30) + \frac{(0.30 - 0.10)^2}{4 \times 1.90}$$

$$L = 4.43\ m$$

Conveyor

The coconut consists of two conveyors: a belt conveyor system consisting of an inclined belt conveyor and a horizontal belt conveyor to ensure smooth material handling and accurate grading of coconuts.

Weighing bucket

The primary purpose of weighing bucket is to precisely weigh coconut before they are distributed, ensuring that the correct amount is used at each process stage. The buck*et al*lows one coconut to pass at a time, with a time difference of 7 seconds between the release of two coconuts, shown in Figure 2. Accurate weight measurements are essential for grader accessories. These attachments can be weighed using single-point load cells to ensure they operate within their design parameters.

Grading unit

Load cell

The accuracy of the load cells ranges from ±0.02% to ±0.1% of the full scale, and their capacities range from a few grams to several tons. An excitation voltage, typically between 5V to 12V DC, powers the output signal, usually an analogue output of 0–10 mV. They are designed with an IP65 or IP67 protection rating, providing deficiency against water and dust intrusion. Additionally, the bridge resistance is typically 350 ohms, making these load cells suitable for a variety of applications.

Proximity sensor

The thru-beam sensor (EN 60947-5-2) detects objects like coconuts within a 40-50 mm range without physical contact. It operates on 10-30V DC, outputs 0-10V analogue signals, and features a switching frequency of up to 5 kHz. With a response time of 0.1-2 millisecond. The GLV 18-8-450/115/120 model offers 1-15% hysteresis and consumes 10-20 mA. Designed with an M18 x 1 threaded housing, it allows flexible mounting through Φ18 mm holes or brackets.

Pneumatic cylinder

A pneumatic cylinder is a mechanical device that uses compressed air to generate linear motion. A cylinder typically consists of a barrel, piston, piston rod, and end caps with seals to prevent air leaks. It operates effectively at a pressure of 6 bar, with a bore diameter of 16 mm and a stroke length of 50 mm. The piston rod diameter varies between 10 mm and 80 mm. Its speed, ranging from 10 mm/sec to 1,500 mm/sec, depends on the load and pressure.

Programmable logic controller (PLC)

PLC is a key component in coconut grader. The system supports programming via instruction, ladder chart, and Visual C, and operates in a cyclic scan program execution mode. With an operation speed of 0.05 microseconds, it features latched memory with Flash ROM and a Li-battery for backup. It has a 128KB user program capacity and supports 16 input points and 14 output points. Internal coils include 1,048 points for X (X0 - X2027) and Y (Y0 - Y1037). The scheduled scan time ranges from 0 to 99 milliseconds. The system also includes self-diagnosis features, such as a monitoring timer, a power-on self-test, and 6-bit ASCII password protection.

Control Panel

The control panel houses PLC and the HMI and the control gears. HMI is used to display the weight of the coconut measured by the load cell. The dimension of the control panel is 400 x 300 mm. PLC works on the principle of ladder logic gates which receives signal from the load cell and transmits to respective proximity sensor.

Delivery channel

A series of delivery chutes was installed along the belt conveyor and precisely aligned with a pneumatic cylinder to ensure accurate discharge of coconuts based on their weight. This configuration facilitated a systematic and efficient separation of the produce into distinct grades, thereby ensuring uniformity and improved ease of handling

Air compressor

An automatic air compressor of 1 HP capacity was used to supply compressed air to the pneumatic system. The compressor operated at a working pressure of 7 kg/cm² with a motor speed of 1020 rpm. It was equipped with an automatic pressure control system integrated with sensors to regulate air supply based on demand. The compressed air generated by the compressor was used to actuate the pneumatic cylinder

Principle of operation of the machine

The feed hopper is used to convey the coconut, and then the coconuts are carried to the weighing bucket through the conveyor belt. The load cell attached to the weighing bucket detects the weight of the nut passing the bucket and the weight is displayed on the display panel. Three proximity sensors are attached with a pneumatic cylinder on the grading part of the grader with four different weight ranges specified for each sensor. The nut with a particular weight is detected by the load cell and a signal is sent to the particular sensor whose specification weight range matches that coconut's weight. When that nut passes through that particular sensor the sensor gets activated and makes the pneumatic cylinder to push the coconut to the outlet (Figure 4). A similar procedure is followed for all coconuts with different ranges of weight.

