Science Journal of Energy Engineering
2025, Vol. 13, No. 2, pp. 71-86
https://doi.org/10.11648/j.sjee.20251302.14

Research Article

Development of a Smart Renewable Energy-Based System for the Automation of Microclimate Management in Poultry Farms in West Africa: Application of the Tak-Avipack1 Prototype to the Beninese Context

Alain Kossoun Tossa[1, *], Said Ibrahim Adetayo Aballo[2], Souad Mamadou[2], Odette Fokapu[3, 4, 5]

[1] Energy and applied mechanics Laboratory, Abomey-Calavi Polytechnic School, Abomey-Calavi, Benin
[2] R&D department, Takaz-Eng, Cotonou, Benin
[3]Biomechanics and Bioengineering, University of Technology of Compiegne, Compiegne, France
[4]Laboratory of Innovative Technologies, University of Picardie Jules Verne, Compiegne, France
[5]Diasporeines Africa Association, Paris, France

Abstract

Availability and optimization of energy consumption are essential for the success of poultry activities. This is a strategic problem for food security in Benin and more broadly in West Africa. This article presents Tak-Avipack 1, an intelligent system designed to ensure availability at lower cost of energy while guaranteeing the main functionalities necessary for the adequate development of poultry: thermal regulation, lighting, hygiene and biosecurity etc. Based on an integrated IoT architecture, Tak-Avipack 1 incorporates environmental sensors (temperature, humidity, NH_3, CO_2, CO, PM2.5), a high-efficiency catalytic gas heater and dynamically controlled LED lighting. Its food is provided by three energy sources: photovoltaics, the conventional network (if available) and gas (which can be butane or biogas). These systems are optimally sized, and their intelligent hybridization guarantees continuous operation in rural areas. A local decision-making algorithm adjusts thermal parameters, air and lighting flows in real time, minimizing energy consumption. With the GSM / GPRS resilient connectivity and an offline mode with local storage, the system remains functional in the absence of a network. An economic assessment carried out on a model farm with 1,000 weighted hens shows a return on investment of less than six months, with an expected increase of 15% of egg production and a 20% reduction in mortality. Tak-Avipack 1 thus represents an appropriate, accessible and scalable solution to support the transition to tropicalized poultry cultivation.

Keywords

Solar Energy, Precision Poultry Farming, Internet of Things (IoT), Energy Efficiency

*Corresponding author: toskalain@gmail.com (Alain Kossoun Tossa)

Received: 15 May 2025; **Accepted:** 30 May 2025; **Published:** 23 June 2025

1. Introduction

Poultry farming is a key lever for food security and socio-economic development in West Africa. In Benin, the demand for poultry products, particularly eggs, increased by nearly 50% between 2020 and 2023 [1]. However, the sector remains characterized by a high dependence on imports and low local productivity, with an average of 0.16 kg of eggs per bird, well below the global average [2]. A recent study shows that only 9% of traditional farms and 18% of modern farms are cost-efficient [2]. Low production is primarily due to technical gaps among producers, rather than poor resource management [3]. Human capital, veterinary care, and the experience of poultry farmers play a crucial role in the performance of farms. In light of the progressive ban on imports, modernizing these farms is essential to achieve national self-sufficiency [4].

Despite their potential, west Africa poultry farms suffer from outdated management systems, lacking precision in controlling environmental parameters and relying on unstable energy sources in rural areas. Additionally, the absence of traceability and disease detection mechanisms leads to economic losses. Advanced technologies, such as IoT-based precision poultry farming, struggle to gain traction due to their cost and integration complexity.

This paper presents Tak-Avipack 1, an innovative solution combining bioclimatic monitoring, energy autonomy, and performance tracking to enhance the productivity of small to medium-sized poultry farms. Based on field data and testing, this solution demonstrates real potential to optimize technical efficiency, reduce losses, and support national self-sufficiency in animal proteins.

1.1. Environmental Factors in a Poultry House

The well-being and productivity of poultry are closely linked to the environmental conditions within the poultry house. Among the most determining factors are temperature and relative humidity, whose combination directly affects thermal comfort. Air quality, measured through concentrations of ammonia (NH_3), carbon dioxide (CO_2), carbon monoxide (CO), hydrogen sulfide (H_2S), and fine particulate matter (PM2.5), also plays a crucial role in the respiratory health of the animals.

1.1.1. Thermal Stress

Thermal stress is one of the primary limiting factors of laying hen performance, especially in tropical regions such as Benin. When ambient temperature exceeds the thermal comfort zone of poultry, typically between 18 and 24°C [5–7], the classic heat dissipation mechanisms (conduction, convection, and radiation) become ineffective. The chickens then rely on panting, a highly energy-consuming process that expels heat through water evaporation, consuming up to 580 calories per gram of water evaporated [5]. This physiological adaptation is typically accompanied by a decrease in food consumption, leading to a reduction in egg production, egg weight, and shell thickness. These physiological alterations reflect an energy imbalance caused by chronic hyperthermia in laying hens. It should be noted, however, that during the brooding phase corresponding to the early stages of chick development higher ambient temperatures are required.

TEMPERATURE AND HUMIDITY STRESS INDEX FOR COMMERCIAL LAYING HENS
(HEAT STRESS INDEX = 0.6 X DRY BULB TEMPERATURE + 0.4 X WET BULB TEMPERATURE)

Relative Humidity (%)

Temperature °F	°C	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
68	20	63	63	63	64	64	64	64	65	65	65	66	66	66	66	67	67	67	67	68	68
72	22	64	65	65	66	66	66	67	67	67	68	68	69	69	69	70	70	70	71	71	72
75	24	66	67	67	68	68	69	69	70	70	70	71	71	72	72	73	73	74	74	75	75
79	26	68	69	69	70	70	71	71	72	73	73	74	74	75	75	76	77	77	78	78	79
82	28	70	70	71	72	72	73	74	74	75	76	76	77	78	78	79	80	80	81	82	82
86	30	71	72	73	74	74	75	76	77	78	78	79	80	81	81	82	83	84	84	85	86
90	32	73	74	75	76	77	77	78	79	80	81	82	83	84	84	85	86	87	88	89	90
93	34	75	76	77	78	79	80	81	82	83	84	84	85	86	87	88	89	90	91	92	93
97	36	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	93	94	95	96	97
100	38	78	79	81	82	83	84	85	86	88	89	90	91	92	93	95	96	97	98	99	100

Bird Comfort Zone (heat index < 70): No action needed; a good time to prepare for future hot weather.

Alert (heat index 70–75): Begin taking heat stress reduction measures in the flock; increase ventilation rate; increase fan speed and use foggers (run foggers based on relative humidity). Monitor bird behavior for signs of heat stress; ensure drinker and ventilation systems are functioning properly.

Danger (heat index 76–81): Heat stress conditions exist; take immediate measures to reduce heat stress in the flock. Increase ventilation rate in closed houses and use evaporative cooling based on relative humidity; in open houses run stir fans and misters. Adjust nutrient density of bird's diet to match any reduction in feed consumption. Move air over the birds at a minimum velocity of 1.8–2.0 meters/second. Periodically flush water lines with cooler water. Closely monitor flock behavior. Maximize nighttime cooling.

Emergency (heat index > 81): Extreme heat stress conditions exist; avoid handling birds for transfer or vaccination. Do not feed during the hottest part of the day. Decrease light intensity to reduce bird activity and body heat production.

Figure 1. Temperature and humidity stress index for laying hens (THI) [10].

