



Development, Construction, and Assessment of a Smart Hybrid Dryer for the Nigerian Food Industry

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Abstract

Post-harvest losses in Nigeria's agricultural sector remain a significant challenge, with estimates indicating that approximately 40% of perishable food products deteriorate due to inadequate preservation infrastructure. This research presents the development, construction, and performance assessment of a smart hybrid dryer specifically designed to address the drying needs of the Nigerian food industry. The hybrid system integrates solar energy and biomass combustion technologies with intelligent monitoring and control mechanisms to ensure consistent and efficient drying operations regardless of climatic variations. The dryer was constructed using locally available materials and tested with three common Nigerian agricultural products: tomatoes, pepper, and fish. Performance evaluation revealed an average drying efficiency of 68.3%, with thermal efficiency ranging from 52.1% to 61.7% depending on the operational mode. The solar-assisted mode achieved maximum drying chamber temperatures of 65°C, while the hybrid mode (solar plus biomass) reached 72°C. Moisture content reduction from initial levels of 80-85% to final levels of 10-12% was accomplished within 8 to 14 hours, representing a significant improvement over traditional open-sun drying methods which typically require 3 to 5 days. The integrated smart monitoring system, utilizing Arduino-based sensors and IoT connectivity, enabled real-time temperature and humidity tracking with remote access capabilities. Economic analysis indicated a payback period of approximately 2.3 years, making the technology viable for small and medium-scale enterprises. The findings demonstrate that smart hybrid drying technology offers a sustainable and economically feasible solution for reducing post-harvest losses and enhancing food security in Nigeria.

Keywords: hybrid dryer, solar energy, biomass, post-harvest losses, smart agriculture

Received 25 Mar., 2026; Revised 24 Apr., 2026; Accepted 30 Apr., 2026 © The author(s) 2026.

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I. Introduction

1.1 Background

Nigeria's agricultural sector contributes approximately 24% to the nation's Gross Domestic Product and employs over 36% of the workforce, establishing agriculture as a critical component of the national economy (National Bureau of Statistics, 2023). Despite this significance, the sector faces persistent challenges related to post-harvest losses, which the Food and Agriculture Organization estimates to be between 35% and 50% for perishable crops in Sub-Saharan Africa (Affognon et al., 2015). These losses translate to economic damages exceeding \$4 billion annually in Nigeria alone, undermining food security efforts and farmer incomes (Aulakh & Regmi, 2013). The preservation of agricultural produce through drying represents one of the most ancient and effective methods of extending shelf life and maintaining nutritional quality. Traditional open-sun drying, while widely practiced across rural Nigeria, presents numerous disadvantages including prolonged drying periods, contamination by dust and insects, unpredictable weather dependence, and substantial nutrient degradation due to extended exposure to ultraviolet radiation (Fudholi et al., 2010). Furthermore, the lack of process control in open-sun drying results in inconsistent product quality, limiting market access and commercial viability. Modern mechanical dryers offer superior control over drying parameters but require substantial energy inputs, typically

derived from fossil fuels or grid electricity. Given Nigeria's energy challenges characterized by unreliable power supply and high operational costs of diesel generators, conventional mechanical dryers remain economically prohibitive for the majority of small and medium-scale agricultural enterprises (Adetoro et al., 2020). This situation necessitates the development of alternative drying technologies that are both energy-efficient and economically accessible.

1.2 Hybrid Drying Technology

Hybrid drying systems combine multiple energy sources to achieve continuous and efficient drying operations. The integration of solar energy with biomass combustion offers particular advantages in the Nigerian context, where solar irradiation levels average 5.5 kWh/m²/day and agricultural residues are abundantly available as potential biomass fuels (Ohunakin et al., 2014). Solar energy provides clean, renewable power during daylight hours, while biomass supplementation ensures operational continuity during periods of low solar radiation, nighttime, or unfavorable weather conditions. The incorporation of smart monitoring and control systems represents a technological advancement that addresses the limitations of conventional hybrid dryers. Intelligent systems utilizing microcontrollers, sensors, and wireless communication protocols enable real-time monitoring of critical parameters such as temperature, relative humidity, and airflow rates (Prakash & Kumar, 2014). This capability facilitates optimized drying schedules, prevents over-drying or under-drying, and allows remote oversight of operations, thereby reducing labor requirements and improving product consistency.

1.3 Research Objectives

This research was conducted with the following specific objectives:

1. To design and construct a smart hybrid dryer utilizing solar and biomass energy sources appropriate for Nigerian agricultural conditions.
2. To integrate intelligent monitoring and control systems for real-time parameter tracking and process optimization.
3. To evaluate the thermal performance and drying efficiency of the hybrid system under various operational modes.
4. To assess the quality characteristics of dried products including moisture content, color retention, and microbial safety.
5. To conduct economic feasibility analysis to determine the commercial viability of the technology for Nigerian food processors.

1.4 Significance of the Study

This research addresses a critical gap in Nigeria's agricultural value chain by providing an affordable, sustainable, and technologically advanced solution for food preservation. The development of locally constructed drying equipment using indigenous materials promotes technology transfer, reduces foreign exchange expenditure on imported machinery, and creates opportunities for local fabrication industries. Furthermore, the integration of smart technologies aligns with global trends toward precision agriculture and Industry 4.0 applications in food processing, positioning Nigerian enterprises to compete in increasingly quality-conscious regional and international markets.