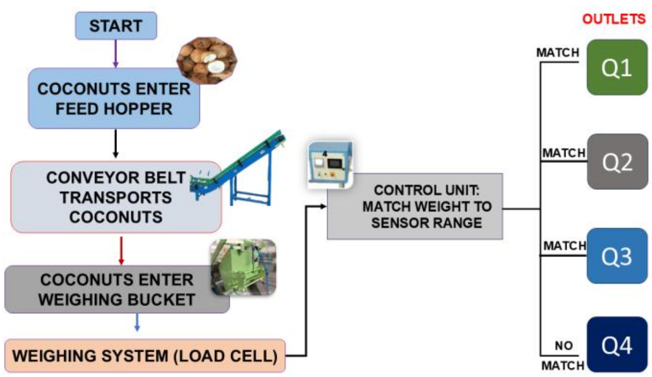

Fig. 4 : Process flow chart of weight-based coconut grader

Performance evaluation

The weight-based grader separates the coconut fruits of different weights in four fractions grade-1 (>600g), grade-2 (450-600g), grade-3 (350-450g), and grade-4 (250-350 g). Let W_t is the total mass of the feed to be graded and the mass of the individual fractions of the material at each outlet are W_1, W_2, W_3 and W_4. After grading of the feeding material, the mass of the products obtained through the outlets is taken as Q_1, Q_2, Q_3 and Q_4 respectively.

The material other than the specified weight in the product outlets Q_1, Q_2, Q_3, and Q_4 were manually separated, and their masses were found separately as q_1, q_2, q_3 and q_4.

$$Q_t = Q_1 + Q_2 + Q_3 + Q_4 \quad [16]$$

$$W_t = W_1 + W_2 + W_3 + W_4 \quad [17]$$

The purity of the product was obtained as:

$$P_1 = \frac{Q_1 + q_1}{Q_1} \quad [18]$$

$$P_2 = \frac{Q_2 + q_2}{Q_2} \quad [19]$$

$$P_3 = \frac{Q_3 + q_3}{Q_3} \quad [20]$$

$$P_4 = \frac{Q_4 + q_4}{Q_4} \quad [21]$$

Where,

P_1 is the purity of the product obtained in outlet 1

P_2 is the purity of the product obtained in outlet 2

P_3 is the purity of the product obtained in outlet 3

P_4 is the purity of the product obtained in outlet 4

q_1 is the fraction of material other than the desired size outlet 1

q_2 is the fraction of material other than the desired size outlet 2

q_3 is the fraction of material other than the desired size outlet 3

q_4 is the fraction of material other than the desired size outlet 4

The fraction yield was calculated by using the following equation [22-25]:

$$Fr_1 = \frac{Q_1}{W_t} \quad [22]$$

$$Fr_2 = \frac{Q_2}{W_t} \quad [23]$$

$$Fr_3 = \frac{Q_3}{W_t} \quad [24]$$

$$Fr_4 = \frac{Q_4}{W_t} \quad [25]$$

Where, Fr_1 is fraction yield at outlet 1

Fr_2 is fraction yield at outlet 2

Fr_3 is fraction yield at outlet 3

Fr_4 is fraction yield at outlet 4

The fraction of each size corresponding to each outlet of total feed was

$$a_1 = \frac{W_1}{W_t} \quad [26]$$

$$a_2 = \frac{W_2}{W_t} \quad [27]$$

$$a_3 = \frac{W_3}{W_t} \quad [28]$$

$$a_4 = \frac{W_4}{W_t} \quad [29]$$

Where, a_1 is the fraction of each size corresponding to grade 1 in total feed

a_2 is the fraction of each size corresponding to grade 2 in total feed

a_3 is the fraction of each size corresponding to grade 3 in total feed

The efficiency was evaluated by the completeness of the extraction of each component in pure form as given by Dhas *et al*. (2004).

$$E = F_{ri} \frac{(P-a)}{(1-a)} \quad [30]$$

The overall effectiveness of the grader was calculated for 4 component mixture graded into 4 fractions,

$$E_i = \sum_{i=1}^{n} Fri \frac{(Pi-ai)}{(1-ai)}, \% \quad [31]$$

Where, E is effectiveness, %

P_i is the purity of the product

a_i is the fraction of each size corresponding to the sieves

F_{ri} is fraction yield

This method was used to evaluate the graders' ability to separate mixtures into more than two fractions in pepper, cardamom and cocoa pod (Balakrishnan *et al*. 2010; Visvanathan and Ashok 2021) was used to evaluate the performance of weight grader. The efficiency of the weight-based coconut grader was evaluated at different feed rates (100 kg/h, 150 kg/h, and 200 kg/h) and belt speeds (0.26 m/s, 0.31 m/s, and 0.37 m/s).

