INTEGRATION OF RENEWABLE ENERGY SYSTEMS IN POULTRY FEED PRODUCTION MACHINES: A PATHWAY TO SUSTAINABLE AGRO-MECHANIZATION

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ABSTRACT

The increasing energy requirements and reliance on fossil fuels in Nigeria's poultry feed sector have intensified the need for sustainable energy alternatives. This review investigates the incorporation of renewable energy systems—namely solar photovoltaic, biogas, wind, and hybrid setups—into poultry feed production equipment as a means to achieve sustainable agro-mechanization. Drawing from recent research and technical documentation, the article assesses system architectures, operational efficacy, and energy efficiency of renewable-powered feed processes such as milling, mixing, pelleting, and drying. The results indicate that properly designed and locally adapted renewable-based systems can greatly decrease production costs, enhance energy reliability, and lessen environmental impact. The study finds that incorporating renewable sources into feed production is both technically achievable and financially advantageous, providing a promising path towards energy stability, climate action, and the growth of rural industries.

Keywords: Renewable energy integration, poultry feed production, solar photovoltaic, biogas, hybrid systems, sustainable agro-mechanization, Nigeria.

INTRODUCTION

Poultry farming provides reasonably priced animal protein and creates jobs for millions of people in both rural and urban areas (Chatterjee et al., 2022; Chatterjee & Rajkumar, 2015; Das et al., 2008), making it an important part of Nigeria's agricultural economy and food security framework. The poultry industry has grown rapidly over the years (Mottet & Tempio, 2017), but its viability is continuously threatened by rising production costs (Landes, 2004). Feed is the largest expense for poultry producers among the numerous elements causing the high production costs. According to empirical research, feed accounts for more than 60% of the total expenses related to poultry production in Nigeria, making it a crucial factor in determining profitability (Abdulrahman et al., 2022). Due to the significant rise in the cost of maize, soybeans, and other vital raw materials used in the production of chicken feed, the situation has gotten worse in recent years. Reports elucidate that the average price of a 25-kilogram bag of feed surged from approximately ₦3,600 in 2019 to a range of ₦8,500 to ₦10,000 by 2022, primarily driven by inflationary pressures, currency depreciation, and escalating energy expenses (InsideBusiness, 2022).

The problem of feed costs and the more general problem of energy availability are closely related. A steady and dependable power source is required for a number of mechanised operations involved in feed production, such as grinding, mixing, pelleting, and drying (Cheng & Sørensen, 2025; Rayhan, 2020). Access to electricity is still a major barrier in Nigeria, especially for small and medium-sized feed producers who work in rural areas. Slightly more than half of the population has access to electricity, according to the National Bureau of Statistics (2024); however, even in urban areas, the supply is unpredictable and prone to regular outages. Due to this situation, many feed millers are forced to rely heavily on diesel generators to run their equipment. The soaring price of diesel, which escalated from approximately ₦350 per litre in 2021 to over ₦1,700 by 2024, has exacerbated production costs and rendered the business environment increasingly challenging (Nairametrics, 2025). The entire productivity of poultry farms is negatively impacted by the unstable power supply, which not only interferes with operational continuity but also reduces feed quality and production efficiency.

In response to these challenges, there is a gradual pivot towards the adoption of renewable energy as an alternative power source for agro-processing and feed production within Nigeria (Yekini et al., 2024). Renewable energy technologies, such as biomass conversion, biogas units, and solar photovoltaic systems, offer more economical and environmentally friendly options for powering feed production equipment (Chel & Kaushik, 2011; Figaj, 2024; Kabeyi & Olanrewaju, 2022a; Lodhi et al., 2024a; Rocha-Meneses et al., 2023). Research conducted in Ado-Ekiti on an off-grid solar and biogas hybrid system demonstrated that renewable energy could effectively satisfy the power requirements of small agro-industrial facilities while simultaneously mitigating energy costs and carbon emissions (Sanni et al., 2019). Similarly, a study undertaken in Kaduna State revealed that a hybrid solar and diesel generator system employed by a commercial poultry farm resulted in a reduction of operating costs by nearly one-third in comparison to traditional diesel-powered systems (Mahmud et al., 2019). These results suggest that adding renewable energy systems to equipment used in the manufacturing of poultry feed has the potential to improve energy security, save costs, and promote environmental sustainability (Idogho et al., 2025; Onyenanu et al., 2015a). The manufacturing of poultry feed using renewable energy is a tangible step towards a more resilient and climate-friendly agriculture sector, in addition to a way to reduce energy costs.

