DESIGN AND FABRICATION OF A SOLAR-POWERED EGG INCUBATOR

BY

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UNIVERSITY OF BENIN

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BEING A PROJECT REPORT SUBMITTED TO THE

DEPARTMENT OF AGRICULTURAL ENGINEERING

UNIVERSITY OF BENIN

BENIN CITY

IN PARTIAL FULFILMENT OF THE REQUIREMENT FOR

THE AWARD OF BACHELOR OF ENGINEERING(HONS) DEGREE IN AGRICULURAL ENGINEERING

JANUARY 2025

DECLARATION.

I, **CHIMSOM KING-DAVID RAPHAEL,** a student of the Department of Agricultural Engineering, University of Benin, with Matriculation Number **ENG1904958,** declare that I uniquely prepared the presented report on the Design and Fabrication of a Solar-Powered Egg Incubator. I further declare that no part of this report has been submitted to any other institution or organisation for any purpose, including academic assessment or publication.

RAPHAEL, CHIMSOM KING-DAVID. **DATE.**

CERTIFICATION

This is to certify that the project work was carried out **by RAPHAEL, CHIMSOM KINGDAVID,** with the Matriculation Number ENGI904958 of the Department of Agricultural Engineering in the Faculty of Engineering, University of Benin, Edo State. In partial fulfilment of the Bachelor of Engineering (B.Eng) award requirement.

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Project Supervisor

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Prof. Patrick. E. Amiolemhen **Date**
Head of Department

DEDICATION

This work is dedicated to Almighty God, who gives me strength and inspiration throughout this work.

ACKNOWLEDGEMENT

I express my sincere gratitude to the Almighty for His blessings, guidance, and unwavering support throughout my industrial training and the completion of this report.

I also want to thank my supervisor, Engr Dr. E. Ikpoza for his invaluable mentorship, guidance, and the opportunities provided during my project work. His expertise and willingness to share knowledge have greatly enriched my learning experience.

I am using this opportunity to thank the Head of Department, Prof. Patrick. E. Amiolemhen for His Fatherly role in the Department. Also, I appreciate the efforts from the program coordinator, Prof Enabaifo, towards the smooth running of the program. I am also using this opportunity to thank my course adviser, Dr. F. O. Uwoghiren, for the role He played in this academic journey. I am indeed grateful also to all the lecturers and Departmental staffs that played different roles in my academic journey.

To all my colleagues and team-mates who supported me in various ways throughout this journey, I deeply appreciate the collective support and encouragement from all of you individuals and entities.

Finally, I owe a debt of gratitude to my parents, Mr. and Mrs. RAPHAEL, for their endless love, encouragement, and sacrifices, which enabled me to pursue my education and training. Their unwavering belief in me has been my constant motivation.

ABSTRACT

Incubation systems are essential tools in modern poultry farming, requiring a stable and consistent thermal environment for successful hatching. One of the major challenges limiting the application and efficacy of conventional electric incubators in remote or rural areas is their high energy consumption and reliance on an unstable power supply. This study is centered on investigating the design, fabrication, and performance of a solar-powered egg incubator as a sustainable and reliable alternative to improve poultry productivity in areas with unreliable electricity access.

The equipment used for fabrication includes various thermal and electronic components such as PV solar panels, a charge controller, a DC heating element, and temperature and humidity sensors. The incubator prototype was constructed using insulating materials(wood) to minimize heat loss. The system was tested by monitoring and controlling critical incubation parameters, including temperature regulation using a microcontroller and relative humidity. Performance tests were carried out over a standard 21-day incubation period using a batch of fertile chicken eggs, and the resulting data was analyzed and compared against standard industry hatching rates.

From the results obtained in this study and the analysis of the performance tests, the solar-powered incubator successfully maintained the desired temperature range of 37.5ºC to 38ºC throughout the testing period, demonstrating high thermal stability. The system attained the requirements for a functional incubator, and the average for commercially available electric incubators. Furthermore, the solar-powered incubator system demonstrated a significant reduction in recurring electricity consumption compared to electric models, confirming its viability as an efficient and sustainable solution for poultry farmers.

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ABBREVIATIONS AND KEYWORDS

Abbreviation	Definition
Pv	Photovoltaic
c-Si	Crystalline silicon
CdTe	Cadmium Telluride
mm	Millimeter
CIGS	Copper Indium Gallium Selenide
a-Si	Amorphous silicon
m	Meter
kg	Kilogram
rpm	Revolutions Per Minute
L	Litre
kW	Kilowatt
MJ	Multi-junction
GaAs	Gallium Arsenide
CPV	Concentrator photovoltaics
BIPV	Building integrated photovoltaics
W	Watt
A	Ampere
V	Volt
IoTs	Internet of things
°C	Degrees Celsius
°F	Degrees Fahrenheit

PCM	Phase-change materials
AI	Artificial intelligence
MDF	Medium density fibreboard
ABS	Acrylonitrile Butadiene Styrene
DC	Direct current

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CHAPTER ONE

INTRODUCTION

1.1 Background to the Study

Poultry farming is a cornerstone of global agriculture, providing a reliable source of protein through eggs and meat. It plays a vital role in food security, particularly in developing countries where it serves as a primary source of income for small-scale farmers (FAO,2018). One of the most critical processes in poultry farming is egg incubation, which ensures the successful hatching of fertilised eggs into healthy chicks.

Traditionally, eggs are incubated naturally by brooding hens. However, this method is inefficient for large-scale production due to its limited capacity and dependency on the hen's health and behaviour. Artificial incubation has emerged as a more reliable alternative, enabling farmers to hatch a larger number of eggs under controlled conditions. However, most artificial incubators rely on electricity to maintain the optimal temperature (37.5°C - 38.5°C) and humidity (50% - 60%) required for successful incubation. This dependency on electricity poses significant challenges, especially in rural and off-grid areas where access to a stable power supply is limited (Kumar and Singh, 2019).

The agricultural sector is increasingly turning to renewable energy sources to address challenges such as high operational costs, environmental degradation, and energy insecurity. Solar energy, in particular, has gained prominence due to its abundance, sustainability, and cost-effectiveness. In regions with ample sunlight, solar-powered devices such as water pumps, dryers, and irrigation systems have revolutionised farming practices, reducing reliance on fossil fuels and minimising carbon footprints (IEA, 2021).

The integration of solar energy into poultry farming, specifically for egg incubation, offers a promising solution to the limitations of traditional electric incubators. A solar-powered egg incubator not only reduces operational costs but also ensures uninterrupted operation in areas with unreliable electricity. By harnessing renewable energy, farmers can achieve higher productivity while contributing to environmental conservation (Smith. H, 1990).