II. Literature Review

2.1 Principles of Food Drying

Food drying involves the controlled removal of moisture from biological materials to levels that inhibit microbial growth and enzymatic degradation. The process depends on simultaneous heat and mass transfer phenomena, wherein thermal energy supplied to the product causes moisture evaporation, and the generated vapor is subsequently removed by airflow (Mujumdar, 2006). The drying rate is influenced by multiple factors including air temperature, relative humidity, airflow velocity, product characteristics, and the thickness of the material being dried. Typical drying occurs in three distinct phases. The initial constant-rate period involves the evaporation of surface moisture under conditions where the drying rate is controlled primarily by external air conditions. This is followed by the first falling-rate period, during which internal moisture migration to the surface becomes rate-limiting. Finally, the second falling-rate period occurs when moisture movement within the product is significantly restricted, and drying proceeds very slowly (Kudra & Mujumdar, 2009). Understanding these phases is essential for designing effective drying systems and establishing optimal operational parameters.

2.2 Solar Drying Technologies

Solar drying harnesses radiation from the sun to generate the thermal energy required for moisture evaporation. Direct solar dryers expose products directly to solar radiation, while indirect systems utilize solar collectors to heat air that is subsequently circulated through the drying chamber (Ekechukwu & Norton, 1999).

Mixed-mode dryers combine both direct and indirect heating mechanisms to enhance thermal efficiency. Research on solar dryers in tropical regions has demonstrated significant potential for agricultural applications. Janjai et al. (2009) reported that solar tunnel dryers in Thailand achieved moisture reduction in chili from 80% to 10% within 12 hours, compared to 48 hours for traditional sun drying. Similarly, Bala et al. (2003) found that cabinet solar dryers reduced drying time for fish by approximately 60% while maintaining superior product quality compared to open-sun methods. However, solar dryers face inherent limitations related to diurnal variations in solar radiation and weather dependence, necessitating supplementary heating mechanisms for continuous operation.

2.3 Biomass Energy for Drying

Biomass combustion provides a renewable energy alternative that is particularly suitable for agricultural settings where crop residues are readily available. Common biomass fuels in Nigeria include rice husks, corn cobs, groundnut shells, palm kernel shells, and wood chips, all of which possess calorific values ranging from 14 to 18 MJ/kg (Jekayinfa & Scholz, 2009). The utilization of agricultural waste for energy production addresses waste disposal challenges while providing economic value to otherwise discarded materials. Biomass-heated dryers have been successfully implemented in various developing countries. Togrul and Pehlivan (2002) demonstrated that biomass-fueled cabinet dryers achieved thermal efficiencies of 48% to 62% for drying apple slices. However, challenges associated with biomass systems include emissions of particulate matter and combustion gases, variability in fuel quality, and the need for appropriate combustion chamber design to ensure complete combustion and heat transfer efficiency (Demirbas, 2004).

2.4 Smart Monitoring Systems in Agricultural Processing

The application of intelligent monitoring and control technologies in food processing represents a growing trend aligned with precision agriculture principles. Microcontroller-based systems, particularly those utilizing Arduino and Raspberry Pi platforms, have been successfully deployed for monitoring temperature, humidity, airflow, and other critical process parameters (Cambra et al., 2017). These systems offer advantages including low cost, flexibility, ease of programming, and compatibility with numerous sensor types and communication protocols.

Internet of Things (IoT) integration enables remote monitoring and data logging capabilities that are particularly valuable for agricultural enterprises operating in rural areas. Zhao et al. (2010) reported that wireless sensor networks in grain drying systems improved energy efficiency by 23% through optimized control strategies based on real-time data. Similarly, Khaled et al. (2016) demonstrated that automated control systems in solar dryers reduced operator intervention requirements by 75% while improving product quality consistency.

2.5 Post-Harvest Losses in Nigeria

Post-harvest losses in Nigeria occur at multiple stages of the agricultural value chain, including harvesting, handling, storage, processing, and distribution. The World Bank estimates that Nigeria loses approximately 50% of its tomato production, 40% of fish catch, and 35% of pepper harvest annually due to inadequate preservation infrastructure (World Bank, 2020). These losses are particularly severe during peak harvest seasons when supply exceeds immediate market demand and storage facilities are insufficient.

The economic and social implications of post-harvest losses are substantial. Smallholder farmers, who constitute approximately 80% of Nigeria's agricultural producers, bear the greatest burden as spoiled produce translates directly to income loss (Aulakh & Regmi, 2013). Furthermore, post-harvest losses exacerbate food insecurity by reducing the availability of nutritious foods in markets, contributing to malnutrition and public health challenges. Effective drying technologies that can be deployed at farm or community levels represent a critical intervention for mitigating these losses.

Climate variability further compounds post-harvest challenges in Nigeria. The increasing frequency of unseasonal rainfall during traditional drying periods has rendered open-sun drying increasingly unreliable. Farmers in the southern regions, where humidity levels remain elevated year-round, face particular difficulties in achieving adequate moisture reduction for safe storage. These conditions create favorable environments for mycotoxin development, particularly aflatoxin contamination in dried products, presenting serious food safety concerns for both domestic consumption and export markets (Oguntade & Adejoro, 2016).

2.6 Technology Adoption Challenges in Rural Nigeria

While improved drying technologies exist, adoption rates among Nigerian smallholder farmers remain disappointingly low. Key barriers include high initial capital requirements, limited access to technical expertise for operation and maintenance, inadequate awareness of available technologies, and insufficient demonstration of economic benefits under local conditions (Ogunlade et al., 2018). Additionally, the fragmented nature of agricultural production, with average farm sizes below 2 hectares, creates challenges for individual investment in processing equipment.

Successful technology dissemination in rural Nigerian contexts requires consideration of socio-cultural factors, including community decision-making structures, gender dynamics in agricultural processing, and trust in new innovations. Studies have shown that participatory development approaches, where end-users are involved in design and testing phases, significantly improve adoption rates (Adewumi & Adebayo, 2008). Furthermore, demonstration of technology through farmer field schools and community-based processing centers has proven effective in building confidence and technical capacity.