Overview of Poultry Feed Production Machines

In light of the escalating demand for both fresh and hygienic feed, numerous poultry farmers and entrepreneurs are establishing poultry feed manufacturing facilities to produce their own feed, thereby reducing reliance on external market sources (Fabon, 2025). A poultry feed processing machine facilitates the transformation of raw materials into nutritionally balanced, easily digestible, and uniform feed pellets or mash specifically designed for broilers, layers, and breeders (Cheng & Sørensen, 2025; Fabon, 2025; Rayhan, 2020). Because they affect the end product's physical attributes, uniformity, and nutrient retention, feed production equipment is crucial to this process (Cheng & Sørensen, 2025; Stark, 2012; Vries & Gerrits, 2018). A series of devices for grinding, mixing, pelleting, drying, cooling, and packaging (Molina, 2022; Rayhan, 2020; Reese, 2016) is integrated into modern feed mills, guaranteeing that each stage improves feed conversion efficiency and bird performance. A number of factors, including feed formulation, energy availability, machine capacity, and operating costs, influence the selection of machinery in Nigeria. The efficiency and adaptability of these machines are critical in establishing the economic viability of poultry operations, as energy costs and power reliability continue to be major concerns (Dupas et al., 2023). Typically, a chicken feed production line is made up of multiple machines that operate sequentially:

Feed Grinder (Hammer Mill)

Feed grinding apparatus, frequently referred to as hammer mills or feed grinders, constitutes the initial machinery in the majority of feed processing lines (Vries & Gerrits, 2018). A hammer mill facilitates the reduction of whole grains such as maize, wheat, soybean, and rice bran into fine powder and various raw materials to the requisite particle dimensions essential for optimal mixing and pelleting processes (Kiarie & Mills, 2019). The operational mechanism involves high-velocity rotating hammers that strike the material within a chamber, with the particle size being regulated by both the screen aperture and the rotor velocity. Conventional commercial hammer mills utilized for feed processing typically function at rotor speeds ranging from approximately 1,000 to 1,800 revolutions per minute, with power requirement of 7.5 HP to 75 HP and motor power capacities spanning from 500 kg/hr to 10 TPH (Fabon, 2025); the throughput can fluctuate from tens of kilograms per hour to several tonnes per hour, contingent upon factors such as screen size, rotor configuration, and feed moisture content (Machinery, 2018).

Figure 1: Feed Grinder (Hammer Mill) (Machinery, 2018)

1.1 Feed Mixer

Mixers are used to produce a uniform distribution of nutrients and micro-ingredients throughout the meal. The most frequent types used in chicken feed manufacturing are horizontal ribbon mixers (U-tanks) and paddle mixers (Topspack, 2025). Ribbon mixers are ideal for blending dry ingredients, whereas paddle mixers are more suited to sticky or moist pre-mixing. Mixer capacity varies from a few hundred kilogrammes to several tonnes per batch (250 kg/batch to 5 ton/batch) (Fabon, 2025), with mixing times ranging from 2 to 8 minutes depending on load and ingredient density (Topspack, 2025). Agitator design, fill ratio, discharge speed, and residence time are all important aspects; inadequate mixing can result in nutrient fluctuation and decreased bird performance (Topspack, 2025).