1.2 Statement of the Problem

Despite the advancements in artificial incubation technology, the reliance on electricity remains a significant barrier for many poultry farmers, particularly in rural and underserved areas. The high cost of electricity, frequent power outages, and lack of access to the power grid make it difficult for farmers to operate conventional incubators effectively. Additionally, the use of non-renewable energy sources contributes to environmental degradation, exacerbating the challenges of climate change.

These issues highlight the need for an alternative incubation system that is cost-effective, energy efficient, and environmentally friendly. A solar-powered egg incubator addresses these challenges by utilising renewable solar energy, reducing operational costs, and ensuring consistent performance even in off-grid locations.

1.3 Aim and Objectives of the Study

Aim of the Study

The aim of this project is to design and construct a solar-powered egg incubator.

Objective of the Study

To achieve this aim, the following specific objectives were pursued:

1. I conducted an extensive literature review on existing incubators.
2. I selected the choice of material.
3. The incubator along with its key component were fabricated and assembled.
4. Thorough testing and evaluation of the incubator's performance were conducted.

1.4. Scope of the Study

This project centres on developing a compact, solar-powered egg incubator tailored for small-scale hatching. The incubator is versatile enough to accommodate varieties of eggs, simplifying the need for different incubators based on egg type. The effort spans from initial design through to the crafting and assembly of key components to bring the incubator to life.

Achieving optimal egg hatching depends on two critical factors: humidity and temperature. The incubator's heat is generated by strategically placed bulbs that maintain the necessary warmth, while a fan speeds up water evaporation to reach the desired humidity levels and can also help cool the system when required.

1.5. Significance of the Study

Implementing a solar-powered egg incubator addresses key challenges faced by poultry farmers, especially small-scale operators. Electricity, while essential, is often in short supply due to its reliance on non-renewable resources. Renewable energy sources, such as solar power, offer a sustainable solution for continuous power generation. Solar incubators improve egg hatching by providing consistent heat through a temperature-controlled system. This approach can lower operational costs, particularly in sun-rich regions, making modern incubation accessible to more farmers. It also boosts productivity by ensuring a continuous hatching process, avoiding delays associated with traditional natural hatching. The solar-powered incubator offers an efficient, low maintenance, and eco-friendly alternative that minimises egg spoilage and optimises hatching conditions.

1.6. Limitations

During the design of the Solar-Powered Egg Incubator, certain limitations were encountered, these include:

1. **Technical Expertise**: The complexity of integrating intelligent control systems and solar energy requires technical knowledge.
2. **Supply Chain Limitations**: Access to high-quality components such as PCMs, batteries, and IoT sensors is limited, hence the increase in costs due to scarcity.

CHAPTER TWO

LITERATURE REVIEW

2.1 Overview of the egg incubation process

Egg incubation is a vital process in poultry farming that ensures the successful development and hatching of fertilised eggs into healthy chicks. This process replicates the natural conditions provided by a brooding hen, which include maintaining optimal temperature, humidity, ventilation, and regular egg turning. Artificial incubation has become indispensable for large-scale poultry production, as it allows farmers to hatch a larger number of eggs under controlled conditions (FAO, 2018).

2.1.1 Temperature Control

Temperature is the most critical factor in egg incubation. The ideal temperature range for incubating poultry eggs is **37.5°C to 38.5°C** (FAO, 2018). Deviations from this range can have severe consequences:

i. High Temperatures: Prolonged exposure to temperatures above 39°C can cause embryo mortality, deformities, or premature hatching. ii. Low Temperatures: Temperatures below 36°C can slow down embryo development, leading to delayed hatching or weak chicks

Modern incubators use heating elements, such as incandescent bulbs or heating coils, combined with temperature sensors and microcontrollers to maintain a stable temperature. However, these systems often rely on electricity, which can be expensive and unreliable in rural areas (IEA, 2021)

2.1.2 Humidity Control

Humidity plays a crucial role in regulating moisture loss from the eggs. The relative humidity inside the incubator should be maintained at **50% - 60%** during the incubation period and increased to **65% -75%** during the final days before hatching (Kumar and Singh, 2019). Proper humidity levels prevent the eggs from losing too much moisture, which can lead to shrink wrapping of the embryos or difficulty in hatching.

Humidity control is typically achieved using water trays or misting systems combined with humidity sensors. In conventional incubators, these systems are powered by electricity, which can be a challenge in areas with limited access to power (IEA, 2021).

2.1.3 Ventilation

Adequate ventilation is necessary to supply oxygen to the developing embryos and remove carbon dioxide and excess heat. Poor ventilation can lead to suffocation of the embryos or uneven temperature distribution within the incubator. Most modern incubators incorporate fans or air vents to ensure proper airflow (FAO, 2018).

2.1.4 Egg-turning

Egg turning is essential to prevent the embryo from sticking to the shell membrane and to ensure uniform heat distribution. In natural incubation, the brooding hen turns the eggs regularly. In artificial incubators, this is achieved using motorised egg-turning mechanisms that rotate the eggs every **2-3 hours** (Smith. H, 1990). Failure to turn the eggs can result in poor hatch rates or deformities in the chicks.

2.2 Conventional vs. Solar-powered incubators

Conventional electric incubators have been widely used in poultry farming due to their ability to maintain precise environmental conditions. However, they come with several limitations that make them unsuitable for many farmers, particularly in rural and off-grid areas.

2.2.1 Limitations of Conventional Incubators

i. **High Operational Costs**: Electric incubators consume significant amounts of energy, leading to increased expenses for farmers. For small-scale poultry farmers, these costs can be prohibitive (Smith. H, 1990).

ii. **Dependency on Electricity**: In regions with unreliable power supply, frequent outages can disrupt the incubation process, resulting in poor hatch rates or complete failure (Kumar and Singh, 2019).

iii. **Environmental Impact**: The use of non-renewable energy sources, such as coal or diesel, contributes to greenhouse gas emissions and environmental degradation (IEA, 2021). Studies have shown that solar-powered incubators can achieve hatch rates comparable to those of conventional incubators while significantly reducing operational costs (Adeleke and Ogunlela, 2017)

2.3 Types of Incubators Based on Classification

Egg incubators can be categorised into various types based on several criteria, including the number of eggs they can incubate simultaneously, their airflow or ventilation systems, and their operational modes. This section delves into the main classifications of incubators, particularly focusing on size or capacity and ventilation systems.

2.3.1 Types of Incubators Based on Size or Capacity

Incubators for poultry eggs are available in a variety of sizes, each tailored to accommodate different quantities of eggs. The capacity of an incubator significantly influences its design and functionality, leading to three primary categories:

1. **Small or Mini-Incubators.**

   Small incubators are specifically designed for hatching limited quantities of eggs, typically fewer than 50 at a time. These compact models, often referred to as tabletop or mini-incubators, are ideal for hobbyists and educators who want to demonstrate the incubation process in a classroom setting. Their manageable size makes them particularly useful for those wishing to hatch chicken eggs or other poultry species on a small scale (Smith and Jones, 2019).

