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Design and Development of a Rotary Dryer-Based Palletizing Machine with Multi-Purpose Drying and Cooling

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ABSTRACT

High initial moisture content (≈70%) in poultry feed and herbal fertilizer pellets poses significant challenges in agro-industrial processing, leading to prolonged drying times, high energy consumption, and inconsistent product quality. This study designs and analytically validates a three-stage rotary dryer integrated with palletizing and in-line cooling to reduce moisture content from 70% to 9% at a throughput of 0.5 T/h within a 10 × 10 m footprint. A systematic product development approach was employed, incorporating agreed specifications with stakeholders, market benchmarking, and weighted Pugh concept selection. Thermal verification was conducted using heat and mass balance calculations to determine evaporation rate, heat load, airflow requirement, residence time, and power demand. The final configuration comprises a 0.5 m diameter, 21 m long rotary drum operating at 5 rpm with controlled air injection at 70–80 °C. Results indicate improved drying control, integrated cooling efficiency, and enhanced process sustainability for agro-industrial applications.

Keywords: Rotary Dryer, Palletizing Machine, Product Development, Poultry Feed, Herbal Fertilizer.

1. INTRODUCTION

Efficient moisture control is a critical requirement in agro-industrial processing, particularly in the production of poultry feed and herbal fertilizer. Freshly formed pellets commonly contain moisture levels as high as 60–70 %, which must be reduced to ensure product stability and quality [1][2]. Excess moisture can lead to microbial growth, reduced shelf life, structural degradation of pellets, and inconsistent combustion or nutrient release characteristics [2].

Various drying technologies are used in solid-processing industries, including rotary, fluidized bed, belt, and flash dryers. Fluidized bed dryers provide high heat and mass transfer rates due to strong gas-solid interactions, resulting in rapid drying; however, they typically require narrow particle size distributions and may cause pellet attrition under turbulent conditions. Belt dryers are suitable for heat-sensitive materials because they enable gentle, controlled drying, though their large installation footprint and longer residence times can limit their use in space-

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constrained facilities. Flash dryers allow extremely rapid moisture removal through suspension drying but are generally limited to fine powders rather than structured pellets [3], [4], [5].

In contrast, rotary dryers remain one of the most widely adopted technologies for bulk solid processing due to their mechanical simplicity, scalability, and ability to handle variable feed characteristics [6]. These features make them particularly suitable for high-throughput agro-industrial operations. However, conventional single-stage rotary dryers may experience uneven temperature distribution, limited process control, and inefficient thermal utilization, often requiring separate downstream cooling units that increase operational complexity. Table 1.0 compares commonly used drying technologies for agro-pellet processing, highlighting that rotary dryers offer a practical balance between throughput capacity, operational robustness, and adaptability to high-moisture pellets, although further improvements in thermal efficiency and process integration remain required.

Table 1: Comparison of drying technologies for agro-pellet processing [3], [7].

DRYER TYPE	HEAT & MASS TRANSFER	ADVANTAGES	LIMITATIONS	SUITABILITY FOR 70% MOISTURE PELLETS
ROTARY DRYER	Moderate (convective, cascading bed)	Robust, scalable, handles high throughput	Lower thermal efficiency in single-stage systems	Highly suitable
FLUIDIZED BED DRYER	High (intense gas–solid contact)	Uniform drying, fast kinetics	Pellet attrition, narrow particle size range	Limited for fragile pellets
BELT DRYER	Moderate (through-bed convection)	Gentle drying, good for heat-sensitive materials	Large footprint, long residence time	Space-constrained limitation
FLASH DRYER	Very high (suspension drying)	Rapid drying, compact	Only for fine powders, not pellets	Not suitable

Recent research on rotary drying systems has primarily focused on improving the thermal and hydrodynamic behavior inside rotary drums, including flight design optimization, residence time modelling, and detailed analysis of heat and mass transfer mechanisms. For example, studies have developed two-phase heat and mass transfer models to predict moisture removal behavior in rotary dryers and to analyze interactions between particles and drying air streams [8]. More recent work has also introduced advanced mathematical modelling frameworks for rotary drum dryers to improve process control and predict outlet moisture conditions under varying operational parameters [9].

Recent studies have explored improved rotary dryer configurations and thermal performance optimization, including systems incorporating air recirculation, thermal storage, and phase change materials to enhance energy efficiency and drying uniformity [10], [11]. These investigations indicate that airflow distribution, heat transfer mechanisms, and system configuration significantly influence drying efficiency and final product quality.