Thermal stress is not solely dependent on dry bulb temperature but also on the temperature-humidity relationship, commonly expressed as the effective temperature. Thus, high relative humidity exacerbates the thermal discomfort of poultry, even with moderate temperatures. To quantify this interaction, several indices have been developed, the most commonly used being the temperature-humidity index (THI), defined as follows [8, 9]:

$$THI = 0.6 \ T_{db} + 0.4T_{wb} \quad (1)$$

where T_{db} *is the dry-bulb temperature and* T_{wb} *is the wet-bulb temperature.*

Based on this index, Hy-Line International [10] developed a thermal stress index table for commercial laying hens during rearing and production phase, shown in Figure 1.

High levels of the temperature-humidity index (THI 81–85) lead to a significant decrease in laying hen performance: egg production drops to 88.3% (compared to 98.7% at THI 68), average egg weight decreases to 48.1 g (compared to 59.7 g), and feed consumption dramatically drops [11]. Controlled condition experiments confirm these effects. This study [12] observed that constant thermal stress (35°C, 50% RH) reduced body weight (1,233 g vs. 1,528 g), decreased consumption (41.6 g/day vs. 86.7 g/day), and increased mortality (31.7% vs. 5%). Similarly, [13] demonstrated that an environment at 31°C and 82% RH decreased egg production and thinned the shell.

In West Africa, as revealed by a study in Nigeria [14], climatic conditions exacerbate this stress: high temperatures (23–29°C), excessive humidity (75–93%), and a low proportion of the day spent within the thermal comfort zone (<24°C). This combination promotes hot spots on the ground and compromises natural ventilation, making active environmental management essential to preserve poultry productivity.

1.1.2. Air Quality

Atmospheric pollutants such as ammonia (NH_3), carbon dioxide (CO_2), fine particulate matter (PM), and hydrogen sulfide (H_2S) have direct and measurable effects on the productive performance of poultry. Prolonged exposure to high concentrations of NH_3 (>100 ppm) significantly reduces egg production (up to -6.3%) [15], causes weight loss, and increases mortality, particularly during the early laying cycle. Similarly, CO_2 levels exceeding 3,000 ppm disrupt acid-base balance and shell quality (a -12% reduction in thickness) [16], while temporarily decreasing egg production and doubling early mortality [17]. These effects are exacerbated in poorly ventilated conditions, where CO_2 levels are further elevated using direct combustion heaters.

Fine particles, although less frequently quantified in direct relation to productivity, cause lung damage and immune stress, which can indirectly affect performance, particularly through increased susceptibility to infections [18, 19]. Hydrogen sulfide (H_2S), even at low concentrations, decreases food intake, reduces live weight (-25%), and impairs product quality (meat, eggs) [20, 21]. Thus, beyond their health impacts, these pollutants represent a major limiting factor in poultry farm profitability, making stringent control of ventilation and environmental conditions essential. Table 1 presents the recommended limit values for laying hens:

Table 1. *Recommended air pollutant limits at the level of laying hens.*

Compound	Target Value (Humane Farm Animal Care 2014)	Maximum Allowed Value (Humane Farm Animal Care 2014)	Measured Values (Nigeria)
Ammonia (NH_3)	< 10 ppm	25 ppm (short-term period)	0,004–61 ppm [22]
Hydrogen Sulfide (H_2S)	<0.5 ppm	2,5 ppm	0,02–13,1 ppm [22]
Carbon dioxide (CO_2)	<3000 ppm	5000 ppm	707,511 – 858,694 ppm [23]
Carbon Monoxide (CO)	≤ 10 ppm	50 ppm	
Particulate Matter (PM)	≤ 1.7 mg/m^3	5 mg/m^3	0.01–1.75 mg/m^3 [22]

A study by [22], conducted in poultry farms in Edo State, Nigeria, reveals that ammonia (NH_3) and hydrogen sulfide (H_2S) are the most critical climatic pollutants in Nigerian poultry houses due to their high concentrations and harmful effects on animal and human health. Measurements show NH_3 concentrations reaching 61 ppm (six times the target value of 10 ppm) in substandard farms, and peaks of H_2S at 13.1 ppm (exceeding the recommended limit of 0.5 ppm by 26 times).

1.1.3. Lighting

Lighting plays a crucial role in poultry house management. It is not limited to providing light for the hens; it profoundly influences their physiology, behavior, and consequently, their productivity.

The photoperiod, i.e., the daily duration of exposure to light, directly impacts egg production in laying hens. Light stimulates the hypothalamus and pituitary gland, regulating the secretion of LH and FSH hormones necessary for ovarian maturation. A stable photoperiod of 14 to 16 hours per day maintains high egg production rates, while a sudden reduction in light exposure can cause a sharp decline in production [24, 25]. In chicks, it also affects growth and immune development. Therefore, lighting management is a key lever, beyond mere illumination, for optimizing zootechnical performance. Figure 2 illustrates a lighting program applied to a flock of laying hens [26], in which the photoperiod is maintained constant throughout the laying period, ensuring hormonal stability and maintaining productive performance. Additionally, experimental data from Lewis (1996) [26] show that the number of eggs per hen increases proportionally with the duration of lighting, reaching an optimal plateau around 16 hours.

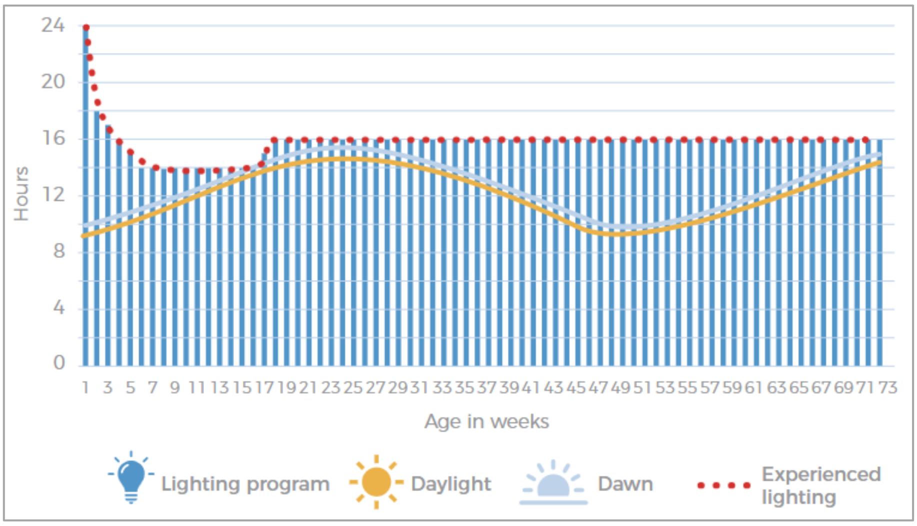

Figure 2. *Lighting program for the breeding and laying of a flock located in Valencia, Spain [26].*

Beyond duration, the quality of light – particularly its color (wavelength) – plays a key role in the performance of laying hens. Several studies have highlighted the differential impact of light colors: red light promotes early sexual maturity, stimulates egg production, and enhances ovulatory frequency, while blue and green lights are more associated with calm behavior and improved growth in young poultry [27, 28]. LED lamps, which allow for precise adjustment of the light spectrum, offer an advantage over traditional fluorescent or incandescent lamps by combining energy efficiency with light spectrum optimization. Moreover, the stability of intensity and the absence of flicker in LEDs contribute to stress reduction and more consistent egg production. Thus, the choice of light source becomes a performance factor, alongside feed and ventilation, in the integrated management of the poultry house.

1.2. Current Technologies for Monitoring and Managing Parameters

1.2.1. Technological Advancements in Poultry Monitoring

The integration of Internet of Things (IoT) technologies and Artificial Intelligence (AI) has profoundly transformed the management of poultry farms, enabling real-time monitoring of environmental temperature conditions and early detection of behavioral anomalies. IoT sensors now measure critical parameters such as, humidity, air quality, and water levels, as demonstrated by a project developed in Tanzania, which improved animal health and reduced labor costs [29]. In parallel, AI is used to automatically analyze poultry behavior, achieving up to 98% accuracy in anomaly detection [30]. Furthermore, some intelligent systems ensure automatic regulation of feeding, drinking, lighting, and ventilation, thereby optimizing resource use and enhancing the overall efficiency of poultry operations [31].