Figure 2: Feed Mixer

1.2 Pellet Mill

Pellet mills, also known as pelletisers, compress mixed feed mash with rollers and force it through dies to create compact pellets (Olotu et al., 2024; Rayhan, 2020). There are two primary varieties: ring-die, which is utilised in bigger industrial mills (Fabon, 2025), and flat-die, which is typical for small to medium enterprises (Fabon, 2025). Die diameter, compression ratio, conditioning (steam, moisture, and temperature), roll surface finish, and throughput all affect pellet quality. Production rates vary according to the typical power of a pellet mill, which can range from a few kilowatts for small flat-die units to more than 100 kW for industrial ring-die systems (Onecpm, 2025b) requiring about 20HP-150HP of power (Fabon, 2025). Pelletising enhances feed handling, lowers particles, increases digestibility for certain formulations, and, by using conditioning heat, can lower pathogens. The key maintenance issues are precise feed conditioning, lubrication, and die and roller wear (Onyenanu et al., 2015b; Onyenanu et al., 2025; Ezechukwu et al., 2025).

Figure 3: Pellet Mill (Onecpm, 2025b)

1.3Cooler

After pelleting, pellet temperature and moisture are controlled by dryers and coolers. To bring product moisture down to safe storage levels, cabinet or drum dryers and mesh-belt (multi-layer) dryers are utilized (Zhang & Deng, 2017). After drying, a counterflow cooler (also known as a countercurrent cooler) is usually used to lower the pellet's temperature and eliminate any remaining moisture, preventing condensation and the growth of mould while it is being stored (Richipelletmachine, 2025; Rose Feedmills, 2025).

Figure 4: Cooler (Rose Feedmills, 2025)

1.4Crumbler

A post-pelleting device called a crumbler is used to break up huge pellets into smaller crumbles that are appropriate for females (Fabon, 2025). It uses two corrugated rollers that rotate in opposing directions to produce uniformly sized particles with few fines. For varying bird ages, adjusting the roller gap guarantees the right crumble size and texture. For chickens, crumbling enhances feed intake, digestion, and growth rate. Commercial-scale chick feed production is supported in Nigerian feed mills by automated crumblers that are integrated with pelleting lines to improve efficiency and feed consistency.

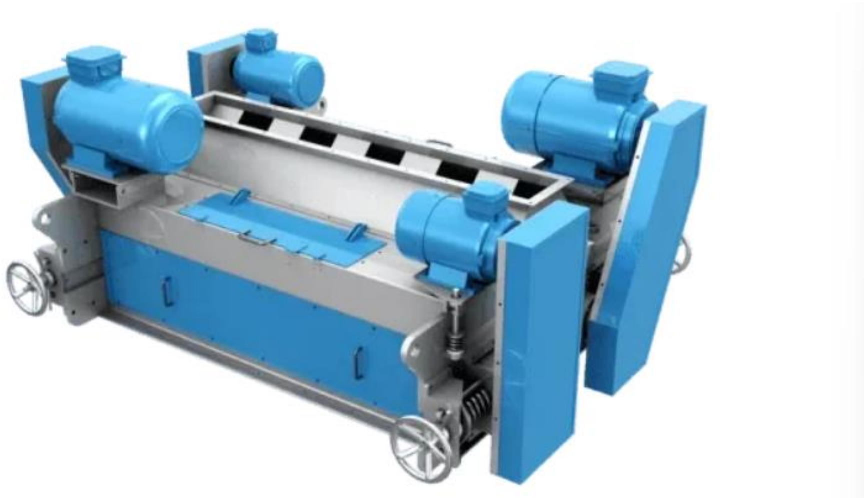

Figure 4: Pellet crumbler (Rose Feedmills, 2025)

1.5Automatic Bagging Machine

Poultry feed is automatically weighed, filled, and sealed into 25–50 kilogram bags using an automatic bagging system (Fabon, 2025). It lowers labour costs, increases packaging accuracy, and lowers the chance of contamination (Richipelletmachine, 2025). Conveyors and digital weighing are integrated into modern systems to guarantee precise feed quantities and consistent output. In Nigeria, switching from manual to automated bagging ensures hygienic packaging while increasing worker safety and productivity. Because of its accuracy and efficiency, the machine is essential for large-scale, sustainable chicken feed operations.