Despite these developments, most existing research focuses primarily on process modelling, thermal analysis, or energy optimization. Compared with integrated multi-stage rotary dryer configurations that combine controlled drying and inline cooling within a compact industrial system, limited attention has been given to them. Many studies emphasize theoretical modelling without incorporating systematic engineering design methodologies such as machine specification formulation, structured concept development, and quantitative concept selection required for practical industrial implementation.

This limitation is particularly relevant for small to medium-scale agro-industrial operations, where processing equipment must operate within space constraints while maintaining moderate throughput and energy efficiency. In Malaysia, agro-based manufacturers such as HPA Industries require compact drying systems capable of reducing pellet moisture content from approximately 70% to below 10% at production capacities of about 0.5 T/h. However, many commercial drying systems require large installation footprints, batch processing, or separate downstream cooling units, which increase material handling and operational complexity.

To address these challenges, this study presents the design and analytical evaluation of a compact three-stage rotary dryer-based pelletizing system incorporating two controlled drying zones and an integrated cooling zone within a single structural framework. The proposed design integrates a systematic engineering development methodology, including stakeholder requirement analysis, market benchmarking, weighted Pugh concept selection, and 3D modelling with analytical heat and mass balance calculations to determine key parameters such as moisture evaporation rate, thermal load, airflow requirement, residence time, and power consumption. By combining structured engineering design with analytical thermal evaluation, the study bridges the gap between theoretical drying analysis and practical industrial system development.

Beyond technical performance, the proposed system also supports sustainable agro-processing practices by improving moisture uniformity and reducing post-processing losses. These improvements contribute to enhanced feed quality and agricultural productivity aligned with Sustainable Development Goal (SDG) 2 (Zero Hunger). The compact modular configuration promotes local industrial innovation consistent with SDG 9 (Industry, Innovation and Infrastructure), while improved thermal utilization and reduced material handling support SDG 12 (Responsible Consumption and Production).

Accordingly, the main contributions of this study are:

I. Development of an integrated multi-stage rotary dryer with embedded cooling for agro-pellet processing;
II. Analytical validation of thermal and mass transfer requirements for 0.5 T/h industrial operation;
III. Systematic concept selection using weighted decision analysis;
IV. Establishment of a scalable engineering design framework for compact agro-industrial drying systems.

2. METHODOLOGY

The stakeholder, during the discussion in Figure 1, required a continuous drying system capable of reducing pellet moisture content from 70 % to ≤ 9 %, while achieving a processing capacity of 0.5 T/h within a limited installation footprint of 10 × 10 m. In addition, the system was expected to support continuous operation and incorporate an integrated cooling stage prior to packaging to ensure product stability and handling efficiency.

Figure 1: Stakeholder discussion and requirement analysis.

Based on the stakeholder requirements and industrial constraints, several design evaluation criteria were established to guide concept selection. These criteria focused on operational performance, system integration, manufacturability, and long-term reliability, as summarized in Table 2.

Table 2: Design Evaluation Criteria Derived from Stakeholder Requirements.

NO.	CRITERIA	DESCRIPTION	RELEVANCE TO CLIENT PROBLEM
1	Space Utilization Efficiency	Ability of the system to integrate drying, cooling, and packaging preparation within a compact footprint.	The client has a limited installation area (10 × 10 m).
2	Operational Safety	Safe operation with stable structure, controlled temperature, and minimal risk to operators.	Required for continuous industrial use.
3	Drying and Cooling Integration	Capability to perform drying and cooling within the same system to reduce handling steps.	The current system requires separate cooling.
4	Throughput Capacity	Ability to achieve the required 0.5 T/h production rate.	Ensures industrial production demand.
5	Temperature Segmentation Control	Ability to control different temperature zones for staged drying and cooling.	Prevents pellet damage and uneven drying.
6	Manufacturability	Ease of fabrication using commonly available industrial materials and processes.	Reduces production cost and complexity.
7	Maintenance and Durability	Structural robustness and ease of maintenance for long-term operation.	Important for industrial reliability.

2.1 MARKET BENCHMARKING

Five commercial rotary dryer systems Table 3 were reviewed to identify common design parameters, including drum diameter, length-to-diameter ratio (L/D), airflow configuration, drive mechanisms, and insulation practices.

Table 3: Market comparison of rotary dryer features.