1.2.2. Existing Tools for Intelligent Poultry Farm Monitoring and Management

Numerous solutions combining IoT, cloud, and automation have emerged to improve poultry management.

Farmspeak Penkeep (Nigeria) offers an IoT platform that measures temperature, humidity, CO_2, NH_3, and water levels, with SMS and email alerts. However, its lack of offline mode and high cost (USD 2,000–3,000) limit its adoption by smallholders [32].

Baku Global (Indonesia) provides a modular system focused on reducing food consumption and CO_2 emissions, but requires software subscriptions and recurring hardware costs, in addition to specialized installation, thus hindering its accessibility in Africa [33].

NYB Systems (Bangladesh) offers IoT multi-sensor gateways compatible with industrial standards (CAN-BUS, MODBUS), targeted at large farms. Despite their robustness, these solutions require stable 4G/Wi-Fi connectivity and advanced infrastructure, which are poorly suited to rural tropical realities [34].

Thus, while technically efficient, these tools face economic and local adaptation constraints, impeding their adoption in resource-limited African poultry farms.

1.2.3. Limitations Specific to the African Context

In several African countries, the adoption of IoT technologies in poultry farming is hindered by significant structural barriers. A study conducted in Tanzania highlighted three main obstacles [29]:

1. Prohibitive Cost: 43% of small farmers forgo these solutions due to their prohibitive cost.
2. Unstable Connectivity: Rural areas suffer from limited Internet access, necessitating solutions capable of operating in hybrid or offline modes.
3. Absence or Instability of the Grid: The instability or absence of electrical networks limits the use of automated systems, forcing farmers to resort to rudimentary and inefficient solutions (charcoal stoves, kerosene lamps, etc.).

These constraints highlight the mismatch between conventional systems and African realities, calling for the development of more resilient, adapted, affordable, and autonomous solutions.

1.2.4. Critical Analysis and Scientific Justification

A comparative analysis of existing solutions allows for the identification of several essential technical and functional criteria for designing a relevant system for resource-poor tropical contexts:

1. Acquisition and Operating Cost
2. Energy Autonomy
3. Energy efficiency
4. Hybrid/Offline Connectivity
5. Multi-Parameter Monitoring (gases, particles, temperature, humidity, etc.)
6. Embedded or Cloud Analysis Capability
7. Ease of Installation and Maintenance
8. Resistance to Tropical Conditions (heat, humidity, dust)

These solutions show notable advances, but none simultaneously meet all these characteristics. This technological and contextual gap forms the scientific basis for the development of Tak-Avipack 1, a frugal, robust, embedded, and scalable solution specifically designed for poultry farms in West Africa.

2. Methodology

2.1. Tak-Avipack 1 System Architecture

The Tak-Avipack 1 system is based on a three-layer interconnected architecture, optimized for poultry farming in rural areas of West Africa.

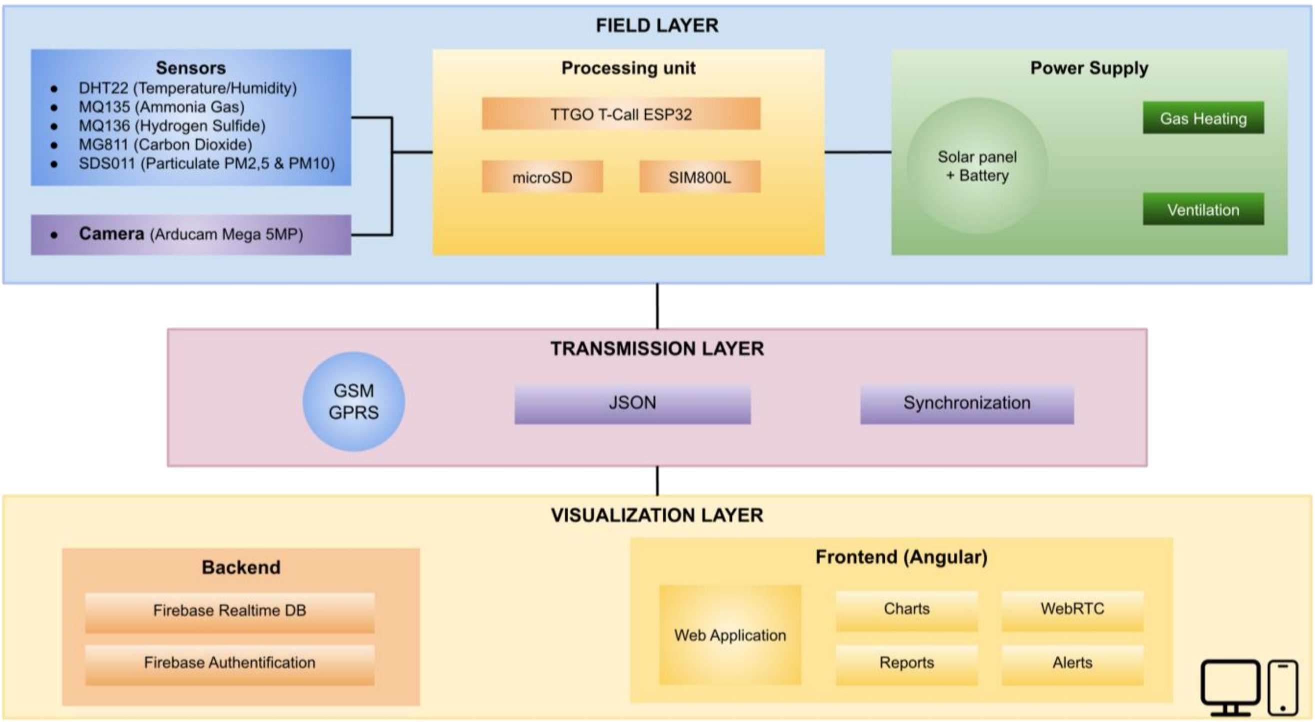

Figure 3. Tak-Avipack 1 System Architecture.

The field layer consists of sensors (DHT22, MQ135, SDS011, etc.) connected to a TTGO T-Call ESP32 micro-controller, which already includes GSM connectivity through the SIM800L module and a microSD card. This setup allows for local measurements (temperature, humidity, NH_3, CO_2, PM2.5, and PM10) and data transmission. The choice of these components reduces costs and simplifies assembly.

The transmission layer uses the GSM/GPRS network to send data in a lightweight JSON format, minimizing data consumption. In case of network outage, measurements are stored locally on the microSD card for later synchronization, ensuring continuity without data loss.

The visualization layer is based on an Angular web application coupled with Firebase Realtime Database. This open-source combination allows for dynamic visualization of parameters, management of alerts and users, while avoiding heavy infrastructure costs. Integrated reporting tools facilitate real-time zootechnical analysis. Figure 3 presents the architectural diagram of the Tak-Avipack 1 system. The diagram now shows only the system components organized according to the three main layers.

2.2. Operating Principle of Tak-Avipack 1 System

Tak-Avipack 1 system is based on an embedded architecture that integrates environmental sensors, intelligent actuators (heating, ventilation, lighting), and a control algorithm based on a hierarchical decision-making logic. Its goal is to ensure an optimal microclimate for poultry, improving productivity while reducing manual interventions.

2.2.1. Thermal Comfort

Sensors Used

1. DHT22: Measures ambient temperature (°C) and relative humidity (%)
2. Calculation of the THI (Temperature-Humidity Index), an indicator of thermal stress based on equation 1:

Table 2 present Critical Thresholds (Thermal Stress Scale) based on THI:

Table 2. Critical Thresholds and Corrective Actions for Thermal Comfort Management.