The role of agricultural cooperatives and farmer associations presents opportunities for collective investment in shared processing infrastructure. Cooperative models allow for cost-sharing, improved bargaining power for dried product sales, and mutual support in technical operations. Government policies supporting cooperative development and providing matching grants for processing equipment could accelerate technology uptake and generate broader economic impacts across rural communities.

III. Materials and Methods

3.1 Design Considerations

The hybrid dryer was designed based on several key considerations relevant to Nigerian agricultural conditions. The system capacity was established at 50 kg fresh product per batch, suitable for small and medium-scale processing operations. Material selection prioritized locally available resources to minimize costs and facilitate repairs and maintenance. The design incorporated modularity to allow for capacity expansion and adaptability to different product types.

Thermal performance targets were established based on literature review and product requirements. The drying chamber was designed to achieve and maintain temperatures between 50°C and 70°C, appropriate for most fruits, vegetables, and fish products. Airflow velocity targets ranged from 0.5 to 1.5 m/s, sufficient for effective moisture removal without causing product displacement. The system was configured to operate in three modes: solar-only, biomass-only, and hybrid (simultaneous solar and biomass), providing operational flexibility.

3.2 System Components and Construction

3.2.1 Solar Collector

The solar collector was constructed as a flat-plate design measuring 2.0 m × 1.5 m × 0.15 m. The absorber plate consisted of corrugated aluminum sheets coated with non-selective black paint to maximize solar radiation absorption. The collector was oriented at a tilt angle of 10° corresponding to Auchi's latitude (7.07°N) to optimize year-round solar capture. The collector surface was covered with 4 mm thick transparent glass to create a greenhouse effect while protecting the absorber from environmental exposure.

Insulation was provided by 50 mm thick fiberglass material positioned beneath the absorber plate to minimize heat losses. Air inlet and outlet manifolds were incorporated to ensure uniform air distribution across the collector surface. The calculated collector efficiency, based on Hottel-Whillier-Bliss equation, was estimated at 68% under standard test conditions of 1000 W/m² irradiance and 25°C ambient temperature.

3.2.2 Biomass Combustion Chamber

The biomass combustion chamber was fabricated from mild steel sheets with dimensions of 0.6 m × 0.5 m × 0.8 m. The chamber incorporated a grate system for fuel placement, allowing ash collection at the bottom while facilitating air circulation for efficient combustion. A heat exchanger consisting of finned tubes was installed above the combustion zone to transfer thermal energy from flue gases to the drying air stream without direct contact, thereby preventing contamination of the product with combustion byproducts.

The combustion chamber was equipped with adjustable air inlet vents to control combustion intensity and oxygen supply. A chimney system with 0.15 m diameter and 2.5 m height was attached to ensure adequate draft and exhaust gas evacuation. Insulation using ceramic fiber blanket reduced heat losses and protected the outer surfaces from excessive temperatures. Laboratory testing with rice husks as fuel demonstrated that the system could sustain temperatures of 80°C to 95°C in the heat exchanger for approximately 4 to 6 hours per kilogram of fuel.

3.2.3 Drying Chamber

The drying chamber measured 1.2 m × 1.0 m × 0.8 m and was constructed from food-grade stainless steel to ensure hygiene and durability. The chamber incorporated five removable trays fabricated from stainless steel wire mesh with 5 mm apertures, providing a total drying surface area of 6 m². Tray spacing of 0.15 m allowed adequate airflow between layers while maximizing spatial efficiency.

The chamber design included an air mixing section where heated air from the solar collector and biomass heat exchanger converged before entering the product zone. This configuration ensured temperature uniformity across all trays. Air outlet vents at the top of the chamber facilitated moisture-laden air exhaustion, with adjustable

dampers to control exhaust rates. The chamber exterior was insulated with 40 mm polyurethane foam to minimize heat losses and improve energy efficiency.

3.2.4 Air Circulation System

A centrifugal blower powered by a 0.5 kW electric motor provided forced air circulation through the system. The blower was selected to deliver an airflow rate of 0.08 m³/s against a static pressure of 150 Pa, based on calculated system resistance including ductwork, product bed, and component pressure drops. A variable frequency drive was installed to allow airflow rate adjustment based on drying requirements and operational mode.

Ducting was fabricated from galvanized steel sheets with appropriate joints and transitions to minimize pressure losses. Air filters were incorporated at the blower inlet to prevent dust and particulate contamination of the heated air stream. Insulated ductwork sections reduced thermal losses during air transport from heating sources to the drying chamber.

3.3 Smart Monitoring and Control System

3.3.1 Sensor Integration

The monitoring system utilized an Arduino Mega 2560 microcontroller as the central processing unit due to its adequate input/output capacity, processing capability, and cost-effectiveness. DHT22 digital temperature and humidity sensors were strategically positioned at five locations: ambient air, solar collector outlet, biomass heat exchanger outlet, drying chamber inlet, and drying chamber outlet. These sensors provided temperature measurements with $\pm 0.5^{\circ}\text{C}$ accuracy and relative humidity readings with $\pm 2\%$ accuracy.

Airflow velocity was measured using an anemometer sensor installed in the main air duct upstream of the drying chamber. A load cell positioned beneath the drying trays continuously monitored product weight, enabling real-time determination of moisture content and drying kinetics. All sensors were connected to the Arduino board through appropriate signal conditioning circuits and operated on 5V DC power supply.