	Rotary Dryer 1	*Rotary Dryer 2*	*Rotary Dryer 3*	*Rotary Dryer 4*	*Rotary Dryer 5*
Model	 *(Maxton) Everflow RD0606*	 *Zengke Machine ZKRD600×60*	 *YI BOO 800×8000*	 *Henan Yuhong Φ600×6000*	 *China Shibo Φ1.2×8.0*
Price (RM)	*41667*	*25000*	*522338*	*22875*	*83334*
Capacity (t/h)	*0.5-1.5*	*0.5-1.5*	*0.8-2.0*	*0.5-1.5*	*1.9-2.4*
Power (kW)	*3*	*3*	*5.5*	*3*	*7.5*
Speed (rpm)	*3-8*	*3-8*	*3-8*	*3-8*	*-*
Diameter (m)	*0.6*	*0.6*	*0.8*	*0.6*	*1.2*
Length (m)	*6*	*6*	*8*	*6*	*8*
Installation Angle (%)	*3-5*	*3-5*	*3-5*	*3-5*	*3-5*
Flight profile			*-*		*-*

2.2 Design Specification Calculation

The design specification calculations were conducted to determine the key operational and structural parameters required for the proposed rotary dryer system. Fundamental heat and mass balance principles were applied to estimate the moisture evaporation rate, heat load requirements, airflow rate, drum dimensions, and residence time, ensuring that the designed system meets both process performance and operational reliability requirements.

2.2.1 Drum Diameter Length

The diameter of the drum was determined using Equation 1:

$$V = \frac{\pi D^2}{4} L \tag{1}$$

Based on throughput and material filling ratio, the internal diameter was fixed at 0.5 m. The required drum length was estimated from the overall heat transfer relationship in Equation 2:

$$Q = U_a A L (\Delta T)_{lm} \tag{2}$$

Total drum length was designed as 21 m, as it is separated into a 14 m drying section and a 7 m cooling section

2.2.2 Retention Time

The retention time (τ) in the rotary dryer is crucial for achieving the desired result, as it represents the duration the material needs to be processed within the dryer [6]. To determine the optimal processing time, these factors can be considered alongside empirical equations like Equation 3, as recommended by AICHE [12]. Utilizing this equation yields a retention time of τ = 140.2042 minutes, offering a quantitative guide for achieving efficient drying outcomes.

$$\tau = \frac{0.23L}{SN^{0.9}D} + \frac{2BLG}{F} \tag{3}$$

The speed of rotation (RPM) of a rotary dryer can be influenced by factors such as the distance the product travels from a point on the circumference of a rotating circular object and the diameter of the rotary drum. Equation 4 provides a means to calculate this speed. Utilizing this equation yields an RPM of approximately 4.8 rpm, which can be rounded to 5 rpm for practical purposes.

$$RPM = \frac{peripheral\ speed}{Diameter} \tag{4}$$

The rotary drum needs to be insulated to minimize heat loss. Fiberglass has been chosen as the insulation. Thermal conductivity is 0.04 W/mK. Steel, on the other hand, has a thermal conductivity of 51.9220 W/mK. The insulation thickness can be calculated using Equation 5. The calculated insulation thickness is 0.03478 m, or equivalently, 34.78 mm.

$$Q = \frac{2\pi\,(\pi)\,(T_2 - T_1)}{\frac{In(\frac{r_2}{r_1})}{k_A}} + \frac{In(\frac{r_2 + t_i}{r_2})}{k_B} \tag{5}$$

The calculated insulation thickness was 34.78 mm; however, for practical industrial implementation, it was standardized to 50 mm of fiberglass insulation, which is commonly used in medium-temperature rotary dryers to minimize heat loss and improve overall thermal efficiency. As a result, the total diameter can be calculated using Equation 6, which combines the outer diameter and the insulation thickness. The computed total diameter is 0.535 meters, or equivalently 517.3 mm, rounded up to 550mm.

$$D_t = D_o + 2t_i \quad (6)$$

To calculate the motor power required to rotate a rotary dryer, Equation 7 can be used [12]. Given the parameters and calculations involved, the motor power per layer of a 7-meter rotary drum can be determined. Utilizing this equation yields a motor power of approximately 0.4123 kW. This value provides a guideline for selecting an appropriate motor to drive the rotary drum, ensuring efficient operation of the dryer system.