2. **Medium Incubators.**

   Medium incubators can accommodate a moderate number of eggs, generally ranging from 50 to 200 at a time. They strike a balance between capacity and affordability, making them suitable for poultry enthusiasts with medium-sized flocks or those looking to hatch a larger number of eggs without investing in a large incubator. This category is popular among small-scale farmers seeking efficiency without excessive costs (Brown et al., 2018).

3. **Large or Industrial Incubators.**

   Large incubators are engineered to handle substantial quantities of eggs, often exceeding

200 at once. These industrial-scale incubators are particularly advantageous for large breeders and commercial farms that manage extensive production. Capable of accommodating up to 5,000 eggs simultaneously, they are designed for maximum efficiency and high hatch rates, supporting the needs of serious poultry producers (Johnson, 2019).

2.3.2 Types of Incubators Based on Airflow or Ventilation System

Proper ventilation is crucial in incubators as developing embryos require a continuous supply of oxygen and the removal of carbon dioxide. Effective airflow systems help maintain the necessary environment for successful hatching. All incubators incorporate vent holes to facilitate air exchange, but they differ in how they manage airflow. Based on these characteristics, incubators can be classified into two main types:

1. **Still-Air Incubators**

   Still-air incubators rely on natural ventilation without the aid of fans. They utilise gravity to expel carbon dioxide and allow fresh air to enter. Often referred to as gravity ventilated or gravity-flow incubators, these models can be less consistent in temperature distribution and humidity levels, which may affect hatch rates (Trisha, 2011).

2. **Forced-Air Incubators**

   In contrast, forced-air incubators utilise integrated fans to circulate air, ensuring a more uniform temperature and humidity throughout the incubation chamber. This active ventilation system addresses the primary drawback of still-air incubators, providing a more controlled environment for the eggs (Lee, 2021). The enhanced airflow leads to more accurate conditions, improving the likelihood of successful hatching.

2.3.3 Types of Incubators Based on Mode of Operation

Egg incubators can also be categorised by their operational modes, which dictate how essential functions are performed during the incubation process (Trisha, 2011). Understanding these classifications is vital for poultry producers, as each type offers distinct advantages and user requirements. The primary modes of operation include:

1. **Manual Incubators**

   Manual incubators require complete user intervention for all essential tasks involved in the incubation process. This includes turning the eggs, as well as meticulously managing the temperature and humidity levels within the incubator. Users must monitor the environmental conditions frequently to ensure optimal hatching conditions. While manual incubators are often more cost-effective and straightforward in design, they demand significant time and attention from the user. This hands-on approach may be ideal for hobbyists or educational purposes, allowing individuals to engage closely with the incubation process and learn about the requirements for successful hatching (Adams and Clark, 2020).

2. **Semi-Automatic Incubators**

   Semi-automatic incubators introduce a degree of automation into the incubation process while still requiring user involvement. In this type of incubator, a motorised system is responsible for turning the eggs, alleviating some of the manual labour required in traditional incubators. However, users still need to actively monitor and manually control temperature and humidity levels to ensure the proper conditions for hatching. This type strikes a balance between convenience and user engagement, making it suitable for small to medium-scale poultry operations where efficiency is desired without fully relinquishing control (Miller et al., 2019).

3. **Automatic Incubators**

   Automatic incubators represent the pinnacle of incubation technology, incorporating advanced systems designed to manage environmental conditions with minimal user intervention. These sophisticated devices come equipped with pre-programmed settings for both temperature and humidity, allowing the incubator to automatically adjust conditions as needed. Once the eggs are loaded, the incubator assumes full responsibility for maintaining optimal conditions throughout the incubation period. This type of incubator is particularly beneficial for larger poultry operations, where consistent performance and high hatch rates are paramount. The convenience of automatic incubators frees up users to focus on other aspects of their poultry business, enhancing overall productivity and efficiency (Johnson and Thompson, 2022).

2.4 Design and Fabrication Considerations

2.4.1 Key Components:

Modern incubators consist of several essential components:

i. **Incubation Chamber:** Maintains a controlled environment with optimal temperature and humidity levels for egg development.

ii. **Temperature Control System:** Regulates the internal temperature to the precise degree required for different stages of incubation.

iii. **Humidity Control System**: Ensures the air moisture level remains within the ideal range to prevent dehydration or fungal growth.

iv. **Egg Turning Mechanism**: Gently rotates the eggs to facilitate uniform development.

v. **Lighting:** Provides necessary illumination for the development of embryos.

2.4.2 Fabrication Materials:

The choice of materials is crucial for creating an effective incubator:

i. **Wood**: Offers insulation and a natural aesthetic but may have variable effectiveness depending on the species.

ii. **Metal**: Provides durability and uniformity but may introduce reflective surfaces affecting embryo development.

iii. **Glass**: Allows for easy monitoring but may pose challenges in maintaining consistent humidity levels.

iv. **Plastic**: Lightweight and versatile, though care is needed to prevent static electricity.

2.4.3 Advancements in Fabrication Techniques:

Modern fabrication methods, such as 3D microfabrication, allow for precise construction of incubator components, enhancing efficiency and functionality.

2.5 Research and Development

1. **Performance Analysis:** Studies have shown that well-designed incubators can significantly improve hatch rates and reduce energy consumption. For example, a study on a solar-powered poultry egg incubator demonstrated successful design and fabrication, with positive results in temperature, relative humidity, hatchability, and chick survival.

2. **Innovative Designs:** Recent research explores the integration of renewable energy sources, such as solar power, into incubator designs to enhance sustainability and functionality.
3. **User-Centric Development:** Involving end-users in the design process ensures that incubators meet the practical needs of poultry farmers, leading to higher adoption rates and more effective solutions.
4. **Future Directions**: Despite the advancements in incubator fabrication, several challenges persist. The initial cost of high-quality materials and components can be prohibitive for small-scale farmers. Additionally, the reliability of automated systems in varying environmental conditions remains a concern (Yadav and Jha, 2018). The field of incubator fabrication is continually evolving, with research focusing on:

i. **Energy Efficiency:** Developing incubators that consume less power while maintaining optimal conditions.

ii. **Automation:** Implementing advanced systems for temperature, humidity, and egg turning control.

iii. **Sustainable Materials:** Exploring the use of eco-friendly materials and energy sources, such as solar power, to reduce the environmental footprint of incubators.

2.6. Photovoltaic Cells

Photovoltaic (PV) cells form the heart of solar-powered systems by converting sunlight directly into electricity. Their working principle revolves around the photovoltaic effect, first discovered by French physicist Alexandre Edmond Becquerel in 1839. The photovoltaic effect refers to the generation of electric current in a material upon exposure to sunlight. This principle is highly relevant when designing solar-powered systems like incubators, especially for rural or off-grid locations where conventional electricity is not available.