Optimisation and Statistical

Experimental data were analysed using RSM (Design Expert- 13) to develop second-order polynomial regression models for each response. Analysis of variance (ANOVA) was performed to evaluate the significance of model terms and the adequacy of the developed models. The optimal operating conditions were determined by maximizing grading accuracy and separation efficiency while maintaining desirable throughput. Model validation was carried out by conducting confirmation experiments under optimized conditions. The engineering characteristics data of coconuts and weight-based grading were analysed using Microsoft Excel 2021. The calculation of essential statistical metrics, such as the mean, maximum, minimum, and standard deviation, to thoroughly assess the dataset for grading purposes.

Results and Discussion

Dimensional properties

The major, intermediate, minor, and primary dimensions of fifty fruits were precisely measured using a vernier calliper to ensure accuracy and reliability in the data. The dimensional properties of coconut per fruit with average and SD values are presented in Table1.

The dimensional properties of coconuts substantially affect post-harvest processing, handling, and grading efficacy. Analysis of coconut samples revealed significant discrepancies in size and weight, necessitating appropriate classification for industrial and commercial purposes. The dimensions measured were 17.73 ± 1.29 cm in length, 10.17 ± 1.32 cm in width, and 8.15 ± 1.59 cm in thickness. The length (L), width (B), and thickness (T) of the coconuts were 17.73 ± 1.29 cm, 10.17 ± 1.32 cm, and 8.15 ± 1.59 cm, respectively. These measurements are essential for the design of mechanical processing equipment, including conveyors, dehuskers, and slicers. The size variation indicates a requirement for automated grading systems to ensure consistency in industrial scale.

The weight of the coconuts exhibited significant variability (551.76 ± 163.6 g), leading to their classification into four distinct grades: Grade-1 (>600 g) with 25 fruits, Grade-2 (450-600 g) with 24 fruits, Grade-3 (350-450 g) with 26 fruits, and Grade-4 (250-350 g) with 25 fruits, while two fruits fell outside these categories. The weight distribution suggests that most fruits (75 out of 100) belong to Grade-1 and Grade-2, which are regarded bigger and favoured in commercial marketplaces due to their higher kernel yield. In contrast, Grade-3 and Grade-4 fruits, being smaller, may be better appropriate for domestic consumption or particular processing applications such as desiccated coconut and oil extraction. The arithmetic mean diameter (D_a) and equivalent diameter (D_e) were reported as 12.01 ± 1.07 cm and 11.36 ± 1.21 cm, respectively, while the geometric mean diameter (GMD) was 11.29 ± 1.22 cm. These results and the sphericity (φ) of 0.641 ± 0.06, show that coconuts are somewhat elongated rather than completely spherical. This impacts their rolling behavior on grading and processing equipment, necessitating customized designs for effective automated handling. The surface area (SA) was determined to be 405.42 ± 84.24 mm², a significant characteristic impacting drying, coating, and other heat processing applications. The observed heterogeneity in surface area reflects changes in moisture loss rates, which might affect the drying kinetics and shelf life of coconut fruits. A similar finding is also reported by (Alonge & Adetunji, 2011), who highlighted variations in coconut dimensions and their impact on post-harvest processing. Grading of coconuts based on weight helps standardize handling and processing. The observed size and weight variations highlight the importance of implementing effective grading systems to enhance uniformity in industrial applications. Further studies could focus on optimizing sorting mechanisms based on shape, size, and weight to improve efficiency in post-harvest operations.

Performance evaluation grader

At a belt speed of 0.26 m/s, the grading system demonstrated moderate effectiveness across all feed rates, with the lowest overall efficiency of 0.927 recorded at 100 kg/h (Table 1). This was primarily due to lighter fractions, where the 250-350 g category showed a low Ei of 0.060 and Fri of 0.077. The mid-weight categories, particularly 450-600 g (Fri: 0.400, Ei: 0.390), contributed most to the overall effectiveness, while the >600 g fraction added moderately (Ei: 0.316). At 150 kg/h, the system achieved its peak effectiveness of 0.946, driven by strong separation in the heavier categories 450–600 g (Fri: 0.410, Ei: 0.410) and >600 g (Fri: 0.381, Ei: 0.381). The 350-450 g fraction also improved (Ei: 0.095), indicating better classification across weight ranges. At 200 kg/h, effectiveness slightly declined to 0.912, with the 450-600 g and >600 g fractions still contributing significantly (Ei: 0.370 and 0.383, respectively), while the 350-450 g category dropped to an Ei of 0.080, suggesting reduced sorting precision for mid-weight coconuts at higher throughput.