$$P_m = \frac{0.3\pi D_i^2}{4} \quad (7)$$

The blower power requirement can be determined by calculating the inlet heat using Equation 7. Substituting the given values into the equation yielded a heat input of approximately 155 kW. Then, using Equations 8 & 9 and considering parameters such as air density, pressure difference, and blower efficiency, the blower power requirement to approximately 12.93 kW.

$$P_b = 2.72 \ x \ 10^{-5} \ Q_{inlet\ air} \ \rho \quad (8)$$

$$Q_{inlet\ air} = \frac{nRT}{P} \quad (9)$$

The total power requirement (P_D) is approximately 43.89 kW. Therefore, the total power needed during full operation of the rotary dryer with the flight profile could be calculated using Equation 10.

$$P_D = \frac{N(4.75D_i W_{material} + 0.1925D' W_{total} + 0.33W_{total}}{100000} \quad (10)$$

2.3 Conceptual Generation

The concept generation phase aimed to develop a range of rotary dryer designs that meet the operational requirements of HPA Industries.

2.3.1 Concept 1 – Concrete Floor-Based System

Concept 1 in Figure 2 is designed with a fixed installation on a reinforced concrete base. The system consists of a hot-air blower, a rotary drum, a gear-driven motor, and a separate cooling room connected via conveyors. The layout is extended horizontally to ensure stable operation and simplified material flow. This configuration emphasizes structural stability and permanent installation for industrial environments.

2.3.2 Concept 2 – Steel Beam Support System

Concept 2 in Figure 3 utilizes a steel beam structural frame to support the rotary dryer components. The hot air blower and rotary drum are arranged linearly on the frame, allowing improved accessibility for assembly and maintenance.

2.3.3 Concept 3 – Three-Level Modular Frame

Concept 3 in Figure 4 adopts a three-level modular steel frame structure to maximize space utilization within the limited installation area. Each level contains an independent rotary drum, air blower, and discharge channel, enabling temperature segmentation and staged drying. This modular configuration allows flexible expansion and improves drying control while maintaining a compact footprint.

2.3.4 Concept 4 – Cross-Section Rotary Drum System

Concept 4 in Figure 5 consists of multiple rotary drums arranged in a cross-sectional series configuration mounted on an iron frame supported by a concrete base. The system includes an input conveyor, a rotating drum assembly, a motor with a gear transmission, and an output conveyor with passive cooling at ambient conditions.

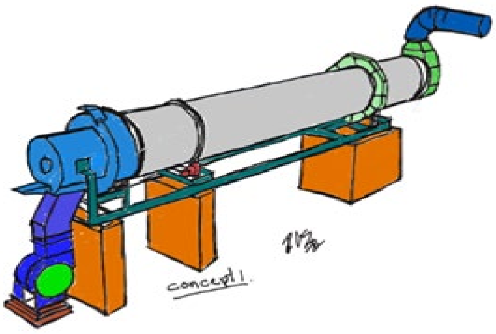


Figure 2: Concept 1.

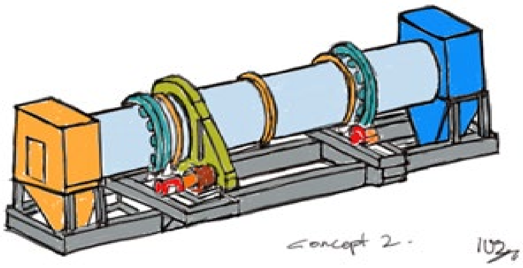


Figure 3: Concept 2.

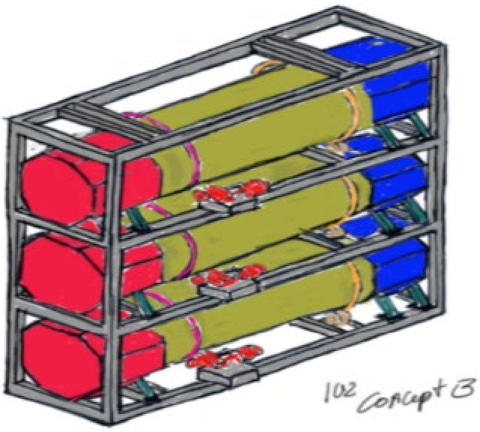


Figure 4: Concept 3.