Level	THI Threshold	Status	Decision
1	THI<70	Comfort zone	No action
2	70<THI<80	Mild Stress	Moderate PWM Ventilation
3	80<THI<85	Moderate Stress	Heating OFF, Maximum Ventilation
4	THI>85	Severe Stress	Alert + Forced Ventilation

2.2.2. Air Quality

Sensors used:

1. MQ135: Ammonia (NH_3)z
2. MQ136 Hydrogen Sulfide (H2S)
3. SDS011: Fine particles (PM2.5 and PM10)
4. MG811: Carbon dioxide (CO_2)
5. MQ7: Carbon monoxide (CO)

The critical thresholds measured by these sensors and the corresponding corrective actions for air quality management are summarized in Table 3.

Table 3. Critical Thresholds and Corrective Actions for Air Quality Management.

Level	NH_3 (ppm)	CO_2 (ppm)	CO (ppm)	H_2S (ppm)	$PM_{2,5}$ et PM_{10} (mg/m^3)	Status	Decision
1	<5	<1000	<5	<0.1	<0.5	Acceptable	None
2	5-10	1000 – 2000	5-10	0.1 – 0,5	0.5-1.7	Moderately Polluted	Moderate Ventilation (30-50%)
3	10-25	3000 – 5000	10-50	0.5-2.5	1.7-5	Polluted	Strong Ventilation (70-100%)
4	>25	>5000	>50	>2.5	>5	Dangerous	SMS Alert + Maximum Ventilation

2.2.3. Lighting

Lighting Program

The lighting program follows a development curve based on the age of the poultry (Table 4):

Table 4. Poultry House Lighting Program.

Age Range (Weeks)	Target Lighting Duration
1 à 12	23 à 12h/jour
13 à 17	12h/jour
18 à 21	13 à 16 h/jour
>21	16h/jour

The goal of the lighting program is to promote feeding and growth during the startup phase, avoid early egg-laying during the juvenile phase, and optimize egg production at maturity.

Control of Light Intensity

The LEDs are gradually turned on/off to simulate dawn and dusk (avoiding stress) [35].

The graph in Figure 4 represents the simulation of a complete day/night cycle over a 24-hour period, with a gradual light transition simulated by sigmoid functions for dawn and dusk. The equations used to model these transitions are as follows:

Dawn

$$I(t) = \frac{Imax}{1+e^{-k(t-to)}} \quad (2)$$

Dusk

$$I(t) = \frac{Imax}{1+e^{k(t-to)}} \quad (3)$$

The main parameters associated with these equations are:

1. Imax: Maximum light intensity (100%),
2. k: Slope factor, which determines the speed of the light transition, here k=5,
3. t0: The central point of the transition (dawn or dusk), specified for a full cycle t = 24h. t0_dawn = 7h, t0_dusk = 18h

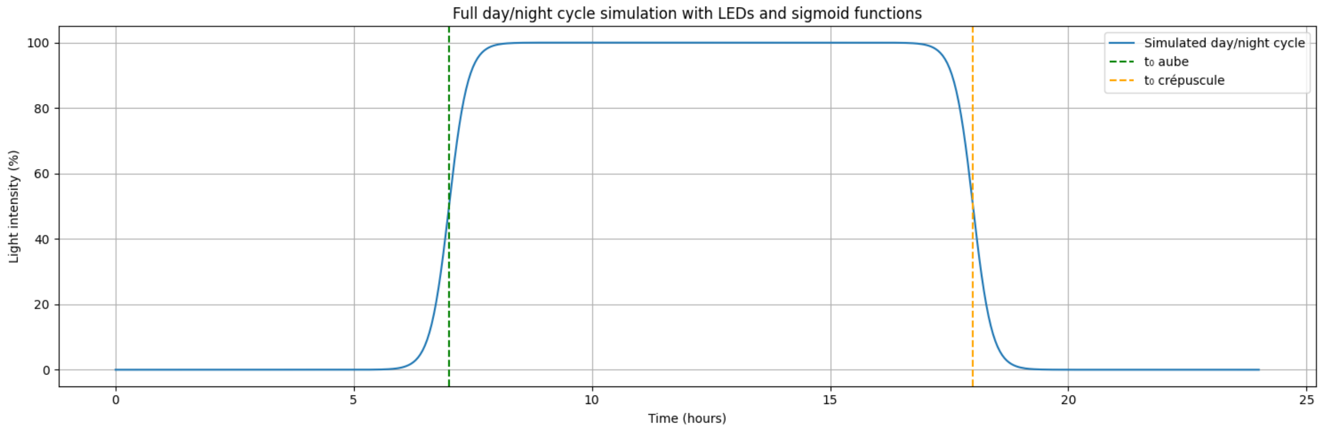

Figure 4. Complete Day/Night Cycle Simulation with a Sigmoid Function.

Automatic Decision

Based on age and time (RTC), the system adjusts:

1. The duration of artificial lighting required.
2. The intensity to simulate the natural ambiance.
3. Compensation if natural light is insufficient.

2.3. Sizing Actuators and Solar Power Supply

The sizing of the Tak-Avipack 1 system is based on the goal of ensuring complete energy autonomy for continuous operation in rural areas with low grid reliability. The consumption estimates were made considering the thermal, photoperiodic, and ventilation requirements of a poultry farm housing 1,000 laying hens.

2.3.1. Lighting

The purpose of the lighting is to ensure a luminous intensity in accordance with poultry standards for 1,000 laying hens, which is 10 lumens/m² throughout the poultry house. Table 5 presents the details of the sizing:

Table 5. *Lighting Sizing.*

Parameter	Value
Stocking density	5 hens/m² [36]
Number of hens	1 000
Required area	1 000 / 5 = 200 m²
Lighting standard	10 lumens/m²
Required luminous flux	200 m² × 10 = 2000 lumens
LED luminous efficiency	100 lumens/W [37]
Total lighting power consumption	2000 / 100 = 20 W
Efficiency (dust, reflection factor, etc.)	25%
Lamp unit power	5 W
Number of lamps	(20 x 1.25) /5=05 lamps

Table 6. *Heating Sizing.*

Parameter	Value
Stocking density (Startup phase)	30 hens/m² [5]
Occupied area	33.33 m²
External ambient temperature (Te)	27 °C
Desired internal temperature (Ti)	35 °C [5]
Temperature difference (ΔT)	8 °C
Overall heat transfer coefficient (U)	5.32 W/m²·°C [38]
Required thermal power (Pth)	1 418.5 W
Thermal power in kcal/h	1 219 kcal/h
Estimated transfer efficiency (Considered Radiation and convection losses)	85%
Corrected useful power	1 219 ÷ 0.85 ≈ 1 434 kcal/h

2.3.2. Heating

Heating in poultry farming in West Africa is essential during the chick startup period (0 to 5 weeks), during which the ambient temperature must be maintained between 31–33°C in the first week, then gradually reduced to the thermal comfort zone (18-24°C) by the fifth week. Table 6 summarizes the heating-sizing information:

2.3.3. Ventilation

The sizing of the ventilation system aims to ensure sufficient air renewal to remove heat, humidity, and harmful gases (NH_3, H_2S, CO_2) produced by the poultry, in accordance with zootechnical recommendations. Table 7 presents the information and sizing of the ventilation system:

Table 7. *Ventilation Sizing.*

Parameter	Value
Average live weight at 30 weeks (Isa Brown)	1 870 kg [39]
Recommended ventilation rate	0.7 à 4 m³/kg/h [5]
Minimum ventilation at 0.7 m³/kg/h	$1{,}870 \times 0{,}7 \times 1000 = 1309 \ m3/h$
Maximum ventilation at 4 m³/kg/h	$1{,}870 \times 4 \times 1000 = 7480 \ m3/h$
Required ventilation range	1 309 - 7 480 m³/h
Selected extractor type	Low consumption extractor 12V-1,700 m³/h / 370W with variable speed to compensate for potential pressure losses

2.3.4. Solar System (PV + Battery)

The Tak-Avipack 1 solar system must cover the following daily energy needs: lighting, burner startup, ventilation, and embedded electronics. Table 8 and Table 9 present the daily consumption estimates and sizing results, respectively.