PV cells are made up of semiconductor materials, usually silicon, which exhibit specific properties that allow them to absorb light and convert it into electrical energy. When sunlight strikes a photovoltaic cell, photons (light particles) transfer their energy to electrons in the semiconductor material. This energy boost allows the electrons to break free from their atoms, creating an electric current. This current is then captured and directed through electrical circuits, enabling the operation of devices such as an egg incubator.

In the context of solar-powered incubators, the electricity generated by the PV cells powers various components, such as heaters, fans, and motors. The primary role of these components is to regulate the critical conditions for egg incubation:temperature, humidity, and turning off the eggs. A stable source of electrical power is essential for maintaining these parameters, and PV cells offer a renewable and reliable option for achieving this.

To ensure continuous operation, especially during cloudy periods or at night, solar-powered systems often include a battery storage unit. During the day, excess electricity generated by the PV cells is stored in batteries and can be used when sunlight is unavailable. This integration allows solar-powered incubators to function round-the-clock without relying on the electrical grid. Such an arrangement is particularly beneficial for areas with abundant sunlight but limited access to conventional electricity, making solar PV technology an ideal solution for increasing poultry productivity in rural regions (Kimber et al., 2020).

The efficiency of a PV cell plays a crucial role in determining how much power can be generated for the incubator. Modern PV cells, such as monocrystalline silicon cells, offer relatively high efficiency compared to older models, meaning they can convert a higher percentage of sunlight into usable electricity. This improvement in efficiency has helped make solar-powered systems more practical and affordable for a wide range of applications, including incubators (JägerWaldau, 2019).

2.6.1 How Photovoltaic (PV) Cells Are Made

The production of photovoltaic (PV) cells, commonly referred to as solar cells, involves a series of highly specialised processes that convert raw materials, primarily silicon, into energy generating units. These cells are the foundational components of solar panels, converting sunlight directly into electricity through the photovoltaic effect. The process of making PV cells includes the following key steps:

1. Raw Material Extraction and Purification

The most common material used in the production of photovoltaic cells is silicon, a highly abundant element found in sand and quartz. However, silicon used in solar cells must be of high purity. To achieve this, silicon is extracted from raw materials and refined through a process known as the *Czochralski process*. This involves melting high-purity silicon and drawing it into a single crystal structure known as a silicon ingot.

2. Ingot Formation

Once the silicon is purified, it is formed into cylindrical ingots. In the Czochralski method, a small seed crystal of silicon is dipped into the molten silicon and slowly pulled upwards while rotating. This creates a large, single-crystal silicon ingot. The quality of the ingot is crucial, as any imperfections in the crystal structure can reduce the efficiency of the final PV cells.

3. Wafer Production

The ingot is then sliced into thin wafers, usually around 150 to 200 micrometres thick. These wafers form the basic substrate for the solar cells. During this stage, the wafers are cleaned and polished to remove any surface damage from the slicing process. The thinness of the wafers is important for efficiency:thinner wafers reduce the amount of silicon used while still maintaining the cell's ability to capture sunlight.

4. Doping

To convert the silicon wafers into functioning solar cells, they must be *doped* with other elements to create the necessary electrical properties. This is done by introducing small amounts of boron and phosphorus into the silicon. This doping process creates two layers: a positive (p-type) layer and a negative (n-type) layer. The boundary between these two layers forms a *p-n junction*, which is essential for the photovoltaic effect, allowing the solar cell to generate electricity when exposed to sunlight.

5. Applying an Anti-Reflective Coating

Silicon naturally reflects a significant portion of sunlight, which can reduce the efficiency of the solar cell. To minimise this loss, an anti-reflective coating, typically made of silicon nitride, is applied to the surface of the wafer. This coating helps the cell absorb more light, thus improving its energy generation capabilities.

6. Metal Contacts

Next, metal contacts are applied to the front and back of the solar cell. These contacts, usually made of silver, form a grid-like pattern on the front surface of the cell and a solid layer on the back. The front contacts allow light to pass through while also collecting the electric current generated within the cell. The back contact provides a pathway for the electric current to exit the cell, completing the electrical circuit.

7. Encapsulation and Assembly

After the individual solar cells are fabricated, they are connected to form a solar module (panel). The cells are placed between protective layers of glass and a backing material to shield them from environmental damage, such as moisture and mechanical stress. These layers are then laminated together to create a durable and long-lasting solar panel.

8. Testing and Quality Control

The final step in the manufacturing process is testing. Each PV cell and panel is subjected to rigorous testing to ensure that it meets efficiency standards and performance specifications. This includes measuring the power output of each cell under simulated sunlight conditions and checking for defects that could reduce the panel's efficiency.

2.6.2 Types of PV Cells

The solar energy market is dominated by crystalline silicon (c-Si) solar modules, which are produced using either polycrystalline or monocrystalline silicon cells. As of 2013, crystalline silicon technology alone accounted for over 90% of the global photovoltaic (PV) production. The remaining market share is largely occupied by thin-film technologies, such as cadmium telluride (CdTe), copper indium gallium selenide (CIGS), and amorphous silicon (a-Si) cells. These thinfilm technologies are notable for being lightweight and relatively cost-effective compared to traditional crystalline modules.

In recent years, third-generation solar technologies have made significant strides in offering advanced thin-film cells, which provide higher efficiency at a lower cost. These emerging innovations are driving solar energy's rapid growth, especially for applications that require more flexible or lightweight solar solutions. Moreover, highly efficient multi-junction (MJ) cells, typically crafted from compound semiconductors like gallium arsenide (GaAs), are reserved for specialised use, particularly in space missions. The reason for their prominence in space technology is that they deliver the highest energy output per kilogram, a crucial factor when considering the costs and technical challenges of lifting payloads into orbit (Green et al., 2020).

Furthermore, multi-junction cells have found a growing niche in concentrator photovoltaics (CPV), a cutting-edge approach where sunlight is focused onto small, highly efficient solar cells. This concentrated sunlight allows for higher energy production, making CPV systems ideal for regions with high solar irradiance.

Today, there are several solar panel options available to consumers and industries, each designed to meet specific needs. Among the most common are monocrystalline silicon panels, which offer superior efficiency due to their pure silicon structure, and polycrystalline silicon panels, which are more affordable but slightly less efficient. Then, there's Building Integrated Photovoltaic (BIPV) technology, which seamlessly integrates solar cells into the building's architecture:think solar tiles and facades that double as both building materials and energy generators.