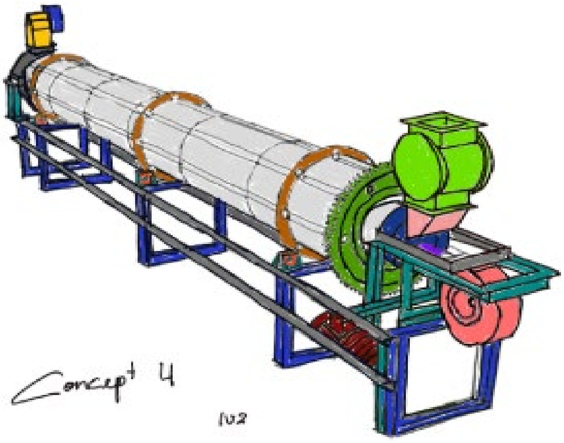
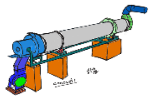
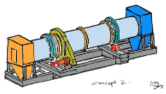
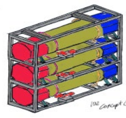
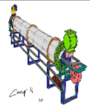


Figure 5: Concept 4

All four designs were developed based on the machine specification[13], [14] to meet HPA Industries' requirements and industry standards. The Pugh Method in Table 4 was then applied to systematically compare and rank the concepts for optimal selection [15], [16].

Table 4: The concept-screening matrix [7], [15].

Selection Criteria	**Concepts Variants**				
	CONCEPT 1	CONCEPT 2	CONCEPT 3	CONCEPT 4	D
					Reff.
Safe Place (Limited area)	0	0	+	-	0
Feasibility (Dry & cooling)	-	-	+	-	0
Performance (0.5T/h)	0	0	+	0	0
Type (Indirect rotary dryer)	-	-	+	0	0
Durability	0	0	0	0	0
Ease of manufacture	0	0	0	0	0
Temperature segmented	-	-	+	-	0
Sum +'s	0	0	5	-	0
Sum 0's	4	4	2	4	7
Sum -'s	3	3	-	3	0
Net Score	-3	-3	5	-3	0
Rank	2	3	1	4	
Continue?	Combine	Combine	YES	No	Combine

Following the initial screening, a more detailed concept-scoring analysis was conducted, incorporating weighted criteria to quantify each concept's relative performance in Table 5.

Table 5: The concept-scoring matrix [15].

CRITERIA	WEIGHT (%)	CONCEPT 1&2 RATING	SCORE	CONCEPT 3 RATING	SCORE	CONCEPT 4 RATING	SCORE
Space Utilization	20	3	0.60	5	1.00	2	0.40
Drying & Cooling Integration	20	2	0.40	5	1.00	3	0.60
Throughput Capacity (0.5 T/H)	20	3	0.60	5	1.00	3	0.60
Temperature Segmentation	15	2	0.30	5	0.75	2	0.30
Operational Safety	10	4	0.40	4	0.40	3	0.30
Manufacturability	10	4	0.40	3	0.30	3	0.30
DURABILITY	5	4	0.20	4	0.20	3	0.15
TOTAL	**100**		**2.90**		**4.65**		**2.65**

(1 = Very Poor, 3 = Moderate, 5 = Excellent)

Concept 3 achieved the highest weighted score 4.65/5, primarily due to superior space utilization, integrated drying–cooling configuration, and temperature segmentation capability. Although manufacturability was slightly lower due to modular structural complexity, the sensitivity analysis confirmed that Concept 3 remained the highest-ranked alternative across ±10% variations in weighting factors, demonstrating the robustness of the selection.

2.4 MATHEMATICAL MODELLING OF DRYING

2.4.1 Heat Transfer Model

The heat transfer mechanism within the rotary dryer is primarily governed by convective heat transfer between the hot drying air and the pellet surface [17]. The rate of heat transfer is expressed in Equation 11:

$$Q = hA(T_a - T_s) \tag{11}$$

2.4.2 Moisture Removal Model

During the moisture reduction process, calculations for moisture loss were performed using the following Equation 12. This equation allows determining the percentage of moisture removed from the chicken pellets by comparing the feed's initial weight before dehydration to its weight after reaching the desired moisture content. By monitoring these values, you can accurately assess the effectiveness of the dehydration process and track progress toward the target moisture level.

$$\text{Moisture Content (\%)} = \left(\frac{Initial\ Weight - Dry\ Weight}{Initial\ Weight}\right) x100 \tag{12}$$

The primary step of the experiment involved setting up the dehydrator machine and spreading the feed evenly across the trays. This arrangement was crucial to avoid overpacking, which could obstruct proper airflow. The temperature was set between 54°C and 71°C, with airflow velocity adjusted to between 2 m/s and 5 m/s, ensuring effective drying while preserving nutrient integrity.