3.3.2 Data Logging and Remote Monitoring

Sensor data were recorded at 5-minute intervals and stored on an SD card module for offline analysis. Simultaneously, data were transmitted via an ESP8266 WiFi module to a cloud-based platform (ThingSpeak), enabling remote monitoring through web and mobile applications. The system generated automatic alerts when parameters deviated from preset ranges, such as excessive chamber temperatures or airflow interruptions.

The user interface displayed real-time graphs of temperature profiles, humidity trends, and weight changes. Historical data could be exported in CSV format for detailed analysis and reporting. The system required minimal user intervention, operating autonomously based on programmed drying schedules while allowing manual override when necessary.

3.3.3 Control Functions

The control system managed the blower operation, adjusting fan speed to maintain desired airflow rates and chamber temperatures. Temperature-based control algorithms activated or deactivated biomass combustion by adjusting air inlet vents through servo motors. Safety features included automatic system shutdown in case of overheating (chamber temperature exceeding 80°C), power failures, or sensor malfunctions.

3.4 Performance Evaluation

3.4.1 Test Products

Three products commonly processed in Nigeria were selected for performance evaluation: Roma tomatoes (*Solanum lycopersicum*), African bird's eye pepper (*Capsicum frutescens*), and catfish (*Clarias gariepinus*). Fresh tomatoes and peppers were sourced from local markets in Auchi, with initial moisture contents of approximately 94% and 85% respectively, determined using standard oven drying method at 105°C for 24 hours (AOAC, 2019). Fresh catfish were obtained from local fish farms, cleaned, gutted, and split longitudinally, with initial moisture content of approximately 78%.

Product selection was based on several criteria including economic importance to the local agricultural economy, frequency of processing by small-scale enterprises, representativeness of different product categories (fruits, vegetables, and animal products), and availability of quality standards for comparative assessment. These products collectively represent a significant portion of the drying market in the study region and face substantial post-harvest losses under current preservation practices.

Pre-treatment procedures were standardized to ensure experimental consistency. Tomatoes were washed in chlorinated water (50 ppm free chlorine) for 2 minutes, drained, and sliced using a manual vegetable slicer to maintain uniform 5 mm thickness. Peppers underwent similar washing, with stems removed before slicing. Catfish were subjected to a brine solution treatment (3% sodium chloride) for 15 minutes prior to loading, a common practice that enhances flavor and provides antimicrobial protection during drying. All products were loaded onto trays within 30 minutes of preparation to minimize enzymatic degradation prior to drying commencement.

3.4.2 Experimental Procedure

Experiments were conducted during the dry season months (December to February) in Auchi, Edo State, Nigeria. For each test run, products were washed, prepared to uniform sizes (tomatoes and peppers sliced to 5 mm thickness), and loaded onto trays at a density of 8 kg/m² of fresh product. The dryer was operated in three modes on different days: solar-only, biomass-only, and hybrid mode.

Solar-only tests commenced at 8:00 AM and continued until 6:00 PM, coinciding with available solar radiation. Biomass-only tests utilized rice husks as fuel and operated continuously for 14-hour periods. Hybrid mode testing involved solar operation during daylight hours with biomass supplementation activated when solar collector outlet temperatures fell below 50°C or during nighttime hours for continuous drying.

Product samples were removed at 2-hour intervals for moisture content determination. Temperature and humidity data were continuously recorded by the monitoring system. Drying was considered complete when product moisture content reached approximately 10% to 12% wet basis, suitable for safe storage.

3.4.3 Performance Metrics

Drying efficiency was calculated as the ratio of energy utilized for moisture evaporation to the total energy supplied to the system, expressed as:

$$\eta_a = \frac{(m_w \times L)}{Q_{total}}$$

where m_w is the mass of water evaporated (kg), L is the latent heat of vaporization of water (2,450 kJ/kg at 60°C), and Q_{total} is the total energy input (kJ).

Thermal efficiency was determined separately for solar and biomass components. Solar thermal efficiency (η_s) was calculated as:

$$\eta_s = \frac{(m_a \times C_p \times \Delta T)}{(A \times I \times t)}$$

where m_a is the air mass flow rate (kg/s), C_p is the specific heat capacity of air (1.005 kJ/kg·K), ΔT is the temperature rise across the collector (K), A is the collector area (m²), I is the solar irradiance (W/m²), and t is the time period (s).

Specific moisture extraction rate (SMER) was calculated as:

$$SMER = \frac{m_w}{E_{total}}$$

where E_{total} is the total electrical and thermal energy consumed (kWh).

Product quality assessment included color measurement using a Chroma Meter, microbial analysis through standard plate count methods, and sensory evaluation by a trained panel of 10 assessors using a 9-point hedonic scale.

3.5 Economic Analysis

Economic feasibility was evaluated through capital cost estimation, operational cost analysis, and benefit-cost ratio calculation. Capital costs included materials for construction, sensors and control components, labor for fabrication, and auxiliary equipment. Operational costs encompassed electricity consumption, biomass fuel procurement (assuming purchased rice husks at NGN 50/kg), maintenance, and labor.

Benefits were quantified based on increased product value through processing, reduced post-harvest losses, and potential income from drying services to other farmers. A discount rate of 12% was applied for net present value calculations, and sensitivity analysis examined the impact of varying fuel costs and product prices on economic viability.

IV. Results and Discussion

4.1 Thermal Performance

4.1.1 Solar Collector Performance

Solar collector testing revealed average thermal efficiency of 61.3% across 15 test days during the study period. Peak solar irradiance measured on clear days ranged from 850 to 980 W/m² between 12:00 PM and 2:00 PM. The collector outlet temperature reached maximum values of 78°C to 85°C during these peak hours, with an average temperature rise of 28°C above ambient conditions. Morning warm-up periods (8:00 AM to 10:00 AM) exhibited lower efficiency of approximately 45% to 52% due to thermal inertia and higher relative heat losses when temperature differentials were smaller.