Table 1: Effectiveness of grading with belt speed 0.26 m/s

S. No.	Weight, g	Q_t	a_i	P_i	F_{ri}	E_i
Federate 100kg/h						
1	250-350	2.10	0.045	0.79	0.077	0.060
2	350-450	2.22	0.360	0.957	0.170	0.161
3	450-600	11.00	0.386	0.985	0.400	0.390
4	>600	9.85	0.334	0.92	0.360	0.316
$E = \sum_{i=1}^{4} Fri \frac{(Pi-ai)}{(1-ai)}$				0.927		
Federate 150kg/h						
1	250-350	2.27	0.062	0.75	0.083	0.060
2	350-450	2.97	0.095	0.74	0.133	0.095
3	450-600	11.17	0.410	1.00	0.410	0.410
4	>600	10.50	0.349	1	0.381	0.381
$E = \sum_{i=1}^{4} Fri \frac{(Pi-ai)}{(1-ai)}$				0.946		
Federate 200kg/h						
1	250-350	2.17	0.079	1.00	0.079	0.079
2	350-450	2.87	0.069	0.50	0.174	0.080
3	450-600	10.17	0.370	1.00	0.370	0.370
4	>600	11.50	0.390	0.99	0.418	0.383
$E = \sum_{i=1}^{4} Fri \frac{(Pi-ai)}{(1-ai)}$				0.912		

At a belt speed of 0.31 m/s, the weight-based grading system demonstrated its highest overall effectiveness of 0.936 at a feed rate of 150 kg/h, as shown in Table 2. This peak performance was attributed to strong separation across all weight categories, particularly for the 450-600 g (40.9%) and >600 g (40.5%) fractions, which contributed significantly to the overall grading accuracy. As the feed rate decreased to 100 kg/h, effectiveness slightly declined to 0.925, despite similar weight distributions. The drop was primarily due to reduced individual effectiveness (Ei) values for the lighter fractions (250-350 g and 350-450 g), indicating diminished sorting precision. At 200 kg/h, the effectiveness further decreased to 0.906, with noticeable reductions in both Fri and Ei for the lighter categories, suggesting that higher throughput compromised the system’s ability to accurately classify smaller coconuts.

Table 2 : Effectiveness of grading with belt speed 0.31 m/s

S. No.	Weight, g	Q_t	a_i	P_i	F_{ri}	E_i
Federate 100kg/h						
1	250-350	2.370	0.500	0.770	0.084	0.050
2	350-450	2.670	0.108	1.000	0.145	0.145
3	450-600	11.270	0.404	0.950	0.438	0.409
4	>600	11.5	0.422	1.00	0.321	0.321
$E = \sum_{i=1}^{4} Fri \frac{(Pi-ai)}{(1-ai)}$x100				0.925		
Federate 150kg/h						
1	250-350	2.370	0.500	0.670	0.084	0.029
2	350-450	2.670	0.108	1.000	0.087	0.093
3	450-600	11.270	0.404	0.950	0.438	0.409
4	>600	9.850	0.384	1.000	0.394	0.405
$E = \sum_{i=1}^{4} Fri \frac{(Pi-ai)}{(1-ai)}$				0.936		
Federate 200kg/h						
1	250-350	2.27	0.083	1.00	0.083	0.083
2	350-450	2.97	0.083	0.727	0.058	0.040
3	450-600	11.17	0.372	0.95	0.410	0.397
4	>600	10.5	0.386	1.00	0.386	0.386
$E = \sum_{i=1}^{4} Fri \frac{(Pi-ai)}{(1-ai)}$				0.906		

This trend highlights the importance of maintaining optimal belt speed and feed rate to ensure grading precision. While 0.26 m/s proved to be the most effective speed, achieving a peak grading efficiency of 94.6% at 150 kg/h (Table 4), further increases in belt speed as seen in Table 3 led to reduced effectiveness. This decline can be attributed to shorter contact time between the coconuts and the grading mechanism, increased turbulence, and reduced stability of particle trajectories. These factors collectively hinder the system's ability to distinguish weight categories accurately, especially under high feed rates. Therefore, for consistent and high-quality grading, it is crucial to operate the system at moderate belt speeds and controlled feed rates. At a belt speed of 0.37 m/s, the system recorded effectiveness values of 0.8518 at 100 kg/h, 0.7837 at 150 kg/h, and 0.7729 at 200 kg/h, confirming the downward trend in grading performance with increased speed and throughput.