Table 8. *Daily Consumption Estimate.*

Component	Power (W)	Operating Time (h/day)	Energy (Wh/day)
LED Lighting (5 lamps × 5 W)	25	12 (semi-dark building)	300

Component	Power (W)	Operating Time (h/day)	Energy (Wh/day)
Burner startup (THD2608)	300	0.2 (estimated 12 min/day cumulative pulses)	60
Low consumption fan	370	6 h/day (estimated minimum ventilation)	2 220
Electronic system (ESP32, sensors, SIM800L, SD card)	5	24	120
Total energy consumed			2 700

Table 9. *Sizing Summary.*

Element	Specifications
Daily energy requirement	2 700 Wh/day
Photovoltaic panels	2 × 400 Wp
Battery capacity	2 × 12V – 300 Ah (with 80% max discharge)
Guaranteed autonomy without sunlight	1.5 days

2.4. Methodology for Evaluating the Expected Performance of the Prototype

The estimation of potential zootechnical gains associated with the implementation of Tak-Avipack 1 is based on a comparative modeling between a reference scenario (traditional farming without automation) and an optimized scenario incorporating the proposed system. Two main sources were used to define the baseline parameters and performance gaps:

The ISA Brown performance sheet [40], which serves as a reference for the expected productivity standards for industrial laying breeds in controlled environments.

The empirical study by [2] on the technical inefficiency of poultry farms in Benin, which provides representative data for the local context.

2.4.1. Definition of Local Reference Values

According to [2], modern laying farms in Benin exhibit:

1. An average laying rate of 74.9%,
2. An estimated annual production of 240 eggs per hen,
3. An average mortality rate of 9.48%,
4. A feed cost of 0.60 USD per egg produced,
5. And an average annual operating result of 6 525 USD for a farm of 1 000 laying hens [41].

These data were used to characterize the reference scenario in the modeling.

2.4.2. Performance Projections with Tak-Avipack 1

The ISA Brown manual [40] identifies optimal performance achievable under controlled environmental conditions:

1. A laying rate > 90% during the stabilized production phase (22 to 50 weeks),
2. An average egg weight of 62 g,
3. A mortality rate reduced to less than 5%,
4. And a feed conversion ratio of less than 2.8 g of feed/g of egg.

The simulations conducted as part of this study did not use these optimal values but applied conservative assumptions adjusted from intermediate results of partially modernized farms. Therefore, the performance objectives set for Tak-Avipack 1 were as follows:

1. Target laying rate: 86.1%,
2. Eggs per hen per year: 276 (+15%),
3. Mortality reduced to 7.6% (i.e., -20%),
4. Reduction in feed cost per egg by 8%, linked to the reduction in thermal stress and optimization of consumption through better temperature and light regulation.

These projections are consistent with the expected impacts of improved microclimate and optimized photoperiod, as documented by [12] and [13], and referenced in the literature review.

2.5. Methodology for Estimating Economic Performance

2.5.1. Framework of the Analysis

The economic evaluation of the Tak-Avipack 1 system was conducted considering a poultry production unit of 1,000 laying hens in a tropical environment. This farm size is representative of mid-scale commercial poultry farming in Benin [42]. The parameters used are based on recent literature averages for the poultry sector in Benin, enhanced by projections derived from the expected performance of the prototype.

2.5.2. Estimation of Additional Revenue from Egg Sales

The additional revenue generated by optimizing egg production is calculated using the difference between the egg selling price and the average production cost before optimization, along with the impact of reducing animal losses. The formula is expressed as follows:

$$RS = (Ps - Cm) \times \left(Np \times (1 - Tpw)\right) \times (Ow - Owt) \quad (4)$$

Where:
Ps: selling price per egg,
Cm: average cost per egg before optimization,
Np: total number of hens,
Tpw: animal loss rate with Tak-Avipack,
Ow: number of eggs produced per hen per cycle with Tak-Avipack
Owt: number of eggs produced per hen per cycle without Tak-Avipack

2.5.3. Estimation of Reduction in Animal Losses

The savings achieved through the reduction in animal losses are given by:

$$RPA = (Tpwt - Tpw) \times Np \times Vp \quad (5)$$

Où:
Tpwt: animal loss rate per cycle without Tak-Avipack,
Np: total number of hens,
Vp: value of one hen at the end of cycle.

2.5.4. Calculation of Total Annual Gains

Total annual gains are obtained by adding the additional revenue from egg sales and the savings from reduced animal losses:

$$R = RS + RPA \quad (6)$$

2.5.5. Investment Cost and Operating Cost

The investment cost is given by Io, and the annual operating cost is given by:

$$Cop = Cmonth \times 12 \quad (7)$$

Where:
Cmonth: monthly operating cost.

2.5.6. Calculation of Net Annual Gain

The net annual gain is obtained by subtracting the annual operating costs from the total annual gains:

$$Gnet = R - Cop \quad (8)$$

2.5.7. Calculation Net Present Value (NPV)

Net Present Value (NPV): The NPV represents the sum of all discounted cash flows generated by the investment, considering a discount rate. It reflects the project's capacity to generate value over its lifetime.

$$NPV = \sum_{t=1}^{n} \frac{Gnet}{(1+r)^t} - Io \quad (9)$$

Where:
Io = Initial Investment Cost (I_0)
r = Discount rate (10%)
n = Project lifetime (5 years assumed)

Discounted Payback Period (DRCI): The DRCI measures the time needed for the cumulative discounted cash flows to equal the initial investment. It adjusts the traditional payback period by accounting for the time value of money.

$$DRCI: Year \ \ where \ \ \sum_{t=0}^{DRCI} \frac{Gnet}{(1+r)^t} \geq Io \quad (10)$$

3. Results

3.1. Visual Presentation of the Prototype

The Tak-Avipack 1 prototype consists of a compact and modular electronic enclosure, integrating environmental sensors, a TTGO T-Call ESP32 microcontroller with a GSM SIM800L module, and thermal and lighting actuators. The entire system is powered by a standalone solar setup, ensuring autonomy for more than 24 hours without sunlight.

Photographs of the electronic assembly (Figure 5 and Figure 6) illustrate the meticulous integration of the components, while screenshots of the Angular web interface display the real-time dashboard, automatic alerts, and exportable history (Figure 7 and Figure 8). This design prioritizes field usability: robustness, energy efficiency, and ease of use.