2. Renewable Energy Technologies Applicable to Feed Production

A sustainable strategy to lessen reliance on fossil fuels and cut operating expenses is to include renewable energy technology in the manufacture of chicken feed. Feed mills can provide a steady supply of energy, improve production efficiency, and lessen their environmental impact by utilizing locally accessible renewable resources. Key renewable energy technologies—solar photovoltaic systems, biomass and biogas, wind energy, and hybrid configurations (Ezechukwu et al., 2025; Madukasi et al., 2025; Onyenanu et al., 2024) —are described in the ensuing subsections, with an emphasis on their technical characteristics, suitability, and potential to increase energy resilience in the production of chicken feed.

3.1 Solar photovoltaic systems

In Nigeria, solar photovoltaic (PV) systems are the most developed and extensively used renewable energy source for small and medium-sized farms. From basic direct-coupled DC drives (PV array → DC motor) on low-power devices to complete PV + battery + inverter systems that provide alternating current for conventional three-phase motors, there are many different architectures available (Errouha et al., 2024; Shaukat et al., 2023; Tchouli et al., 2025). A charge controller/MPPT (maximum power point tracker) to optimise energy collection, inverter(s) for AC loads, PV modules, mounting and wiring, batteries for storage, and balance-of-system protection and switching are essential parts (Elbaset et al., 2019). Iterative sizing (array sizing, battery capacity, and inverter rating) is demonstrated in standard design guides and examples to satisfy continuous or intermittently scheduled loads. Sizing is contingent upon daily energy need, desired autonomy, solar resource, and inverter efficiency. For smaller grinders or conveyors, direct-drive DC solutions (BLDC or PMDC motors) can be very effective and prevent inverter losses (Gottipati, 2011); bigger pelletisers typically need inverter + three-phase motors or specific direct-drive designs from manufacturers (Wankhede et al., 2021). Although solar PV is quickly deployable and flexible, its intermittent nature necessitates scheduling or storage techniques for ongoing operations. Engineering manuals and case studies provide extensive documentation on practical PV design and sizing techniques.

3.2 Biomass and biogas systems

Biomass and anaerobic digestion (biogas) generate thermal energy or biogas for internal combustion engines or gasifiers using poultry litter, processing wastes, and agricultural residues (Santos Dalólio et al., 2017; Sasikumar et al., 2021). Poultry waste as digester feeding has been studied in Nigeria through feasibility studies and pilot projects, indicating possibilities for small-scale plant electricity and heat (Ogunsanya, 2023). Heat recovery, a biogas engine or combined heat and power (CHP) unit, gas handling and purification, and a digester (continuous or plug flow) are examples of typical systems (Han et al., 2016; Kabeyi & Olanrewaju, 2022b). Temperature, retention duration, feedstock feed rate, and volatile solids concentration all affect performance parameters (Ajuluchukwu et al., 2025; Nwigbo, 2025). While usable energy yields can generate continuous baseload power, feedstock consistency is crucial (Lodhi et al., 2024b; Nighoskar et al., 2025). Feedstock collection logistics, managing pathogens and ammonia in poultry litter, digester maintenance, and gas cleanup for engine longevity are some of the limitations. Where co-digestion (manure + crop residues) is feasible and poultry waste volumes are sufficient, biogas is appealing.

3.3 Wind energy (small turbines)

Although they are site-specific by nature, small wind turbines are quite mature in some agricultural sectors and can be profitable in areas with reliable wind regimes. Small turbines, typically ranging from 1 to 10 kW (Al-Bahadly, 2011), can supplement PV arrays in hybrids or power low to moderate loads. Higher capital and maintenance costs per kW compared to PV, siting/tower requirements, and generally low and irregular near-surface winds in various agro-regions are the key obstacles facing Nigerian poultry farms. Small turbines provide a constant supplement to the solar pattern when wind resources are sufficient, but they need to be carefully micro-sited and resistant to dust and storms.