3. RESULTS AND DISCUSSION

The design and development of a rotary dryer-based palletizing machine successfully addressed the limitations of conventional drying systems. By incorporating a three-stage configuration with integrated cooling, the system ensures effective moisture reduction, operational efficiency, and consistent product quality.

3.1 Design Specifications

Design calculations for drum sizing, shell thickness, insulation, gradient, retention time, and rotation speed are summarized in Table 6 [18][19][20][21].

Table 6: Key design specifications and calculated parameters.

Dimensions	
Material of Construction	Carbon Steel (SA 285, Grade C)
Inclination	3-8 degrees (able to adjust the angle)
Inside Diameter	0.5 m
Total Diameter	0.55 m
Length	21 m (14m Dryer,7m cooler)
Shell Thickness	8.34 mm
Insulation Thickness	50 mm (Fiberglass)
Technical Data	
Rotational Speed	5 rpm

Air flow Arrangement	Direct Air flow
Drive Assemblies	Gear & pinion mechanisms
Motor Power Requirement	0.4123 kW (per layer of 7 meters rotary drum)
Blower Power Requirement	12.93 kW
Dryer Power Requirement	43.89 kW

3.2 Proposed Design

SolidWorks was employed to develop the 3D modelling and assembly design of the proposed system to verify structural configuration, component integration, and spatial compatibility. Based on the results of the concept screening and concept scoring analyses, Concept 3 was identified as the most suitable design alternative and selected for detailed engineering development.

Following this selection, a comprehensive 3D model was constructed to transform the conceptual design into a detailed engineering representation. The modelling process enabled systematic evaluation of assembly relationships, component clearances, and potential interference between mechanical parts. In addition, the digital assembly environment facilitated verification of modularity, structural alignment, and manufacturability considerations prior to physical fabrication.

Figure 6 illustrates the proposed three-layer rotary drum configuration developed for HPA Industries. The system layout consists of the rotary drum assembly, the hot air blower unit, the drive transmission system, and the supporting frame structure. Detailed technical drawings were subsequently generated from the 3D model to ensure dimensional accuracy, tolerance consistency, and proper spatial coordination among the major components. Particular attention was given to integrating the hot air blower, drum support mechanism, and drive assemblies to ensure efficient airflow distribution, stable drum rotation, and reliable mechanical operation during the drying process.

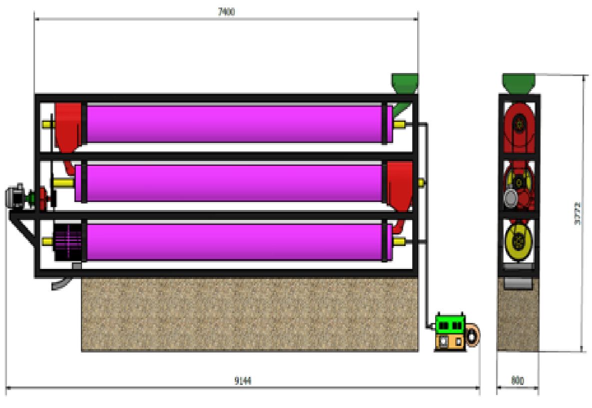


Figure 6: Proposed Design for HPA Industry Rotary.

The proposed rotary drying system introduces several innovations over conventional designs, developed specifically to meet the requirements outlined in the specification. As shown in Figure 7, the process begins at the upper hopper, where raw chicken pellets are fed into the first rotary drum to initiate drying.

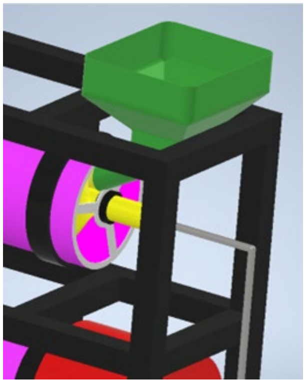


Figure 7: Hopper and entry section of the rotary drum.