Table 3 : Effectiveness of grading with belt speed 0.37 m/s

S. No.	Weight, g	Q_t	a_i	P_i	F_{ri}	E_i
Federate 100kg/h						
1	250-350	2.07	0.048	0.895	0.076	0.067
2	350-450	2.57	0.062	0.87	0.074	0.078
3	450-600	9.17	0.337	1.0	0.343	0.343
4	>600	9.95	0.328	0.997	0.365	0.363
$E = \sum_{i=1}^{4} Fri \frac{(Pi-ai)}{(1-ai)}$				0.8518		
Federate 150kg/h						
1	250-350	2.0	0.0412	0.561	0.073	0.0397
2	350-450	2.07	0.076	1.0	0.076	0.0775
3	450-600	11.42	0.419	0.99	0.373	0.3665
4	>600	8.05	0.295	1.0	0.295	0.300
$E = \sum_{i=1}^{4} Fri \frac{(Pi-ai)}{(1-ai)}$				0.7837		
Federate 200kg/h						
1	250-350	2.11	0.077	0.726	0.056	0.0377
2	350-450	2.56	0.094	1.0	0.0958	0.0958
3	450-600	11.11	0.352	0.862	0.408	0.3274
4	>600	10.22	0.357	0.768	0.357	0.3125
$E = \sum_{i=1}^{4} Fri \frac{(Pi-ai)}{(1-ai)}$				0.7734		

The performance of the weight-based grading system was strongly influenced by the interplay between belt speed and feed rate, as evidenced across Tables 1, 2, and 3. Among the tested configurations, a belt speed of 0.26 m/s consistently demonstrated the highest overall grading efficiency, peaking at 94.60% at 150 kg/h. This speed offered an optimal balance between particle momentum and residence time, enabling precise separation across all weight categories, particularly for mid to heavy fractions. In contrast, the intermediate speed of 0.37 m/s, while still effective, showed slightly lower peak efficiency (93.6% at 150 kg/h) and a gradual decline at higher feed rates (90.6% at 200 kg/h), likely due to reduced contact time and increased particle velocity.

Conversely, the fastest belt speed of 0.37 m/s introduced excessive turbulence and shortened interaction time between coconuts and the grading mechanism, leading to erratic trajectories and diminished sorting accuracy especially for lighter fractions. This was reflected in the lowest recorded efficiency of 77.29% at 200 kg/h, indicating that high-speed operation compromises classification precision.

These findings underscore the critical importance of optimizing belt speed to achieve high-resolution grading performance. A moderate speed of 1.0 m/s strikes the most favorable balance between throughput and classification accuracy, making it the most suitable for commercial-scale operations where both efficiency and precision are paramount. Understanding this dynamic is essential for designing scalable grading systems that maintain consistent performance across varying operational loads.

The results, as presented in Table 5, demonstrate that the grader's efficiency varied notably with changes in belt speed and feed rate. At a feed rate of 150 kg/h, the highest efficiency of 94.6% was achieved at 0.26 m/s, followed by 93.6% at 0.31m/s, and dropped to 78.31% at 037 m/s. A similar observation was reported by Asha Monicka *et al*. (2021) for dehusked coconut, suggesting that higher belt speeds may reduce grading accuracy due to improper positioning of the product or insufficient sensor response time.

At the highest feed rate of 200 kg/h, the efficiency values were 91.2% at 0.26 m/s, 90.6% at 0.31 m/s, and 77.29% at 0.37 m/s, showing a clear reduction at elevated belt speeds. This trend can be attributed to the combined effect of increased particle velocity and reduced interaction time, which limits the system's ability to accurately classify coconuts especially under high throughput. Although efficiency tended to decrease with increasing speed, the decline was less pronounced at higher feed rates, suggesting that the grader's optimized design helps sustain reasonable performance under load, particularly for heavier weight fractions.