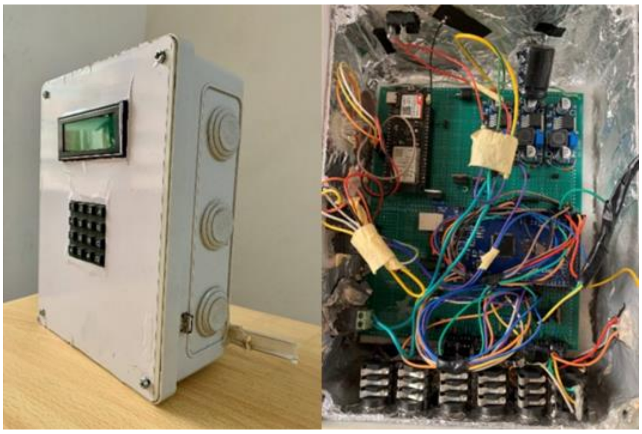

Figure 5. *Photos of Tak-Avipack 1 electronic system.*

Figure 6. *Photos of Tak-Avipack 1 deployed on a poultry house model.*

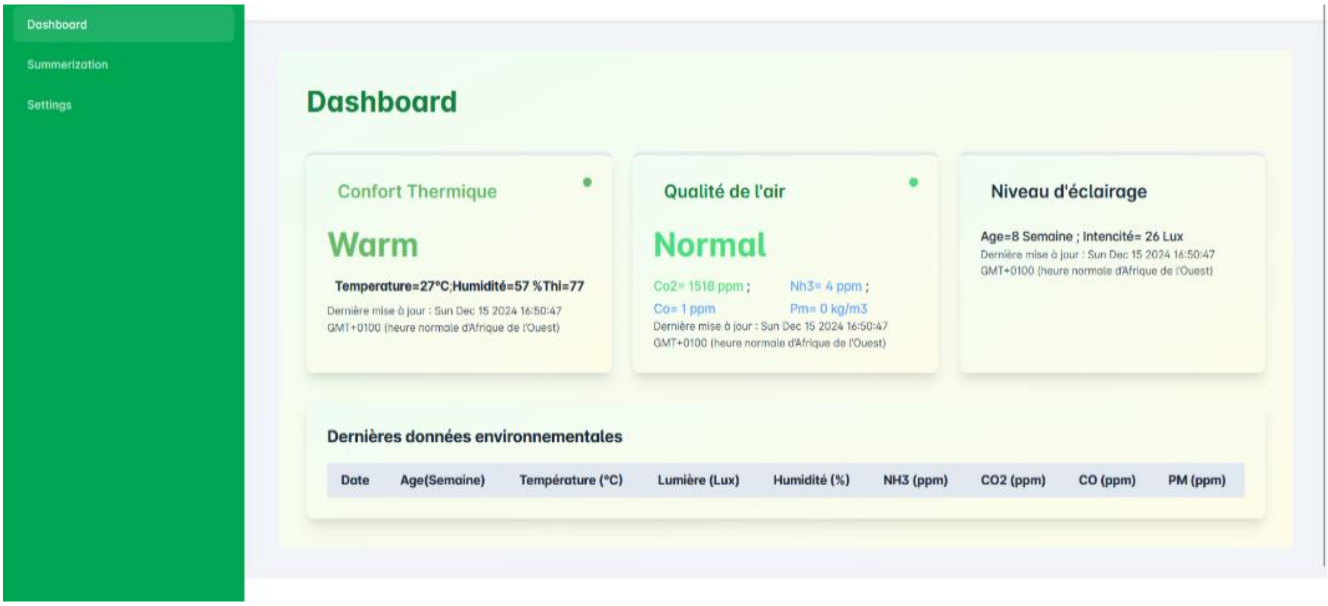

Figure 7. *Preview of the web interface: Dashboard.*

Figure 8. *Preview of the web interface: Lighting programming.*

Figure 9 presents the experimental data collected during the testing of the Tak-Avipack 1 system on the poultry house model over the first six weeks of operation. The graph shows the evolution of ambient temperature, the activation cycles of the burner and the fan, and the resulting internal temperature regulation. These tests were conducted under simulated Cotonou Benin hot and humid climatic conditions (23–29°C, high humidity), to assess the system's capacity to maintain thermal comfort during the brooding and early growth phases. The results demonstrate the responsiveness and effectiveness of Tak-Avipack 1 in stabilizing the poultry house environment, despite external thermal variations.

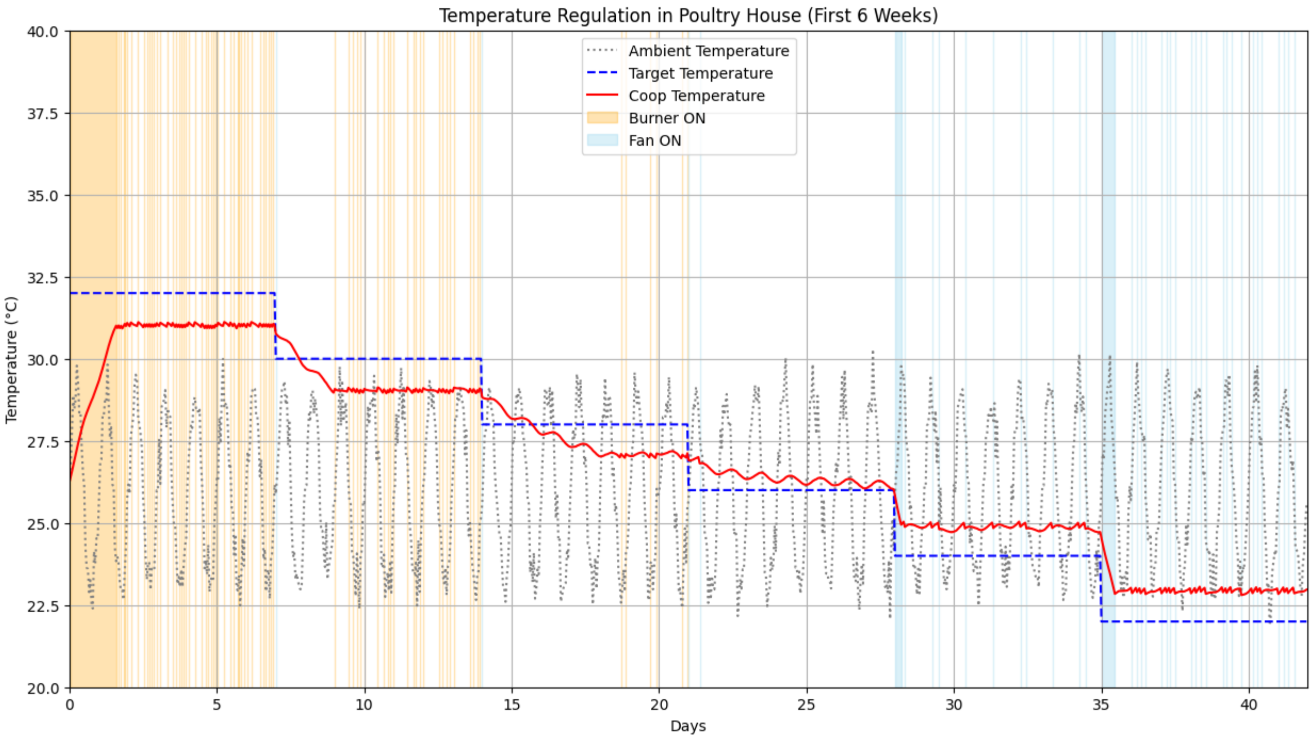

Figure 9. *Temperature regulation in poultry houses for 06 weeks.*

3.2. Economic Evaluation

The baseline assumptions used for the comparative analysis are summarized in Table 10:

Table 10. *Assumptions of Tak-Avipack 1 performance.*

Indicator	Without Tak-Avipack 1	With Tak-Avipack 1	Expected Change
Egg production rate (%)	74.9	86.1	+15%
Annual production (eggs/hen)	240	276	+15%
Average egg weight (g)	60	62	+3.3%
Mortality rate (%)	9.48	7.6	-20%
Feed cost per egg (USD)	0.060	0.055	-8.0%

Based on this, the economic performance for a 1,000-hen farm is estimated in Table 11:

***Table 11.** Economic Performance of Tak-Avipack 1 for a 1,000-Hen Farm.*

Parameter	Value (USD)
Additional revenue (RS)	1 330.56
Reduction in animal losses (RPA)	94.00
Total annual gains (R = RS + RPA)	1 424.56
Initial investment cost (I_0)	1 612.50
Annual operating cost (Cop)	60.0*
Net annual benefit (R - Cop)	1 364.56
Net Present Value (NPV) (5 years, 10% discount rate)	3 560.26
Payback Period (DRCI)	1.33 years (~1 year 4 months)

* The recurring operating costs are estimated at 5 USD per month, including: preventive maintenance of the sensors, the GSM/GPRS package (data transmission), and basic software management.