3.4 Hybrid systems and microgrids

Hybrid systems increase dependability and cost-effectiveness by combining two or more sources (Agajie et al., 2024; A. Khan et al., 2025) (PV + battery + diesel or PV + biogas + battery). Techno-economic assessments demonstrate that hybrids can save operating costs compared to diesel-only systems and increase uptime when constructed with proper control and storage systems. Hybrids are commonly utilised in rural Nigerian farms. Microgrid approaches allow multiple farm loads (irrigation pumps, feed mills, cold rooms) to share generation and storage, improving utilization and financial viability (Ghasemi, 2018; Ukoba et al., 2024). The design and maintenance of hybrid systems are more complex and require integrated control, appropriate sizing, and consideration of lifespan costs (A. Khan et al., 2025; A. A. Khan et al., 2022).

Table 1: Summary of Previous Studies on Renewable Energy Applications in Poultry Feed Production and Agro-Processing Systems

Citations	Location	Technology	Key finding
Umar (2019)	Kaduna, Nigeria	PV + diesel + battery hybrid	The hybrid system lowered operating cost vs diesel-only and improved availability; modeled with HOMER.
Asumini et al. (2024)	Uganda	Solar-powered pelletizer (prototype)	Solar-driven pelletizer feasible for small-scale feed production; demonstrates DC motor/MPPT approach.
Chukwuma et al. (2021)	Anambra (bio-waste mapping)	Biomass/biogas potential	GIS assessment indicates poultry waste is a viable local resource for biogas in Nigerian states with concentrated production.
Emezirinwune et al., (2024)	Nigeria	Hybrid renewable energy systems (HRES)	Hybrid systems are technically promising for agriculture in Nigeria, but require financing and capacity building.

4 System integration approaches and engineering solutions

Designing renewable-powered feed production necessitates careful engineering considerations in power matching, controls, storage, retrofitting, and operations (Owuama, 2025; Onyenanu et al., 2021). Integration efforts must ensure that power supply matches machine demands through correct motor selection, control systems, and energy storage. Engineers also decide whether to modify old equipment or create purpose-built renewable-powered machinery. These technologies improve efficiency, lower operational costs, and promote sustainable, low-carbon poultry feed manufacturing.

4.1 Power matching: motor selection, gearing, and speed control

The main integration challenge is matching the electrical supply to mechanical loads. Determine the maximum and ongoing mechanical power requirements for each equipment (Avram & Xirouchakis, 2011; Li et al., 2011) (dryer, mixer, pellet mill, and grinder). For instance, depending on capacity and type, small hammer mills may require 2–10 kW, whereas pellet mills may require 5 kW (small flat-die) to 100+ kW (industrial ring-die). To prevent inverter losses, two popular approaches are to use direct DC/BLDC motors for smaller machines or to use inverter-friendly three-phase motors (and scale the inverter accordingly). Suppliers provide direct-drive pellet mills that make it easier to connect to electrical drives. Direct-drive designs, in which the motor shaft couples directly to the mill or pellet die, minimise maintenance and transmission losses. Variable frequency drives (VFDs) are crucial for soft starting, torque control, and energy savings in situations where torque and speed requirements differ (Saidur et al., 2012). VFDs can significantly lower power consumption and guard against mechanical stress during initiation. Prior to choosing motor/VFD ratings for retrofitting older equipment, consider shaft speeds, torque curves, and duty cycles.