Table 4 : Effectiveness of weight-based grader

Belt speed (*m/s*)	Federate (*kg/h*)	Efficiency (%)
0.26	100	92.7
	150	94.6
	200	91.2
0.31	100	92.5
	150	93.6
	200	90.6
0.37	100	85.18
	150	78.31
	200	77.34

Optimization

Table 5 illustrated the experimental design for 16 runs for the custom design. To attain the response such as efficieny, the findings of the experiments were investigated using Quadratic regression model.

$$Efficiency = 92.69 - 1.94A - 6.19B - 1.78AB - 0.78A^2 - 4.96B^2$$

[37]

Where y = response, $\beta_0, \beta_{1,}, \beta_{12}$ *and* β_{22} = model coefficients, A and B is the two independent variables. The model coefficients and the associated statistical parameters for each term were obtained.

Table 5 : Experimental Design

Run	Factor A Feedrate (kg/h)	Factor B Belt speed (m/s)	Response Efficiency (%)
1	200	0.37	77.34
2	150	0.26	94.62
3	100	0.37	85.18
4	150	0.26	94.61
5	100	0.31	92.50
6	150	0.31	93.60
7	100	0.26	92.71
8	200	0.26	91.20
9	150	0.31	93.601
10	150	0.26	94.609
11	150	0.37	78.31
12	100	0.26	92.705
13	200	0.31	90.6
14	100	0.37	85.18
15	200	0.37	77.37
16	150	0.31	93.608

The quadratic response surface model developed for efficiency was statistically significant (F = 64.12, *p = 0.0001*), confirming that the chosen factors feed rate (A) and belt speed (B) strongly influence grader performance. Among the model terms, feed rate (A) ($p = 0.0022$), belt speed (B) ($p = 0.0001$), the quadratic effect of belt speed (B^2, $p = 0.0001$), and the interaction term (AB, $p = 0.0080$) were significant contributors (Fig. 5). This indicates that both linear and higher-order interactions play a critical role in determining efficiency. The model also demonstrated strong predictive capability, with $R^2 = 0.968$, Adjusted $R^2 = 0.952$, and Predicted $R^2 = 0.885$, all within acceptable agreement.

Thus, the optimization analysis suggests that an intermediate feed rate (150 kg/h) combined with a lower belt speed (0.26 m/s) yields the highest grading efficiency. This balance minimizes fruit misplacement while maintaining throughput, aligning with industrial requirements for both accuracy and productivity. The validated model can therefore be reliably used to predict grader performance and guide scale-up or operational adjustments.

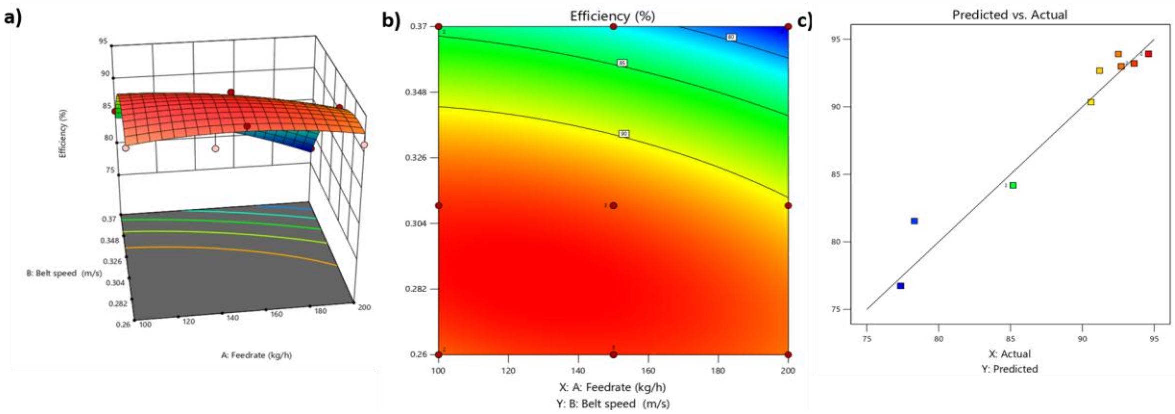

Fig. 5 a) 3D surface plot, **b)** Predicted vs actual efficiency **c)** Contour plot