The first-stage rotary drum (primary drying), shown in Figure 8, consists of a stationary drum, a rotating screw conveyor, a hot air system, and a back cover. In this stage, drying begins as hot air removes surface moisture from the chicken pellets through convective heat transfer. The pellets are transported approximately 7 m along the screw conveyor while being exposed to hot air at 70–80 °C. The rotating screw helps move and mix the pellets, allowing better contact with the hot air for more uniform drying. The air then passes through the pellet bed and exits through the end of the screw conveyor, carrying the evaporated moisture out of the system. The partially dried pellets are then discharged into the second-stage drum for further drying.

Figure 8: First-stage rotary drum assembly.

As the pellets descend into the second drum, they pass through a strip mechanism located at the drum outlet Figure 9. The strip functions to break up and redistribute the pellets, ensuring uniform exposure to the drying air.

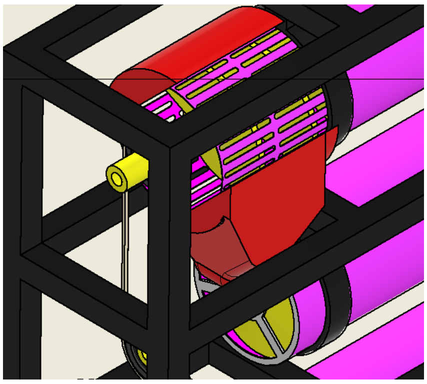


Figure 9: Outlet strip mechanism of the rotary dryer.

In the second drum (Figure 10), the pellets undergo further drying while traveling an additional 14 meters under controlled temperature. This stage provides the necessary residence time for the pellets to reach the desired moisture content, as specified by the client.

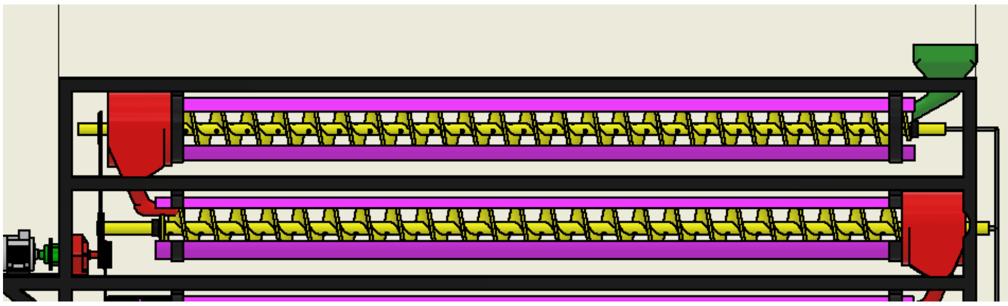


Figure 10: Second-stage rotary drum assembly.

At the end of the second drum, the pellets fall into the third drum for cooling Figure 11. In this final stage, the material is gradually cooled to near-ambient temperature, making it suitable for immediate packaging.

Figure 11: Third-stage rotary drum assembly.

The modular configuration of this system enables flexibility in operation. Drum speed and temperature settings can be adjusted based on the material type and the desired final product characteristics. The complete assembly consists of three drums, screw conveyors, a structural frame, motor mechanisms, and an integrated heating system.

3.3 Drying Rate Among the HPA Design

Figure 12 presents the moisture-reduction trends for HPA V1, V2, and V3, while Table 7 summarizes the corresponding drying rates and performance indicators compared with the reference dryers. The results demonstrate a progressive increase in drying rate from 0.1107 (V1) to 0.1166 (V2) and 0.1181 units/min (V3), indicating continuous improvement in moisture removal efficiency across the design iterations.

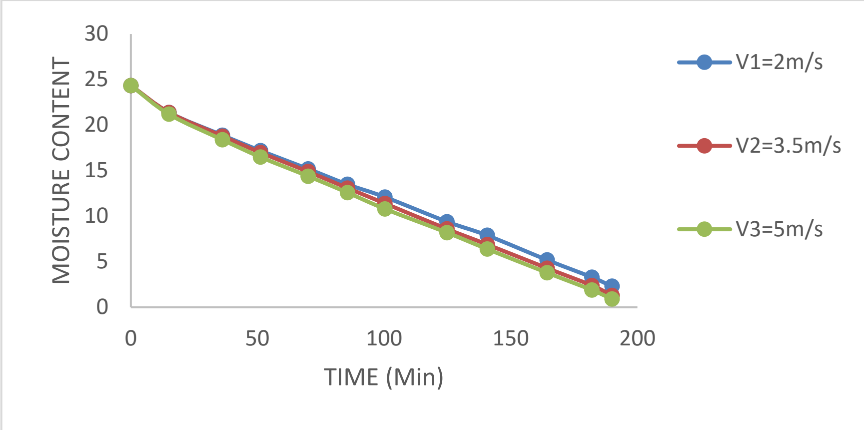


Figure 12: Moisture Content vs Time (V_1, V_2 and V_3).