4. Discussion

The cross-analysis of existing solutions in the field of connected poultry monitoring has identified eight essential criteria for their adoption in tropical contexts: (i) affordable acquisition and operational costs, (ii) energy autonomy, (iii) hybrid connectivity (including offline operation), (iv) diversity of environmental parameters measured (temperature, humidity, gases, particulate matter), (v) embedded analytical capabilities, (vi) ease of installation, (vii) hardware robustness, and (viii) adaptation to tropical conditions. An evaluation grid based on these criteria was applied to four reference solutions: Penkeep (Farmspeak), Zeus. AI (Zeus International), Baku Global, and NYB Systems.

Based on this framework, Tak-Avipack 1 stands out as the only solution that satisfactorily meets all these criteria. Economically, its deployment cost, under 1 600 USD, is significantly more affordable than other systems (ranging from 2 500 to 4 000 USD for most), while avoiding recurring subscription fees. Its operating cost, limited to 5 USD, makes it particularly accessible to small and medium-sized poultry farmers in Africa. In terms of energy, the fully solar-powered system guarantees autonomy in areas with unstable electricity supply. Furthermore, its GSM/GPRS connectivity, combined with offline operation and local storage, provides a decisive advantage for rural areas with limited broadband internet coverage.

Functionally, Tak-Avipack 1 integrates, from its basic version, temperature, humidity, ammonia (NH_3), carbon dioxide (CO_2), carbon monoxide (CO), and fine particulate matter (PM2.5) sensors, offering an extensive bioclimatic coverage rarely seen in this price range. In comparison, Penkeep and NYB Systems are limited to thermal and humidity measurements, while gas and particulate sensors in Zeus or Baku are available as optional modules or upon request. Additionally, Tak-Avipack 1 includes embedded decision-making logic, allowing automated activation of heating, lighting, or ventilation devices without relying on cloud infrastructure.

However, Tak-Avipack 1 does not yet feature artificial intelligence modules for behavioral analysis or early detection of diseases, unlike Zeus. AI or Penkeep, which already offer AI components integrated into their cloud. Nevertheless, its modular design, based on the ESP32 microcontroller, and its open software architecture allow for gradual complexity scaling, with the potential for these features to be integrated in future versions. These elements fully justify the approach leading to the development of Tak-Avipack 1: a frugal, robust, tropicalized, and scalable solution designed to democratize access to precision poultry farming in resource-limited countries.

5. Conclusion

The development of the Tak-Avipack 1 system addresses a structural issue in poultry farming in West Africa: the need to improve the zootechnical performance of farms in a context of high climatic variability, limited technical resources, and restricted access to imported innovations. By integrating environmental sensors, embedded control logic, and a web interface tailored to local realities, this prototype demonstrates the feasibility of a frugal yet effective technological approach for the automated management of laying hen living conditions. The results obtained through economic modeling and functional testing indicate that Tak-Avipack 1 can significantly contribute to improving egg production rates, reducing losses related to thermal stress and atmospheric pollutants, while also enabling a measurable reduction in production costs. Moreover, its energy autonomy, compatibility with GSM networks, and ease of use make it a viable solution for small and medium-sized farms in rural areas, often excluded from technological innovation dynamics.

Beyond its immediate relevance, Tak-Avipack 1 paves the way for new perspectives, including the future integration of artificial intelligence algorithms for the early detection of behavioral or health anomalies, as well as the networking of multiple units for regionalized farm monitoring. In this regard, this work represents the first step toward tropicalized precision poultry farming that is economically sustainable and technologically autonomous.

Symbol

Tdb	Dry-bulb Temperature (°C)
Twb	Wet-bulb Temperature (°C)
THI	Temperature-Humidity Index
Imax	Maximum Light Intensity (%)
k	Slope Factor of the Sigmoid Function
to	Center of the Transition (dawn/dusk time, in hours)
t	Time (hour of the day)
Ps	Selling Price per Egg (USD)
Cm	Cost per Egg before Optimization (USD)
Np	Number of hens
Tpw	Mortality rate with Tak-Avipack
Ow	Eggs per hen per Cycle with Tak-Avipack
Owt	Eggs per hen per Cycle without Tak-Avipack
Tpw	Animal Loss Rate with Tak-Avipack
Tpwt	Mortality Rate Without Tak-Avipack
Vp	Market Value of a Hen at the End of Cycle (USD)
R	Total Annual Revenue Gain (USD)
RS	Additional Revenue
RPA	Reduction in animal losses
Gnet	Net Annual Gain
Cop	Annual operating cost (USD)
Io	Initial investment cost (USD)
r	Discount rate (e.g., 10%)
n	Project lifetime (years)
DRCI	Discounted Payback Period
NPV	Net Present Value

Abbreviations

AI	Artificial Intelligence
CO	Carbon Monoxide
CO_2	Carbon Dioxide
DHT22	Digital Humidity and Temperature Sensor
EPAC	Polytechnic School of Abomey-Calavi
ESP32	32-bit Microcontroller by Espressif Systems
FSH	Follicle-Stimulating Hormone
GPRS	General Packet Radio Service
GSM	Global System for Mobile Communications
H_2S	Hydrogen Sulfide
IoT	Internet of Things
LED	Light Emitting Diode
LEMA	Laboratory of Energy and Applied Mechanics
LH	Luteinizing Hormone
MG811	CO_2 Gas Sensor
MQ135	Air Quality Sensor (NH_3, CO_2, etc.)
MQ136	Hydrogen Sulfide Sensor
MQ7	Carbon Monoxide Sensor
NH_3	Ammonia
NPV	Net Present Value
OCIS	Organization for the Competitiveness of Industries and Services *(assumed)*
PM	Particulate Matter
PM2.5 / PM10	Fine Particles (diameter < 2.5 µm / 10 µm)
PV	Photovoltaic
PWM	Pulse Width Modulation
RTC	Real-Time Clock
SD	Secure Digital (memory card)
SDS011	Sensor for Fine Particles (PM2.5 and PM10)
SIM800L	GSM/GPRS Module
Tak-Avipack 1	Prototype System for Climate-Smart Poultry Management
THI	Temperature-Humidity Index
TTGO T-Call	ESP32 Board with Integrated GSM (SIM800L)
USD	United States Dollar

Conflicts of Interest

The authors declare no conflicts of interest.

References

[1] DSA Bénin. LES CHIFFRES DEFINITIFS DE LA CAMPAGNE AGRICOLE 2023-2024 2024.

[2] Crinot FG, Adégbola YP, Fatunbi AO, Adéguélou KR. Inefficiency of laying hens farms in Benin: an input directional distance function approach. Agric Food Secur 2024; 13: 22. https://doi.org/10.1186/s40066-024-00471-7

[3] Siéwé Pougoué EB, Manu I, Labiyi Adédédji I, Bokossa T. Efficacité technique des exploitations avicoles productrices d’œufs au sud du Bénin. Rev D’élevage Médecine Vét Pays Trop 2019; 72: 23–32. https://doi.org/10.19182/remvt.31728

[4] OCIS. Substitution des produits locaux aux biens importés : Projecteur sur la filière viande de volaille 2025.

[5] Hendrix Genetics. Commercial Management Guide : Hot & Tropical Climates 2021.

[6] John Brown, DVM, Pig Health Today. 5 steps to preventing heat stress in layers 2021. https://www.thepoultrysite.com/articles/5-steps-to-preventing-heat-stress-in-layers

[7] Sukanshi Yadav1 A. Thermoregulation in Layer Poultry 2022. https://doi.org/10.5281/ZENODO.7194884

[8] Kilic I, Simsek E. The Effects of Heat Stress on Egg Production and Quality of Laying Hens 2013.