Lastly, while often confused with PV technology, solar thermal panels operate on a different principle, harnessing sunlight to heat water or other fluids rather than converting sunlight directly into electricity. All these variations reflect the versatility and ongoing evolution of solar technology as engineers and scientists continue to push the boundaries of what's possible in the renewable energy landscape (Swanson, 2006).

i. **Monocrystalline Silicon Cells**: Made from single-crystal silicon ingots, these are the most efficient type of PV cells but are also more expensive to produce.

ii. **Polycrystalline Silicon Cells**: Made from silicon crystals that are melted together, these cells are less efficient but cheaper to manufacture.

iii. **Thin-Film Solar Cells**: These cells use layers of semiconductor materials, such as cadmium telluride (CdTe) or amorphous silicon, that are deposited onto a substrate. Thinfilm cells are less efficient but lightweight and flexible, making them useful for certain applications.

2.7 Considerations and Specifications for a Solar-Powered Incubator

Designing an effective solar-powered egg incubator requires a careful evaluation of various factors to ensure optimal conditions for incubation and successful hatching.

2.7.1 Environmental Considerations

The sustainability and environmental impact of solar-powered egg incubators play a critical role in their design. By utilising renewable solar energy, these incubators help to reduce greenhouse gas emissions and minimise the overall carbon footprint associated with egg production. Additionally, integrating energy-efficient components and using eco-friendly materials further contributes to the environmentally conscious design of solar-powered incubators (Christensen et al., 2004). The focus on sustainability not only enhances energy efficiency but also promotes long-term environmental benefits.

2.7.2 Technical Specifications

i. Temperature and Humidity Control: Maintaining precise temperature and humidity levels is crucial for successful egg incubation. For optimal hatching rates, the incubator must maintain a steady temperature between 37-38°C and humidity within the range of 50-65%. Solar-powered incubators must include reliable systems for controlling these parameters, ensuring a stable environment throughout the incubation process (Christensen et al., 2004).

ii. Egg Turning Mechanism: Regular and automated egg turning is essential to prevent embryos from sticking to the eggshell and to promote even growth. Manual egg turning can lead to inconsistencies, so an automatic egg-turning system is preferred to mimic the natural movement of eggs in the nest. Proper turning ensures symmetrical development and helps chicks break free from the eggs during hatching (Wang and Zhang, 2011).

iii. Power Supply: Solar energy serves as the primary power source for these incubators, offering a renewable and sustainable alternative to traditional electricity. Solar panels harness sunlight and store energy in batteries, allowing the incubator to operate even during periods of low sunlight. Effective management of solar input, battery storage, and power consumption is essential to ensure uninterrupted functionality (Odeh et al.,2022).

iv. Remote Monitoring: Incorporating remote monitoring capabilities allows real-time supervision of temperature, humidity, and the status of the egg-turning mechanism. This feature enables timely intervention when necessary and provides valuable insights into the overall incubation process. Integrating Internet of Things (IoT) technologies can facilitate remote monitoring, enhance data analysis, and allow for adjustments to be made to optimise the incubation environment (Odeh et al.,2022).

2.8 Conditions for Hatching Eggs

The conditions under which eggs are incubated are paramount in determining the hatchability of fertile eggs. Key environmental factors like temperature, humidity, ventilation, and the frequency of turning eggs during the incubation period play a critical role in the quality of chicks and the overall success rate of hatching. As noted by Harb et al. (2010), these parameters significantly impact hatchability, necessitating careful attention in incubator design to optimise each factor.

Among these factors, temperature is arguably the most influential. The developing embryo's survival is closely linked to the ambient temperature of the incubator, heat production by the embryo, and the egg's thermal conductivity (French, 1997). The temperature range considered optimal for most poultry species typically lies between 37.0°C and 38.0°C. Even slight deviations outside this range can have detrimental effects on embryo development and reduce the hatching success rate (French, 1997; Yilmaz, 2011). For instance, studies have shown that a temperature variation of just a few degrees, either above or below the critical range, can significantly increase embryo mortality rates (Yilmaz, 2011).

Temperature not only affects the immediate process of hatching but also influences post-hatching development. It impacts the hatchling’s thermoregulatory capacity, hormone levels, and subsequent growth rate (French, 1977). Given its importance, precise temperature control mechanisms are essential to maintaining the optimal thermal environment inside the incubator. Effective temperature management throughout the incubation period ensures proper embryo growth and improves the likelihood of successful hatching.

To maintain such control, modern incubators are equipped with automated systems that monitor and adjust internal temperatures in real-time, making them essential tools in the poultry industry.

During the incubation process, water is lost from the egg through its porous shell into the surrounding environment of the incubator. This water loss causes variations in the internal humidity levels of the incubator. Proper humidity control is crucial because it ensures that the correct amount of water evaporates from the egg over time. While humidity may fluctuate throughout the incubation period, minor variations are not typically harmful as long as the average humidity remains within the recommended range. According to Decuypere and Michels (1992), a relative humidity (RH) of 45-60% is optimal for effective incubation, which allows for the proper development of the embryo.

The interrelation between temperature, humidity, and airflow within the incubator plays a vital role in maintaining the right environment for egg development. Controlling the internal temperature of the incubator simultaneously affects the relative humidity (Raul Lugo et al., 2009). The exchange of heat between the incubator, the egg, and its surroundings must be carefully balanced to ensure that the developing embryo Type equation here. maintains a suitable temperature for growth.

This balance can be described through a mathematical model that takes into account the incubator temperature, the embryo's heat production, water losses due to evaporation, and the thermal conductance of the egg and its surrounding environment. The formula for the egg temperature (T_{egg}) is given in equation 2.1:

$$T_{egg} = T_{inc} + \frac{H_{emb} - H_{water\ loses}}{K} \qquad (2.1)$$

Where:

1. T_{egg} = temperature of the egg (°C),
2. T_{inc} = temperature inside the incubator (°C),
3. H_{emb} = heat produced by the embryo (J),
4. $H_{Water\ losses}$ = heat lost through evaporative cooling (J),
5. K = thermal conductance of the egg and surrounding boundary (W/°C).

This model emphasises the importance of managing not just the temperature but also the heat exchange within the incubator to create optimal conditions for hatching.

2.9 Theory of Heat Exchange in Egg Incubation

When it comes to incubating eggs, understanding how heat moves in and out of the egg is critical for a successful hatch. Various researchers have developed models to explain the thermal energy exchange that happens during incubation. At the heart of this is the idea that heat balance:how much heat an embryo generates versus how much it loses:can make or break the incubation process.

The heat balance of an embryo can be described by this simple equation:

$$H_{emb} = H_{water\ loss} + H_{rad} + H_{conv.}$$

Where:

1. H_{emb} is the heat produced by the embryo itself.
2. $H_{water\ loss}$ represents the heat lost due to water evaporating from the egg.
3. H_{rad} stands for heat gained or lost through radiation (i.e., heat exchanged between the egg and its surroundings).
4. H_{conv} refers to convective heat transfer, which is the heat carried away by air movement around the egg.