Although all HPA configurations achieved the target final moisture content of approximately 9%, V3 exhibited the highest drying rate, confirming enhanced airflow distribution and thermal utilization within the three-stage system. The slight increase in time to reach 10% moisture (160–170 min) reflects controlled and stable drying behaviour rather than instability.

Table 7: Summarizes The Corresponding Drying Rates and Performance[22], [23].

DESIGN	DRYING RATE	FINAL MOISTURE	TIME TO REACH 10%
HPA V1	0.1107	~9%	160 min
HPA V2	0.1166	~9%	165 min
HPA V3	0.1181	~9%	170 min
REF 1	Lower	5% @ 200 min	Slower
REF 2	Lowest	>10% @ 200 min	Slowest

In contrast, Reference Dryer 1 [24] and Reference Dryer 2 [23] showed slower moisture reduction, with Ref 2 retaining more than 10% moisture even after 200 minutes. Overall, the comparative analysis verifies that the developed HPA rotary dryer, particularly V3, provides superior drying efficiency and improved process reliability under the evaluated operating conditions.

3.4 Drying Performance Validation

Table 8 presents a quantitative comparison between the mathematical modelling results and the experimental validation of the developed rotary dryer system. The mathematical model predicted a final moisture content of 8.5% within 165 minutes, whereas the experimental measurement indicated a final moisture content of approximately 9.0% after 170 minutes. The close agreement between the predicted and observed results demonstrates that the mathematical model can reliably describe the drying behaviour of the developed system.

The deviation in final moisture content was within 5–8%, while the variation in drying time remained below 5%. Such deviations are considered acceptable in thermal drying studies, where modelling predictions are typically validated against experimental measurements to evaluate reliability and predictive capability. Similar ranges of deviation between model predictions and experimental data have been reported in previous drying studies, confirming the applicability of simplified mathematical approaches for engineering design and performance evaluation [5], [25].

The predicted average drying rate of 0.115 unit/min closely matched the experimentally obtained value of 0.1181 unit/min, with an error margin of less than 5%, further confirming the consistency between analytical predictions and the observed drying kinetics. From an error analysis perspective, the small discrepancies between predicted and experimental results may be attributed to several practical factors, including heat losses to the surrounding environment, non-uniform airflow distribution inside the drum, and variations in feed material properties during the drying process. These factors are typically simplified or assumed constant in mathematical modelling, which may introduce minor deviations when compared with real operating conditions [5], [25], [26].

Furthermore, the V3 configuration demonstrated the most stable drying behaviour during the experimental trials. This improved performance can be attributed to enhanced airflow circulation and more uniform thermal distribution within the three-stage drying chamber, which promotes consistent moisture removal throughout the drying cycle. The structural configuration also contributes to a more stable material residence time within the drum, thereby improving drying efficiency.

Overall, the results indicate that the mathematical model provides a reliable predictive framework for evaluating the drying performance of the proposed rotary dryer system. The relatively small deviation between predicted and experimental results confirms the robustness of the modelling approach and supports its applicability as a design and performance assessment tool for industrial-scale rotary drying applications, consistent with established drying system validation practices reported in the literature [5], [25], [26].

Table 8: Comparison Between Mathematical Model, CFD Prediction and Experimental Results.

PARAMETER	MATHEMATICAL MODEL	EXPERIMENTAL RESULT	DEVIATION (%)
Initial Moisture (%)	70	70	–
Final Moisture (%)	8.5	9.0	5–8%
Drying Time (Min)	165	170	3–5%
Average Drying Rate (Unit/Min)	0.115	0.1181	<5%
Air Temperature (°C)	75	70–80	Acceptable

4. CONCLUSION

The design and development of the rotary dryer-based palletizing machine effectively overcame the limitations of conventional drying systems. The three-stage configuration with integrated cooling ensures efficient moisture reduction, stable operation, and consistent product quality. With a processing capacity of 0.5 T/h, the system fulfills industrial requirements for compactness, reliability, and energy efficiency. This study highlights the effectiveness of a systematic design approach in developing innovative and practical solutions for agro-industrial drying applications.

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