Conclusion

The coconut grading system that was developed based on weight was technically effective and practically feasible to apply in the process of post-harvest. They have been fitted with a load cell, a conveyor system, pneumatic cylinder and PLC controlled system to ensure that there is an accurate and consistent separation of the coconuts into four specific weight groups with limited wastes. Feed rate and belt speed were good predictors of grading performance, and optimum conditions which resulted in maximum efficiency of 94.60 % was the biggest predictor of performance. The statistical modelling has demonstrated the presence of high interaction effects of operating parameters and good predictability of the important responses. The treatments showed a stable fractional recovery indicating that there is stable system operation and similar material treatment. The system has potential applications in coconut procurement centers, processing industries, and commercial markets. The grader classifies coconuts solely based on weight and does not assess external quality attributes such as size, shape, maturity, shell defects, or internal quality, which may influence overall market value.

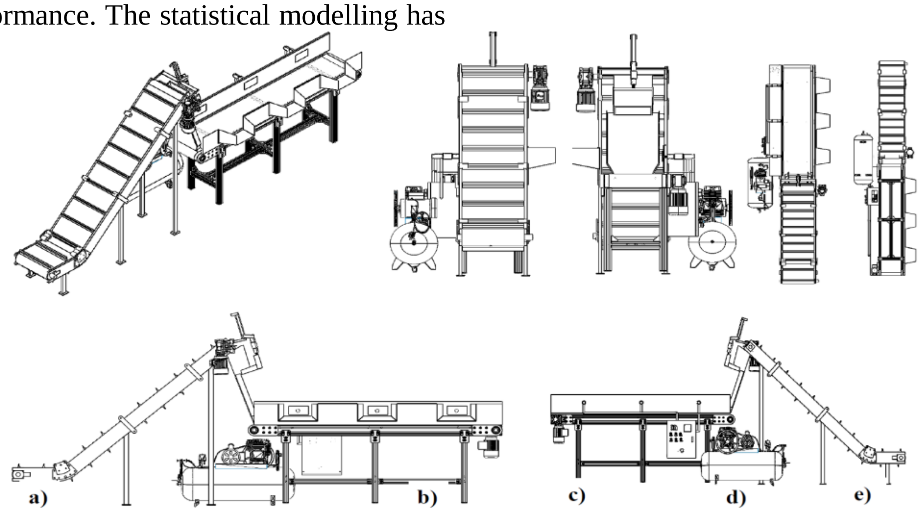

Fig. 1: Different view of weight-based coconut grader

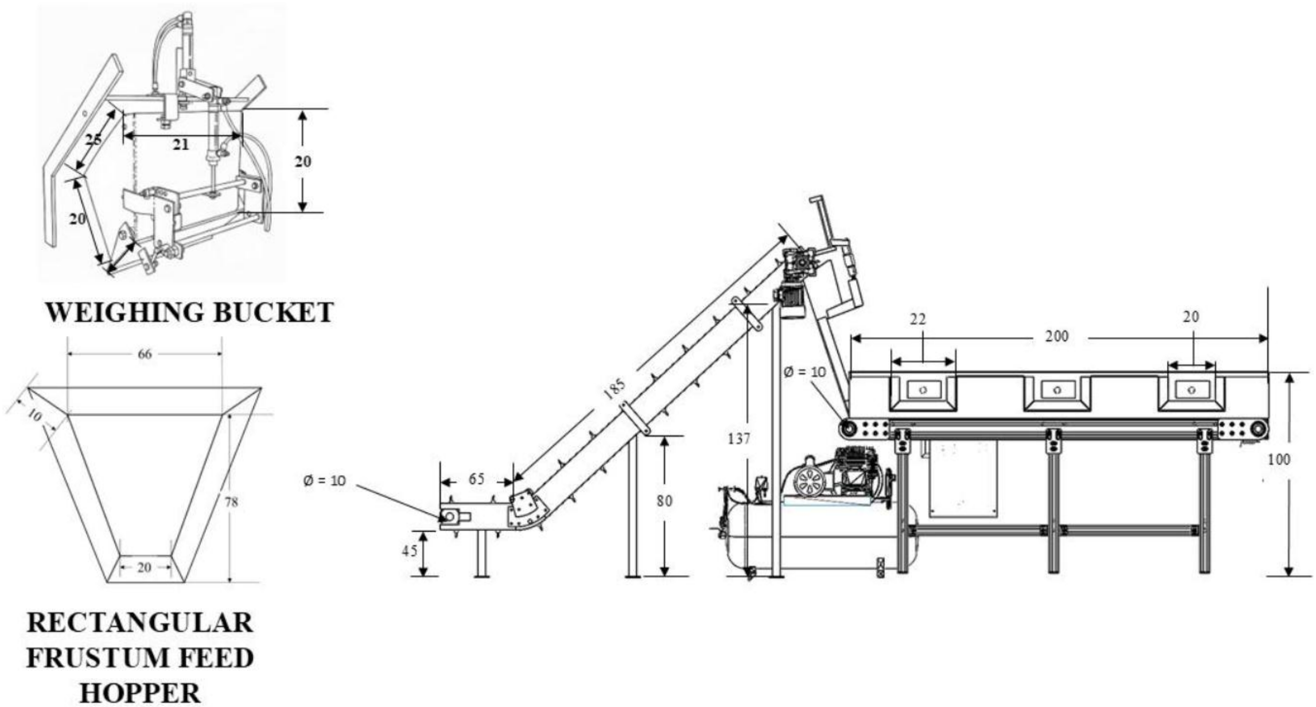

Fig. 2 : Dimensional details of the weight-based coconut grader (dimensions in cm).

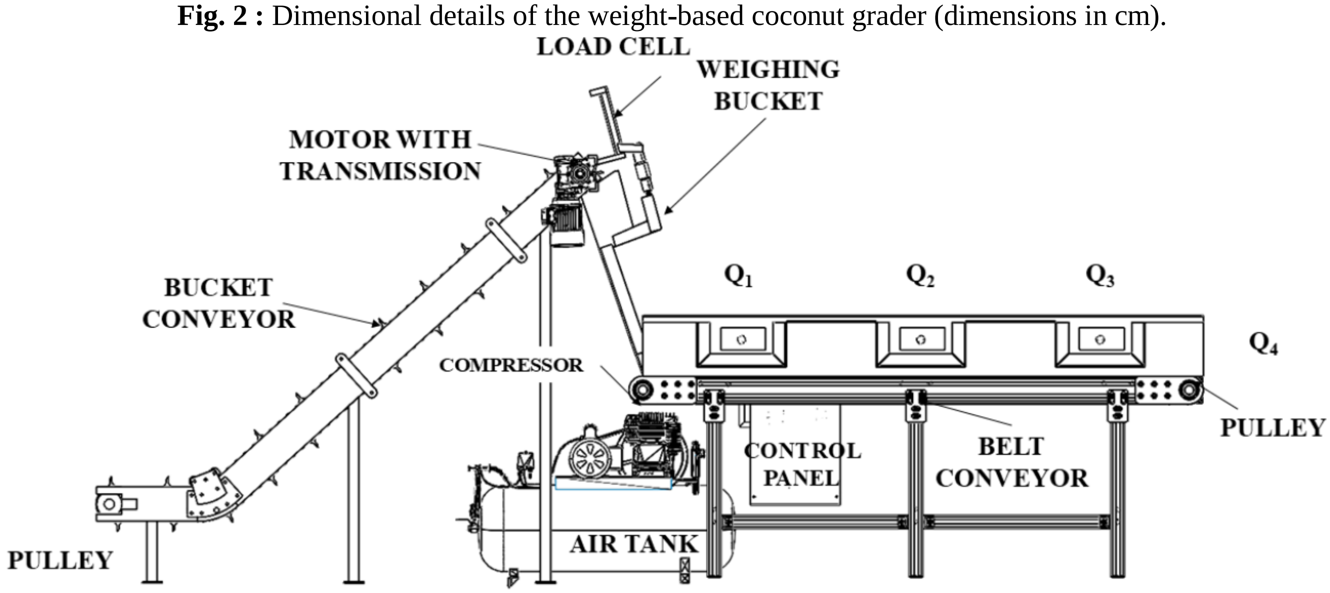

Fig. 3 : Schematic diagram of the developed weight-based coconut grader showing major components.

Author contributions

T. Pandiarajan: Supervision, Formal analysis, project administration, writing and reviewing draft; **Hemant Kumar:** Writing - original draft; Investigate, conceptualization, Software analysis; Visualisation; **P. Sudha:** Visualisation; validation; data curation; **M. Anand:** Supervision, Formal analysis, Visualisation; validation; data curation. writing and reviewing draft; **M. Balakrishnan:** Project administration, Supervision, Formal analysis, writing and reviewing draft.

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