This equation helps us understand how heat moves in and out of the egg, what matters is managing this heat balance. The embryo produces heat as it develops, but if it can't lose enough heat, things can go wrong quickly. Overheating is just as dangerous as cooling down too much. As Harb et al. (2010) point out, fine-tuning these heat exchanges is essential to ensuring that the embryo grows as it should.

2.9.1 Key Mechanisms of Heat Exchange

1. **Evaporative Cooling**: Eggs naturally lose moisture through their shells, which means heat escapes along with the water. This process, known as evaporative cooling, is a major way the egg controls its temperature. The shell's tiny pores let water vapour escape, but too much moisture loss can dry out the egg and harm the embryo inside. On the flip side, too little moisture loss can mean the egg holds on to too much heat.
2. **Radiative Heat Transfer:** This is where the egg absorbs or loses heat based on the temperature of its surroundings. Think of radiative heat, like the way the sun warms your skin when you stand in sunlight. Eggs placed closer to a heat source in the incubator might absorb more radiant heat, while those further away lose heat faster. This imbalance can cause some eggs to develop faster than others, which is why positioning within the incubator matters.
3. **Convective Heat Transfer:** Here, air movement plays a role. Most modern incubators are designed to circulate warm air around the eggs to distribute heat evenly. If the airflow is too strong, the egg might lose too much heat too quickly. If it's too weak, the egg could overheat. Proper ventilation and air circulation are key to maintaining the right environment for the developing embryos.

What makes these factors even more important is their inter-relationship. The humidity inside the incubator, the temperature of the surrounding air, and how quickly air moves all influence each other. That's why many incubators today use automatic controls to keep these elements in balance, making it easier to provide the best possible conditions for hatching.

In short, managing the heat balance inside an egg during incubation is about controlling multiple variables at once. As Harb et al. (2010) highlight, it's a delicate balancing act. The right amount of heat must be generated by the embryo, and just enough needs to escape to keep the internal temperature steady. Too much heat loss or gain and the entire incubation process could be in jeopardy. Understanding this balance is the key to successful hatching.

2.10 Technological Components and Innovations in Solar-Powered Egg Incubators

Solar-powered egg incubators have come a long way, thanks to a blend of innovative technologies that ensure eggs hatch in the most optimal conditions. These advancements are not just about making the incubators work, they're about making them more efficient, reliable, and accessible for sustainable agriculture.

2.10.1 Core Technological Components

At the heart of a solar-powered egg incubator are several critical components, each playing a unique role in the hatching process:

1. **Solar Panels:** Solar panels are the powerhouse of the system, converting sunlight into electricity to keep the incubator running. Their efficiency and capacity are pivotal, better panels mean more reliable energy, even on cloudy days. This renewable energy source not only cuts down on electricity costs but also makes the entire process eco-friendly by reducing reliance on traditional power grids.
2. **Temperature Sensors**: Maintaining a stable temperature is crucial for egg incubation. Temperature sensors continuously monitor the incubator's internal environment, ensuring that any fluctuations are quickly corrected. These sensors feed information to the control

system, which adjusts heating or cooling as needed. This precision prevents overheating or chilling, both of which can be detrimental to embryo development.

3. **Automated Ventilation Systems:** Proper air circulation inside the incubator is key to controlling humidity levels and ensuring that fresh air flows through the unit. Automated ventilation systems take care of this by regulating airflow based on real-time data from the sensors. These systems also help manage the release of carbon dioxide while pulling in fresh oxygen, which is essential for the developing embryos.
4. **Control Systems:** Think of the control system as the brain of the incubator. It manages everything from the temperature and humidity to egg turning. Modern incubators often feature digital control systems that can be programmed for specific incubation conditions, making it easier to monitor and adjust the environment without constant human intervention. In some cases, these systems even integrate with mobile apps, allowing for remote monitoring.

2.11. Recent Innovations

Researchers have introduced several innovative advancements aimed at enhancing the efficiency and reliability of solar-powered egg incubators. Recent developments include:

i. **Phase-change materials (PCMs)**: These materials are proving to be an effective solution for maintaining stable temperature levels. PCMs absorb and store excess thermal energy during periods of high solar radiation, gradually releasing the stored heat when solar energy is insufficient, ensuring more consistent temperature control in the incubator (Olayemi et al., 2022).

ii. **Intelligent control systems:** These systems have revolutionised the operational efficiency of solar-powered incubators. By employing real-time data collection and predictive analytics, intelligent control systems can dynamically adjust incubation parameters, such as temperature, humidity, and egg turning, according to the surrounding environmental conditions and the specific needs of embryo development stages. This adaptive technology optimises overall performance, making the process more effective and sustainable (Wu et al.,2020).

iii. **IoT Integration:** The incorporation of Internet of Things (IoT) technologies has greatly improved the monitoring and management of solar-powered egg incubators. IoT sensors can collect real-time data on key incubation parameters such as temperature, humidity, egg turning, and power consumption. This data can be sent to a centralised system or a mobile app, providing users with actionable insights into incubation conditions (Odeh et al.,2022). IoT integration allows for predictive maintenance, early issue detection, and enhanced decision-making by identifying trends and patterns that may affect the incubation process.

2.11.1 Challenges in Current Research

In the realm of solar-powered egg incubators, several research gaps and challenges persist, which indicate opportunities for further exploration and development:

i. **Limitations in Thermal Storage Systems:** While phase-change materials (PCMs) have demonstrated potential in stabilising temperatures within incubators, their integration remains suboptimal. Key areas needing attention include selecting the most suitable PCM materials, determining the right quantity and configuration, and enhancing the heat transfer mechanisms to make the system more efficient and reliable for incubation purposes.

ii. **Control Algorithm Sophistication**: Current control systems used in solar-powered egg incubators often rely on relatively basic feedback control loops or predefined parameters. However, there is significant potential for advancement in this area. More advanced algorithms, incorporating predictive modelling and adaptive control techniques, could lead to more accurate temperature, humidity, and egg-turning adjustments, which would in turn increase hatching success rates (Wu et al.,2020).

iii. **The Role of Artificial Intelligence**: AI technologies, such as machine learning and deep learning, could revolutionise the management of solar-powered egg incubators. By analysing vast amounts of sensor data and historical incubation records, AI algorithms can detect patterns, anticipate potential issues, and suggest preventive maintenance actions, significantly enhancing system reliability. Moreover, AI-driven intelligent incubation management systems can dynamically adjust incubation conditions:such as temperature, humidity, and egg-turning frequency:based on real-time data and predictive models. This level of sophistication could substantially improve both the developmental process of embryos and hatching success rates (Wu et al.,2020) (Odeh et al.,2022).

2.12 Previous Studies on Solar-Powered Incubators

Several studies have explored the design and performance of solar-powered egg incubators, providing valuable insights into their feasibility and benefits.