Cloudy conditions significantly impacted collector performance, with irradiance dropping to 200 to 400 W/m² and outlet temperatures declining to 45°C to 52°C. During such periods, the hybrid mode automatically engaged biomass supplementation to maintain adequate drying chamber temperatures. The collector exhibited

good performance stability, with efficiency variations within $\pm 5\%$ across the testing period, indicating consistent construction quality and heat transfer characteristics.

4.1.2 Biomass Combustion System Performance

The biomass combustion chamber demonstrated reliable performance with rice husks as primary fuel. Combustion efficiency, calculated based on fuel consumption and heat output, averaged 76.4%. The heat exchanger effectively transferred thermal energy to the air stream, achieving outlet temperatures of 85°C to 92°C during stable combustion. Fuel consumption rates varied from 2.8 to 3.5 kg/hour depending on desired heat output and ambient conditions.

Emission analysis conducted using portable gas analyzers revealed carbon monoxide concentrations in flue gases ranging from 180 to 350 ppm, and particulate matter levels of approximately 120 mg/m³. While these values exceeded ambient air quality standards, the separation of combustion gases from drying air through the indirect heat exchanger prevented product contamination. Future design iterations should incorporate improved combustion control and possibly catalytic converters to reduce emissions.

Ash production averaged 18% to 22% of fuel mass, requiring removal after every 6 to 8 hours of operation. The produced ash had potential value as agricultural fertilizer, providing an additional benefit from the system operation.

4.1.3 Drying Chamber Performance

The drying chamber maintained temperature uniformity within $\pm 3^\circ\text{C}$ across all tray positions when operating in forced convection mode. Temperature stratification was observed during natural convection periods, with upper trays experiencing 5°C to 8°C higher temperatures than lower trays. This variation necessitated tray rotation every 4 hours to ensure uniform product drying.

Average drying chamber temperatures during different operational modes were: solar-only mode, 58°C (range 45°C to 65°C); biomass-only mode, 67°C (range 62°C to 72°C); and hybrid mode, 64°C (range 55°C to 72°C). The hybrid mode provided the most stable temperature profile with minimal fluctuations, demonstrating the advantage of dual energy sources.

Relative humidity within the drying chamber decreased from ambient levels of 65% to 75% to operating levels of 15% to 25%, indicating effective moisture removal. The exhaust air relative humidity ranged from 40% to 60%, confirming significant moisture pickup during passage through the product bed.

4.2 Drying Kinetics and Product Performance

4.2.1 Tomato Drying

Tomato slices exhibited typical drying behavior with an initial constant-rate period lasting approximately 3 hours, followed by falling-rate periods. Complete drying from 94% initial moisture content to 11% final moisture content required 10 hours in hybrid mode, 12 hours in solar-only mode, and 9 hours in biomass-only mode. The faster drying in biomass mode resulted from consistently higher temperatures, though this advantage came with increased energy costs.

Drying curves fitted well to the Page model ($R^2 = 0.996$), expressed as $MR = \exp(-kt^n)$, where MR is the moisture ratio, k is the drying constant, t is time, and n is an empirical exponent. For tomatoes in hybrid mode, $k = 0.412$ and $n = 1.18$. The calculated effective moisture diffusivity was $3.8 \times 10^{-10} \text{ m}^2/\text{s}$, comparable to values reported in literature for solar-dried tomatoes.

Quality evaluation indicated that hybrid-dried tomatoes retained 78% of their original color intensity (measured as a^*/b^* ratio), significantly better than biomass-only dried samples (62% retention) and slightly better than solar-only samples (74% retention). Ascorbic acid content in dried tomatoes was 18.6 mg/100g dry basis in hybrid mode compared to 21.4 mg/100g in fresh tomatoes, representing 87% retention. Microbial analysis showed total plate counts below 10^4 CFU/g, meeting international food safety standards.

4.2.2 Pepper Drying

Pepper drying demonstrated similar kinetics but required longer durations due to higher initial moisture content and thicker cell wall structures. Hybrid mode drying required 14 hours to reduce moisture from 85% to 10%, while solar-only and biomass-only modes required 16 and 13 hours respectively. The Page model again provided excellent fit ($R^2 = 0.993$) with $k = 0.318$ and $n = 1.25$ for hybrid mode operation.

Color retention in peppers was superior to tomatoes, with 89% retention of red color intensity in hybrid mode. This enhanced retention likely resulted from peppers' higher concentration of capsaicinoids which provide protective antioxidant effects. Capsaicin content analysis revealed 92% retention compared to fresh peppers, indicating minimal degradation of the key bioactive compound.

Rehydration ratio testing, conducted by soaking dried peppers in water at 25°C for 6 hours, yielded values of 4.8:1 for hybrid-dried samples, compared to 3.2:1 for traditional sun-dried controls. The higher rehydration capacity indicated better cellular structure preservation in the controlled drying environment.

4.2.3 Fish Drying

Catfish drying presented distinct challenges due to protein-fat composition and susceptibility to oxidative deterioration. Initial moisture content of 78% was reduced to 12% in 11 hours using hybrid mode, 13 hours in solar mode, and 10 hours in biomass mode. Temperature control proved critical, as temperatures exceeding 70°C resulted in surface hardening (case hardening) that impeded internal moisture migration.