[9] Lallo CHO, Cohen J, Rankine D, Taylor M, Cambell J, Stephenson T. Characterizing heat stress on livestock using the temperature humidity index (THI)—prospects for a warmer Caribbean. Reg Environ Change 2018; 18: 2329–40. https://doi.org/10.1007/s10113-018-1359-x

[10] Hy-Line International. UNDERSTANDING HEAT STRESS IN LAYERS : Management Tips to Improve Hot Weather, Flock Performance 2016.

[11] Kim D-H, Song J-Y, Park J, Kwon B-Y, Lee K-W. The Effect of Low Temperature on Laying Performance and Physiological Stress Responses in Laying Hens. Animals 2023; 13: 3824. https://doi.org/10.3390/ani13243824

[12] Mashaly MM, Hendricks GL, Kalama MA, Gehad AE, Abbas AO, Patterson PH. Effect of Heat Stress on Production Parameters and Immune Responses of Commercial Laying Hens. Poult Sci 2004; 83: 889–94. https://doi.org/10.1093/ps/83.6.889

[13] Song Z, Liu L, Sheikhahmadi A, Jiao H, Lin H. Effect of Heat Exposure on Gene Expression of Feed Intake Regulatory Peptides in Laying Hens. J Biomed Biotechnol 2012; 2012: 1–8. https://doi.org/10.1155/2012/484869

[14] Ogunlowo QO, Azeez AA, Na WH, Rabiu A, Adesanya MA, Zakir E, et al. Analysis of microclimate temperature and relative humidity distribution of local poultry house in a subtropical area of Nigeria. J Agric Eng 2024. https://doi.org/10.4081/jae.2024.1561

[15] Deaton JW, Reece FN, Lott BD. Effect of Atmospheric Ammonia on Pullets at Point of Lay. Poult Sci 1984; 63: 384–5. https://doi.org/10.3382/ps.0630384

[16] Helbacka NV, Casterline JL, Smith CJ. The Effect of High CO_2 Atmosphere on the Laying Hen. Poult Sci 1963; 42: 1082–4. https://doi.org/10.3382/ps.0421082

[17] ROUSSET N, CREACH P, JABRI ME, BOUVAREL I. Pourquoi est-il important de maîtriser la concentration en CO_2 dans son élevage ? Impact sur la santé et le bien-être des poulets de chair 2018.

[18] David B, Moe R, Michel V, Lund V, Mejdell C. Air Quality in Alternative Housing Systems May Have an Impact on Laying Hen Welfare. Part I—Dust. Animals 2015; 5: 495–511. https://doi.org/10.3390/ani5030368

[19] Wang K, Shen D, Dai P, Li C. Particulate matter in poultry house on poultry respiratory disease: a systematic review. Poult Sci 2023; 102: 102556. https://doi.org/10.1016/j.psj.2023.102556

[20] Klentz RD, Fedde MR. Hydrogen sulfide: Effects on avian respiratory control and intrapulmonary CO_2 receptors. Respir Physiol 1978; 32: 355–67. https://doi.org/10.1016/0034-5687(78)90123-8

[21] Wang Y, Huang M, Meng Q, Wang Y. Effects of atmospheric hydrogen sulfide concentration on growth and meat quality in broiler chickens. Poult Sci 2011; 90: 2409–14. https://doi.org/10.3382/ps.2011-01387

[22] Adams R, Idemudia BI, Imarhiagbe EE, Ikhajiagbe B, Ukpebor E, Department of Chemistry, University of Benin, Benin City, Nigeria;, et al. Comparative assessment of indoor and outdoor air environment of poultry farms in Edo State, Nigeria. Stud Univ Babeş-Bolyai Biol 2022; 67: 107–30. https://doi.org/10.24193/subbbiol.2022.1.06

[23] Ogunleye TJ, Taiwo AM, Akinhannmi TF, Oyediran LO, Arowolo TA. Assessment of air quality, health status and lung function of workers from selected poultry management systems in Ogun State, Nigeria. Clin Epidemiol Glob Health 2022; 18: 101159. https://doi.org/10.1016/j.cegh.2022.101159

[24] Hy-Line International. UNDERSTANDING POULTRY LIGHTING : A Guide to LED Bulbs and Other Sources of Light for Egg Producers 2017.

[25] Farghly MFA, Alhotan RA, Mahrose KM, Attia YA, Abdelfattah M, Abougabal M, et al. Intermittent light program impacts on reproductive performance, health and welfare of breeding hens. Arch Anim Breed 2023; 66: 315–24. https://doi.org/10.5194/aab-66-315-2023

[26] H&N International. Lighting programs Part II 2021.

[27] Huber-Eicher B, Suter A, Spring-Stähli P. Effects of colored light-emitting diode illumination on behavior and performance of laying hens. Poult Sci 2013; 92: 869–73. https://doi.org/10.3382/ps.2012-02679

[28] Yu Y, Li Z. Research Progress and Effects of Light on Poultry Circadian Rhythm Regulation Based on CiteSpace. Appl Sci 2023; 13: 3157. https://doi.org/10.3390/app13053157

[29] Lufyagila B, Machuve D, Clemen T. IoT-powered system for environmental conditions monitoring in poultry house: A case of Tanzania. Afr J Sci Technol Innov Dev 2022; 14: 1020–31. https://doi.org/10.1080/20421338.2021.1924348

[30] Ahmed MM, Hassanien EE, Hassanien AE. A smart IoT-based monitoring system in poultry farms using chicken behavioural analysis. Internet Things 2024; 25: 101010. https://doi.org/10.1016/j.iot.2023.101010

[31] Chigwada J, Mazunga F, Nyamhere C, Mazheke V, Taruvinga N. Remote poultry management system for small to medium scale producers using IoT. Sci Afr 2022; 18: e01398. https://doi.org/10.1016/j.sciaf.2022.e01398

[32] Farmspeak Technology. Introducing Penkeep: Conquering Poultry Mortality, One Farm at a Time! 2023. https://medium.com/@farmspeakafrica/introducing-penkeep-conquering-poultry-mortality-one-farm-at-a-time-e8d548361d40

[33] Baku Inovasi Lestari. Poultry IOT Solution 2025. https://baku.global/en/smart-farming-poultry-iot-solution/ (accessed April 15, 2025).

[34] NYB Systems. Cloud-Based Smart Poultry Farm that Enhances Productivity, Saves Energy, and Builds a Better Planet 2024. https://nybsys.com/solutions/smart-poultry-farm/

[35] Tanaka T, Hurnik JF. Behavioral Responses of Hens to Simulated Dawn and Dusk Periods. Poult Sci 1991; 70: 483–8. https://doi.org/10.3382/ps.0700483

[36] Aimée Tchokanaka, Cheik Amadou Bello, Chambre Régionale d'Agriculture de Zinder. Fiche technico-économique poules pondeuses : Région de Zinder 2017.

[37] Morgan Pattison P, Hansen M, Tsao JY. LED lighting efficacy: Status and directions. Comptes Rendus Phys 2017; 19: 134–45. https://doi.org/10.1016/j.crhy.2017.10.013

[38] Akshay Sable, Tushar Dongre, Mayuresh Modase, Anjali Surushe, Vivek Diware. Brooding Systems in Poultry Farm a Review 2018.

[39] Hendrix Genetics. ISA Brown : Commercial Management Guide 2010.

[40] Hendrix Genetics. ISA Product Performance 2012.

[41] ACED. OPPORTUNITÉS D'AFFAIRES POUR LES JEUNES AU SEIN DES CHAINES DE VALEUR AGRICOLES 2017.

[42] Idrissou Y, Aboudou M, Worogo HSS, Seidou AA, Traoré IA. Diversity of poultry farming units in urban and peri-urban areas of North Benin 2018.