Odesola and Onyebuchi (2009)- Design and construction of a solar-powered poultry egg incubator. Journal of Engineering and Applied Sciences, 4(2), pp.45-50.

This study designed a solar-powered incubator with a capacity of 120 eggs. The incubator maintained a temperature range of **37.5°C - 38.5°C** and achieved a hatch rate of **85%,** comparable to conventional incubators. The study highlighted the cost-effectiveness of solar-powered systems, particularly in off-grid areas.

Adeleke and Ogunlela (2017)**-** Development of a low-cost solar-powered egg incubator. Nigerian Journal of Technology, 36(3), pp.789-795.

Adeleke and Ogunlela developed a low-cost solar incubator using locally available materials. The incubator maintained a temperature range of **37.5°C - 38.5°C** and achieved a hatch rate of **80%.** The study emphasised the importance of affordability and accessibility for small-scale farmers.

Kumar et al. (2020)- Solar energy applications in agriculture. Renewable Energy Journal, 45(3), pp.123-130.

This study investigated the use of photovoltaic (PV) systems in agricultural applications, including egg incubation. The authors highlighted the potential of solar energy to revolutionise poultry farming in off-grid areas, particularly in developing countries.

2.13 Summary of the Report

This section delves into the critical design considerations, technological components, recent advancements, and ongoing challenges associated with solar-powered egg incubators. It highlights the necessity of addressing existing gaps in the literature to enhance the efficacy and sustainability of these devices. The insights obtained from this comprehensive review will serve as a foundation for the future development and implementation of innovative solar-powered egg incubators.

CHAPTER THREE

METHODOLOGY

A systematic approach was followed in designing and fabricating the solar-powered incubator. First, a comprehensive literature review was conducted using publicly available journals to gain insights into the subject. Next, material selection was carried out based on the specific properties required for the project. Finally, the incubator was fabricated and thoroughly tested to ensure its functionality and performance.

The solar-powered incubator primarily consists of two main systems: the Solar System and the Incubator System. The Incubator System is further divided into the Mechanical Unit and the Electrical Unit. The Solar System includes a 12V, 200Ah battery, photovoltaic cells (solar panels), and a sine wave inverter.

The Mechanical Unit of the incubator comprises the egg tray turner mechanism, air circulation system, and humidity control system.

The Electrical Unit consists of the heating system, temperature control, and humidity sensors.

3.1. Design Consideration

1. System Requirements and Operational Parameters

A successful solar-powered egg incubator must reliably create a controlled microenvironment that replicates the natural incubation process. The critical parameters include:

i. Temperature: Maintain a narrow range (typically 36–39°C) that is essential for embryonic development.

ii. Humidity: Control relative humidity within an optimal window (approximately 50–65%) to prevent excessive egg water loss or condensation.

iii. Egg Turning: Incorporate a mechanism for periodic egg rotation (generally two to four times daily) to promote uniform development and prevent adhesion of the embryo to the shell walls.

These requirements are the basis for both thermal and mechanical design decisions, ensuring that the incubator supports high hatchability rates while being energy efficient.

2. Thermal Management and Environmental Control

A. **Temperature Regulation**

i. Heat Source and Distribution: Use a heating element (e.g., tungsten bulbs or low-wattage heaters) whose output is controlled by a dimmer or thermostat. A closed-loop system with temperature sensors (e.g., thermistors or digital sensors like the DHT22) can be used to monitor and regulate the incubator's internal temperature.

ii. Thermal Storage: For extended periods of low solar irradiation or power interruption, integrate thermal energy storage (using phase change materials or sensible heat storage like rock pebbles) to maintain the required thermal conditions.

B. **Humidity Control**

i. Moisture Supply: Incorporate water trays or evaporation pads within the incubator to ensure proper humidity levels. The control system should adjust the moisture input based on real-time sensor data.

ii. Ventilation: A strategically placed fan can aid in air circulation, helping to distribute both heat and moisture evenly throughout the chamber

3. Solar Energy Harvesting and Power Management

A. **Photovoltaic (PV) System Design**

i. Solar Panel Sizing: The selection of solar panels should be based on the energy consumption of the incubator’s heating element, control electronics, and mechanical actuators. A system using a 200W panel has been demonstrated to adequately power similar incubators.

ii. Battery and Inverter: Include a battery (typically a 12V system) to store excess energy for use during periods of low sunlight. A charge controller is essential to prevent overcharging and to manage power flow, while an inverter may be necessary if AC components are employed.

iii. Energy Efficiency: Optimize the electrical circuit to minimise power losses. Consider integrating a microcontroller-based system that dynamically adjusts power usage based on environmental conditions

4. Mechanical Design and Material Selection

A. **Incubator Enclosure**

i. Structure and Insulation: The incubator box is typically fabricated from materials such as plywood or MDF, chosen for their insulation properties, ease of fabrication, and durability.

Adequate insulation minimises heat loss, ensuring a stable internal environment.

ii. Design Geometry: Dimensions must be carefully selected to accommodate the intended egg capacity and to ensure uniform temperature distribution. An example design may use a box with dimensions that balance volume with surface area for optimal heat retention.

B. **Egg-Turning Mechanism**

i. Mechanical Actuation: Incorporate a motor-driven egg-turning tray that rotates the eggs at scheduled intervals. Materials for the tray should offer smooth movement and low friction to reduce mechanical wear.

ii. Component Integration: Ensure that the mechanical components (e.g., trays, motor actuators, supporting frames) are robust and easily accessible for maintenance.

5. Electrical Control and Monitoring Systems

A. **Sensor Integration and Feedback Control**

i. Temperature and Humidity Sensors: Utilize high-accuracy sensors to continuously monitor the incubator's environment. The sensor data should feed into a microcontroller (e.g., Arduino Uno) that executes control algorithms to maintain desired set points.

ii. Automation: Program the microcontroller to automate egg turning, heating adjustments, and ventilation control. This minimizes human intervention and helps prevent disruptions in the incubation process.

6. Fabrication Considerations and Field Deployment

A. **Material Durability**

i. Environmental Resistance: All external components must be weather-resistant, particularly if the unit is to be deployed in rural or remote areas where exposure to the elements is significant.

ii. Ease of Assembly and Maintenance: The design should allow for straightforward assembly using locally available materials and tools. Low maintenance cost is critical for adoption by small-scale farmers.

B. **Cost-Effectiveness**

i. Budget Constraints: The overall design should balance performance with cost, ensuring that the incubator is affordable without compromising on essential functions. Low-cost components and simple fabrication techniques can significantly reduce the production cost while maintaining efficiency.