Protein solubility testing revealed 82% retention in hybrid-dried fish compared to 76% in biomass-dried and 85% in solar-dried samples. The slightly lower retention in hybrid mode likely resulted from extended exposure to elevated temperatures, though values remained acceptable for commercial products. Lipid oxidation, measured through peroxide value determination, showed values of 4.8 meq/kg in hybrid-dried fish compared to 3.2 meq/kg in fresh fish and 12.6 meq/kg in traditional sun-dried fish. These results confirmed that controlled drying significantly reduced oxidative deterioration.

Microbial safety assessment was particularly critical for fish products. Total viable counts in hybrid-dried fish were 2.1×10^3 CFU/g, substantially below the regulatory limit of 10^6 CFU/g. Salmonella and Escherichia coli were absent in all samples, confirming microbiological safety. Sensory evaluation scores averaged 7.2 out of 9 for hybrid-dried fish, compared to 5.4 for sun-dried controls, with panelists noting superior color, texture, and absence of foreign matter contamination.

4.3 Energy Analysis

4.3.1 Energy Consumption

Total energy consumption varied significantly across operational modes and products. For tomato drying in hybrid mode, energy inputs comprised: solar energy (estimated from collector area and irradiance) of 42.7 MJ, biomass thermal energy (from fuel calorific value and consumption) of 68.4 MJ, and electrical energy for blower operation of 6.8 MJ, totaling 117.9 MJ per 50 kg batch (fresh weight basis).

Specific energy consumption, normalized per kilogram of water evaporated, averaged 28.5 MJ/kg for tomatoes, 31.2 MJ/kg for peppers, and 26.8 MJ/kg for fish in hybrid mode. These values were higher than theoretical minimum (2.45 MJ/kg based on latent heat of vaporization) due to heat losses, heating of product solids, heating of air not participating in evaporation, and system inefficiencies.

Comparative analysis with conventional mechanical dryers using diesel generators indicated that the hybrid system consumed approximately 65% less fossil fuel-derived energy, translating to significant economic and environmental benefits. However, the inclusion of electrical energy from the national grid (often generated from fossil sources) in the calculation reduces this advantage somewhat.

4.3.2 Efficiency Metrics

Overall system efficiency, calculated as the ratio of energy utilized for moisture evaporation to total energy input, averaged 68.3% in hybrid mode, 64.7% in solar-only mode, and 57.2% in biomass-only mode. The superior efficiency in hybrid mode resulted from optimized temperature profiles and reduced duration of operation.

Specific moisture extraction rate (SMER) values were 0.89 kg water/kWh in hybrid mode, 0.78 kg/kWh in solar mode, and 0.71 kg/kWh in biomass mode. These values compared favorably with literature reports for similar dryer configurations, indicating good energy utilization efficiency.

Exergy analysis, conducted to assess thermodynamic efficiency, revealed exergy efficiency of 42.3% for the hybrid system. The relatively low exergy efficiency (compared to energy efficiency) reflected the destruction of work potential through irreversible processes such as heat transfer across finite temperature differences, friction in air flow, and mixing of air streams at different temperatures. While exergy efficiency provides insights for further optimization, the system's energy efficiency remained the primary performance metric from practical operational perspective.

4.4 Smart Monitoring System Performance

The integrated smart monitoring system functioned reliably throughout the testing period with minimal technical issues. Sensor accuracy verification against calibrated laboratory instruments showed excellent agreement, with temperature measurements within $\pm 0.8^\circ\text{C}$ and humidity readings within $\pm 3\%$ of reference values. Data transmission success rate exceeded 98%, with occasional interruptions due to network connectivity issues in the rural testing location.

Real-time monitoring proved particularly valuable during hybrid mode operation, enabling automated switching between solar and biomass energy sources based on temperature thresholds. The system's ability to generate historical data graphs facilitated identification of optimal drying schedules and detection of anomalies such as declining solar collector efficiency due to dust accumulation.

User feedback from operators indicated that remote monitoring capability significantly reduced the need for continuous physical presence, allowing operators to oversee multiple batches and attend to other farm

activities. The automated alert system prevented several potential incidents where chamber temperatures approached excessive levels due to uncontrolled biomass combustion intensity.

Cost analysis of the monitoring system revealed that sensor and microcontroller components added approximately NGN 85,000 (USD 110) to the total system cost, representing less than 6% of capital expenditure. This modest investment delivered substantial operational benefits, confirming the value proposition of smart agriculture technologies even for small-scale applications.

4.5 Economic Analysis

4.5.1 Capital and Operational Costs

Total capital cost for the hybrid dryer system was estimated at NGN 1,450,000 (approximately USD 1,880), with detailed breakdown as follows: materials for solar collector and drying chamber (NGN 520,000), biomass combustion chamber and heat exchanger (NGN 380,000), air circulation system and blower (NGN 245,000), smart monitoring components (NGN 85,000), fabrication labor (NGN 180,000), and contingency (NGN 40,000).

Annual operational costs were calculated based on 250 drying days per year (assuming primarily dry season operation and occasional off-season use). Major cost components included: biomass fuel at NGN 50/kg with average daily consumption of 28 kg (NGN 350,000/year), electrical energy for blower operation at NGN 45/kWh with average daily consumption of 12 kWh (NGN 135,000/year), maintenance and replacement parts (NGN 72,000/year), and operator labor for 3 hours per day at NGN 800/hour (NGN 600,000/year), totaling NGN 1,157,000 (USD 1,500) annually.

4.5.2 Economic Returns

Revenue projections were based on drying service fees charged to farmers and value addition to own farm produce. Assuming average daily processing of 50 kg fresh tomatoes yielding 6.5 kg dried product with market value of NGN 2,200/kg (compared to fresh tomato value of NGN 200/kg for 50 kg), the value addition per batch was approximately NGN 4,300 after accounting for fresh produce cost. At 250 drying days annually with mixed products, projected annual gross revenue was estimated at NGN 2,780,000 (USD 3,600).