4.2 Control systems: sensors, energy management, and demand scheduling

Rule-based energy management is a simple but effective approach: plan the most energy-intensive processes to coincide with peak renewable generation (for example, grind and pellet during solar daytime), while low-power operations (mixing, packaging) can run on stored energy. More complex controllers include MPPT for PV arrays, battery charge monitoring, automated start/stop for diesel backup, and load-shedding logic to prioritise critical processes. Sensors (current, voltage, temperature, and vibration) feed a programmable logic controller (PLC) or microcontroller for protection and predictive maintenance, while IoT telemetry enables remote monitoring and troubleshooting. Demand scheduling can improve renewable resource utilisation while reducing storage capacity requirements.

4.3 Energy storage choices: batteries, mechanical, and thermal storage

The most popular short-term storage solution is still batteries. While lithium-ion has a higher initial cost but a longer cycle life, a greater usable depth of discharge (Ning et al., 2003; Park et al., 2023), and a lower total cost of ownership per usable kWh, lead-acid is less expensive up front but has a limited cycle life and depth of discharge. On a lifecycle basis, lithium-ion frequently proves to be cost-effective for systems that see daily cycling and regular use. Dryers find thermal storage (hot water/thermal mass) appealing for thermal loads because it allows heat to be stored and released, reducing process energy requirements. At the agricultural level, larger-scale solutions and mechanical storage (flywheels) are rarely feasible. Select storage based on maintenance capacity, replacement schedule, depth of discharge, and necessary autonomy hours.

4.4 Retrofitting existing machines vs designing purpose-built renewable-driven machines

Although retrofitting has a reduced starting cost, it is frequently limited by inefficient coupling and speed/torque mismatches. VFDs and inverter-rated motors are frequently used to retrofit existing diesel or electric motor systems (Abdelhafez, 2020; Matthews, 2024); make sure the motor's insulation class, starting torque, and thermal capacity accommodate intermittent renewable input.

Although they may need a larger initial investment and local manufacturing capacity, purpose-built renewable-driven machines—such as direct-drive pelletisers with DC/BLDC motors—are more effective and easier to connect with PV arrays. While purpose-built systems can be piloted for long-term benefits, retrofits with standardised VFDs and appropriate protection offer practical scalability for Nigerian situations.

5. Performance evidence: technical and operational outcomes

Evaluating the integration of renewable energy technologies into poultry feed production requires not only theoretical justification but also empirical validation through field studies and technical benchmarks. Existing research and pilot projects across sub-Saharan Africa have demonstrated the practicality and measurable benefits of renewable energy applications in agro-mechanization systems. These studies emphasize the potential of solar photovoltaic (PV), biogas, and hybrid systems to reduce energy costs, improve uptime, and enhance production sustainability (Mahmud et al., 2019; Emezirinwune et al., 2024; Sanni et al., 2019).

Table 2: Summary of Reported Performance Outcomes of Renewable Energy Applications in Poultry Feed Production and Agro-Processing Systems

Study (year)	Tech	Scale	Reported throughput/machine	Energy metric (kWh/ton or % savings)	Uptime/reliability	Notes
(Umar, 2019)	PV + diesel + battery	Farm microgrid	Multiple farm loads incl. processing	Operating cost ↓ (modelled) 25–30% vs diesel	Improved availability vs diesel only	HOMER modelling; economic focus
Asumini et al. (2024)	Solar-driven pelletizer	Prototype (small)	Small pelletizer: tens kg/hr	System runs on PV + battery (no grid)	Feasible for small co-ops	Demonstration; useful for smallholder scale
Chukwuma et al. (2021)	Biomass mapping	Regional assessment	—	Biogas potential identified; energy densities vary	—	GIS shows feasibility where poultry density is high

The performance results of renewable energy technologies applied to the manufacture of chicken feed and other associated agro-processing processes are summarized in Table 2. Umar (2019), for instance, stated that a hybrid solar PV–diesel–battery system at Adora Farms, Kaduna, maintained better energy availability through optimized hybrid control modeled in HOMER, while achieving a 25–30% reduction in operating expenses when compared to a diesel-only configuration. In a similar vein, Asumini et al. (2024) successfully ran small-scale feed manufacturing machinery in Uganda using just photovoltaic energy, avoiding grid dependence, after designing and testing a solar-powered pelletizer prototype. By mapping the biomass and poultry waste resources in Anambra State, Chukwuma et al. (2021) offered additional spatial validation and showed a substantial correlation between the density of bio-waste and the technical viability of localized biogas energy generation. When taken as a whole, these results show that renewable-powered systems improve the operational resilience of small and medium-sized feed producers while simultaneously guaranteeing energy autonomy.