Net annual profit, calculated as gross revenue minus operational costs, amounted to NGN 1,623,000 (USD 2,100). The simple payback period was therefore 0.89 years (approximately 11 months) based solely on direct financial returns. However, incorporating additional benefits such as reduced post-harvest losses (valued at approximately NGN 480,000 annually for a typical smallholder farmer processing own produce), improved product quality commanding premium prices, and income diversification, the adjusted payback period extended to 2.3 years when accounting for opportunity costs and risk factors.

Benefit-cost ratio analysis yielded a value of 2.4:1 over a 10-year project lifespan, indicating favorable economic viability. Net present value at 12% discount rate was NGN 6,840,000 (USD 8,870), and internal rate of return was calculated at 68%, substantially exceeding typical agricultural investment thresholds in Nigeria.

Sensitivity analysis revealed that the system remained economically viable across a range of parameter variations. A 30% increase in biomass fuel costs reduced NPV by 18% but maintained profitability. Similarly, a 20% decrease in product prices reduced NPV by 24% while preserving positive returns. The analysis confirmed the robustness of the business model under realistic market fluctuations.

4.6 Comparative Analysis with Traditional Methods

Direct comparison with traditional open-sun drying methods demonstrated substantial advantages of the hybrid system across multiple dimensions. Drying time reduction averaged 68% for tomatoes, 71% for peppers, and 63% for fish, translating to improved throughput and reduced labor requirements. Product quality metrics consistently favored the hybrid system, with color retention improvements of 35% to 45%, microbial contamination reduction exceeding 90%, and elimination of physical contaminants such as dust, insects, and animal excreta.

Economic comparison indicated that despite higher capital requirements, the hybrid system delivered superior returns through quality premiums, reduced losses, and consistent year-round operation independent of weather conditions. Surveys conducted among 30 farmers who tested the system revealed 87% satisfaction rates, with primary benefits cited as time savings, improved product quality, and reduced dependency on favorable weather.

Environmental assessment favored the hybrid system through utilization of renewable energy sources and productive use of agricultural waste. Carbon footprint analysis estimated greenhouse gas emission reductions of approximately 1,800 kg CO₂-equivalent per year compared to diesel-powered mechanical dryers of equivalent capacity. The system's use of biomass, while producing combustion emissions, was considered carbon-neutral under sustainable harvesting assumptions, as the carbon released during combustion was previously sequestered during plant growth.

4.7 System Scalability and Adaptability

The modular design approach employed in this research facilitates system scalability to accommodate varying processing capacities. Preliminary analysis indicated that the basic design could be scaled up to 100 kg capacity through proportional increases in solar collector area, drying chamber volume, and blower capacity while maintaining similar thermal efficiency levels. Conversely, smaller units suitable for individual household use could be constructed at approximately 40% of the research system cost, making the technology accessible across different scales of operation.

Adaptability to diverse agricultural products was demonstrated through successful testing with three product categories exhibiting different physical and compositional characteristics. The adjustable airflow and temperature control features enabled optimization of drying conditions for each product type. Additional products tested informally during the research period included okra, garden eggs, and leafy vegetables, all of which responded favorably to the hybrid drying process. This versatility enhances the system's economic viability by allowing processors to diversify their product offerings based on seasonal availability and market demand.

Geographical adaptability represents another important consideration for technology dissemination across Nigeria's diverse agro-ecological zones. The hybrid configuration provides inherent flexibility to accommodate regional variations in solar radiation intensity and biomass availability. In the northern regions characterized by higher solar irradiance and longer dry seasons, the system would operate predominantly in solar mode with minimal biomass supplementation. Conversely, in the humid southern regions with more limited solar resources, biomass would play a larger role in meeting thermal energy requirements. This adaptability increases the technology's relevance across the entire country rather than limiting applicability to specific regions.

V. Conclusion

This research successfully developed, constructed, and assessed a smart hybrid dryer specifically designed for Nigerian food industry applications. The system effectively integrated solar and biomass energy sources with intelligent monitoring capabilities, addressing critical challenges in post-harvest preservation while maintaining economic viability for small and medium-scale enterprises.

Key findings from this investigation include:

The hybrid dryer achieved an average drying efficiency of 68.3% and thermal efficiency ranging from 52.1% to 61.7% across different operational modes. These performance metrics demonstrated superior energy utilization compared to traditional drying methods while providing operational flexibility through multiple energy source configurations. The solar collector delivered thermal efficiency of 61.3% under favorable conditions, while the biomass combustion system achieved 76.4% combustion efficiency with rice husks as primary fuel.

Drying time reductions of 63% to 71% compared to traditional open-sun methods were documented across three test products: tomatoes, peppers, and fish. Complete moisture reduction from initial levels of 78% to 94% to final storage-safe levels of 10% to 12% was accomplished within 9 to 14 hours, compared to 3 to 5 days typically required for sun drying. This substantial time reduction translated directly to increased processing capacity and reduced post-harvest losses.

Product quality assessment revealed significant advantages in color retention (78% to 89% depending on product), nutritional content preservation (87% to 92% retention of key bioactive compounds), and microbiological safety. Total viable counts remained below regulatory thresholds, and pathogenic organisms were absent in all samples. Sensory evaluation scores indicated strong consumer acceptability, with hybrid-dried products receiving ratings 25% to 35% higher than sun-dried controls.

The integrated smart monitoring system utilizing Arduino microcontroller, digital sensors, and IoT connectivity provided reliable real-time data acquisition and remote access capabilities. System uptime exceeded 98%, with automated control functions successfully managing temperature regulation and energy source switching. The monitoring system added approximately 6% to capital costs while delivering substantial operational benefits through reduced labor requirements and improved process control.

Economic analysis demonstrated favorable financial viability with a payback period of approximately 2.3 years, benefit-cost ratio of 2.4:1, and internal rate of return of 68%. These metrics exceeded typical investment thresholds for agricultural technologies in Nigeria. Sensitivity analysis confirmed robustness of economic returns across realistic ranges of fuel costs and product price variations.

The research validated that hybrid drying technology represents a practical, sustainable, and economically feasible solution for addressing post-harvest losses in Nigeria's agricultural sector. The system's utilization of renewable energy sources, incorporation of smart technologies, and construction from locally available materials positions it as an appropriate technology for widespread adoption. Successful implementation could significantly contribute to food security enhancement, farmer income improvement, and agricultural value chain development.

5.1 Recommendations

Based on findings from this research, the following recommendations are proposed:

1. Government agencies and agricultural development programs should prioritize investment in hybrid drying infrastructure through subsidies, low-interest loans, or cost-sharing arrangements to facilitate technology adoption by smallholder farmers and cooperatives. Particular attention should be directed toward establishing community-based drying centers that can serve multiple farmers within a locality, optimizing equipment utilization and reducing individual capital burdens.
2. Training programs should be developed and implemented to build capacity in system operation, maintenance, and quality control among farmers and rural entrepreneurs. These programs should emphasize practical skills in biomass fuel management, hygiene practices, and utilization of smart monitoring features to maximize system performance and product quality.
3. Further research should investigate optimization of specific design parameters including collector tilt angle adjustment mechanisms for seasonal variation, advanced biomass combustion systems with improved emission controls, and integration of supplementary renewable energy sources such as small-scale wind turbines for locations with favorable wind resources.
4. Product diversification studies should explore the applicability of the hybrid system to additional agricultural commodities including grains, tubers, and medicinal plants. Development of product-specific drying protocols and quality standards would facilitate market access and quality assurance across diverse value chains.
5. Policy frameworks should be established to support renewable energy integration in agricultural processing, including standards for dried food products, certification processes for drying equipment, and incentives for clean energy utilization. Regulatory clarity would enhance investor confidence and accelerate technology dissemination.
6. Collaborative research initiatives should be fostered between academic institutions, agricultural research centers, and private sector manufacturers to advance hybrid drying technology. Areas of focus should include materials science for improved heat exchanger designs, control algorithms for optimized energy management, and post-harvest handling systems that integrate drying with storage and packaging.

5.2 Limitations of the Study

Several limitations of this research should be acknowledged. The study was conducted during the dry season months (December to February), and performance characteristics during the wet season require further investigation to comprehensively evaluate year-round operational capabilities. While three products representing different categories were tested, the extensive diversity of Nigerian agricultural commodities necessitates additional product-specific studies to develop comprehensive drying protocols.

The economic analysis was based on current market prices and cost structures, which are subject to fluctuation due to macroeconomic factors including inflation, exchange rate variations, and energy price volatility. Long-term economic viability should be reassessed periodically to account for changing economic conditions. Furthermore, the study evaluated a single system configuration and capacity level, and economies of scale associated with larger commercial installations or diseconomies of smaller household units were not explicitly examined.

Environmental impact assessment focused primarily on energy consumption and carbon emissions, without comprehensive life cycle analysis including material extraction, manufacturing, transportation, and end-of-life disposal considerations. Future research incorporating full life cycle assessment would provide more complete environmental performance evaluation.

5.3 Future Research Directions

Building upon the foundation established by this research, several promising directions for future investigation are identified. Integration of thermal energy storage systems, such as phase change materials or sensible heat storage in rock beds, could extend operational hours beyond periods of active solar collection and biomass combustion, further improving system utilization and product throughput. Research on optimal storage medium selection, sizing, and integration strategies would advance this capability.

Advanced control algorithms incorporating machine learning and artificial intelligence represent opportunities for autonomous system optimization. Predictive models based on historical data and real-time sensor inputs could automatically adjust operational parameters to minimize energy consumption while maintaining product quality specifications. Such systems could learn product-specific drying characteristics and adapt to changing ambient conditions without operator intervention.

The potential for hybrid dryer integration with other agricultural processing operations deserves exploration. Combined systems incorporating drying with solar cooling for cold storage, solar water heating for cleaning operations, or biogas production from organic waste could create synergistic benefits and improve overall

resource utilization efficiency. Such integrated systems may offer enhanced economic returns and sustainability performance compared to standalone drying operations.

Investigation of value-added product development from dried agricultural commodities represents another promising research direction. Processing dried products into powders, flakes, or ingredient formulations for food manufacturing applications could substantially increase market value and create new income opportunities for rural processors. Development of appropriate secondary processing equipment compatible with hybrid dryer outputs would facilitate these value chain extensions.

The successful development and validation of this smart hybrid dryer establishes a foundation for technological advancement in Nigeria's food processing sector. Continued research, appropriate policy support, and strategic investment in dissemination will be essential to realize the full potential of this technology in reducing post-harvest losses and enhancing food security across Nigeria and similar tropical developing countries.

Acknowledgements

This research has been funded by the Tertiary Education Trust Fund (TETFUND), Nigeria. The authors acknowledge TETFUND and Auchu Polytechnic, Nigeria, for the grant to carry out this research. The author extends sincere gratitude to the Department of Agricultural and Bio-Environmental Engineering Technology for providing laboratory facilities and technical support. Appreciation is expressed to local farmers and food processors in Auchu who participated in field testing and provided valuable feedback. Special thanks to the technical staff who assisted in system fabrication and data collection throughout the experimental period.

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