Table 3: Typical Power Requirements, Throughput, and Energy Considerations of Poultry Feed Production Machines

Machine	Typical power rating (kW)	Typical throughput (kg/hr)	Notes/energy considerations	Citations
Small hammer mill	2–15 kW	50–800 kg/hr	Power varies with screen size; suitable for PV + inverter or DC motor.	(Leonics, 2013)
Flat-die pelletizer (small)	3–15 kW	50–300 kg/hr	Can be direct-drive; good candidate for solar battery.	(Onecpm, 2025a)
Ring-die pelletizer (industrial)	50–250+ kW	1,000–6,000+ kg/hr	Requires robust three-phase supply and significant storage if off-grid.	(Onecpm, 2025a)
Mixer (ribbon/paddle)	1–30 kW	batch sizes 100–3,000 kg	Low duty but critical for quality; can be scheduled for solar peaks.	(Fandapelletmill, 2025; Feedpelletplants., 2025)
Dryer (mesh belt)	10–200+ kW thermal	depends on the dryer size	Thermal storage or biogas heat are cost-effective options.	(Billicomgroups, 2025; Dibio, 2025)

The appropriate energy characteristics and mechanical needs of poultry feed processing machines are revealed by an evaluation of equipment-level performance indicators in addition to the field evidence. The power requirements of common feed processing units vary significantly among machine types and operational scales, as shown in Table 3. For example, small hammer mills are suited for direct solar or inverter-fed drives because they typically require 2–15 kW and achieve throughput rates of 50–800 kg/hr (Leonics, 2013). While industrial ring-die pelletizers, which use 50–250+ kW and require a strong three-phase power infrastructure and substantial storage capacity, flat-die pelletizers, which operate at 3–15 kW, are perfect for small-scale solar–battery systems (Onecpm, 2025a). The electrical and thermal energy requirements of dryers and mixers also vary greatly, suggesting that appropriate load management and system scaling are essential for the best possible integration of renewable energy sources (Rayhan, 2020; Zhang & Deng, 2017).

CONCLUSION

A crucial step toward attaining sustainable agro-industrial growth is the incorporation of renewable energy systems into equipment used in the manufacturing of chicken feed. As demonstrated by this analysis, renewable technologies—specifically solar photovoltaic, biogas, and hybrid energy systems—provide both technically and financially realistic substitutes for traditional fossil fuel-based power sources. These solutions directly assist cost-effective and climate-resilient feed manufacturing operations by cutting greenhouse gas emissions, improving supply reliability, and lowering energy costs. According to the study, when appropriate load assessment, system size, and management strategies are used, well-designed renewable energy systems may effectively power the majority of feed production operations, including grinding, mixing, pelleting, cooling, and drying. Additionally, combining regional renewable resources like solar radiation and biogas produced from chicken manure offers the advantages of waste management and energy production. These collaborations enhance rural energy independence and promote circular economy ideas in the agriculture industry.

RECOMMENDATIONS

To fully integrate renewable energy technologies into chicken feed manufacturing, a comprehensive implementation strategy is recommended. The initial step is for policymakers to promote renewable energy adoption by providing low-interest loans, tax incentives, and subsidies to agro-processors. Next, to reduce dependence on imported equipment, research and development should focus on locally adaptable designs, such as dryers that utilize biogas and mixers powered by solar energy. Finally, to ensure energy reliability and balance between electrical and thermal needs, hybrid solutions combining solar PV and biogas systems should be prioritized.

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