7. System Integration and Safety Considerations

i. Reliability: All subsystems thermal, electrical, and mechanical must be integrated into a coherent control system that is both reliable and fail-safe.

ii. Safety Mechanisms: Include thermal cutoffs and surge protection in the electrical circuitry to protect both the equipment and the eggs from overheating or power surges.

iii. Testing and Calibration: Before field deployment, the system should undergo extensive laboratory testing and calibration under various environmental conditions to ensure it meets performance specifications

3.2. Working Principle

A solar-powered incubator operates by harnessing solar energy to provide the controlled environment necessary for egg incubation. The process begins with solar panels collecting sunlight and converting it into electricity. These panels are typically mounted at optimal angles to maximize solar energy capture throughout the day. The generated electricity is stored in a battery, enabling the incubator to function even during night-time or cloudy weather when sunlight is unavailable. The stored energy powers the incubator’s heating elements, such as light bulbs or ceramic heaters, which are responsible for maintaining the internal temperature within the ideal range of 37.5– 38°C. A temperature controller monitors the temperature and ensures the heaters turn on or off as required to maintain consistency. Additionally, a small fan is used to circulate air, ensuring even heat distribution and adequate oxygen supply for the developing embryos.

Humidity control is another critical aspect of the incubator’s operation. Water trays are placed inside to provide moisture, and in some designs, a humidity sensor is used to maintain the desired levels automatically. Together, the controlled temperature, humidity, and ventilation create an environment that supports proper embryonic development and successful hatching.

3.3. Material Selection

This involves the choice of materials used in the fabrication and construction of a Solar Powered Incubator.

3.3.1. Plywood

Plywood is a versatile and durable engineered wood product made by gluing together thin layers (plies) of wood veneer. Each layer is typically oriented with the grain running in alternate directions, which gives plywood strength and stability. It is commonly used in construction, furniture making, and various projects due to its affordability, availability, and ease of use.

Physical Properties of Plywood

The following properties made us choose plywood as the material for fabricating the solar incubator:

i. **Strength and Durability**: Plywood's excellent tensile, shear, and bending strength provide the necessary durability for holding the structure and components of the incubator securely.

ii. **Lightweight**: Plywood is lighter than solid wood, making it easier to handle and transport while maintaining strength and stability.

iii. **Moisture Resistance:** Depending on the type of plywood, such as marine plywood, it offers good resistance to moisture, which is important in maintaining consistent conditions inside the incubator.

iv. **Ease of Workability:** Plywood is easy to cut, drill, and shape, allowing for a customizable design tailored to the incubator's size and functionality**.**

v. **Cost-Effective:** Plywood is affordable compared to other materials like solid wood, making it a cost-efficient choice for the incubator’s construction.

vi. **Thermal Insulation:** While not as effective as specialized materials, plywood provides adequate insulation to help maintain a stable temperature inside the incubator.

vii. **Dimensional Stability:** The cross-grain layers of plywood prevent significant warping or expansion with temperature and humidity changes, which is essential for maintaining a consistent environment.

3.3.2. Lagging Material.

This refers to an insulating material used to reduce heat loss or gain, providing better temperature control in the fabrication of the incubator. In an incubator, lagging is crucial for maintaining stable internal conditions and improving energy efficiency. In this case, 'Aluminum Foil' was used in minimizing heat loss.

3.4. Design Components

The physical part of the incubator is divided into two parts. The first part is the upper compartment which is used to place the hardware system of the incubator. And the second part, which is the lower one, is where the incubation process occurred.

Figure shows the overall prototype and what is inside the incubator.

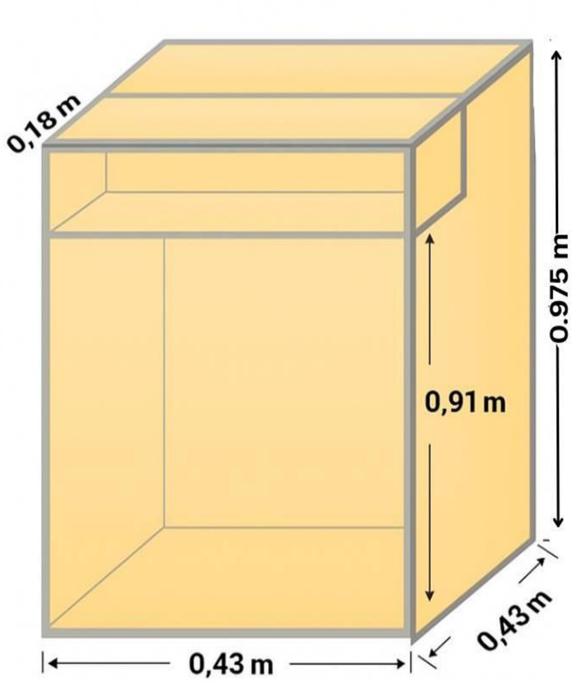

Figure 3.1: Dimensional Diagram of the Incubator

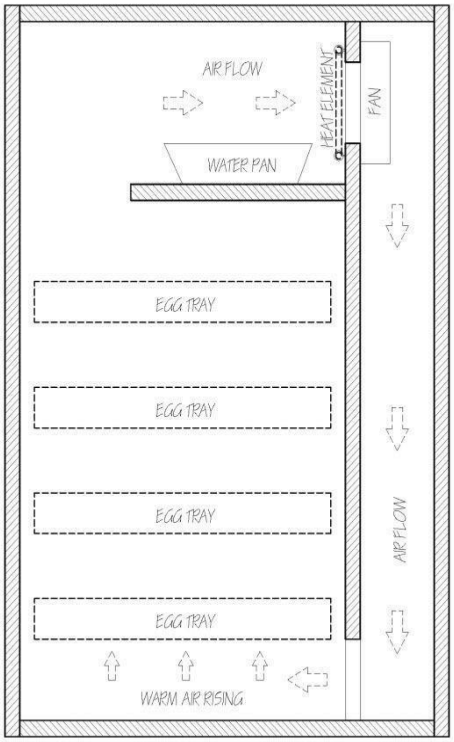

Figure 3.2: Cross section of the incubator showing the heat and airflow direction

Each of these elements can be described as the following:

1. The physical incubator itself; is divided into two layers which are upper and lower layers.
2. The top compartment is where all the control systems are stored
3. At the lower compartment; a light bulb is attached with a KT100 sensor placed.
5. 5v Servo motor used to control the rotation of egg turner, at the lower compartment.
6. DC fan, whose purpose is to keep the air inside the box fresh.
7. Egg turner that has been programmed to rotate every four hours. Beneath is where the water is running to keep the humidity at about 50%-65%

A. Incubator System

Below are parts of the Incubator System.

1. Heating Element
2. Temporary controller/sensor
3. Dc Motor
4. Fan
5. Humidity system
6. Egg rack.

3.4.1 Temperature and Humidity Sensor KT100

The KT100 is a digital humidity and temperature controller capable of simultaneously controlling both temperature and humidity. It can also be connected to other heating/cooling and humidification/dehumidification devices concurrently.

This device is designed for ease of usage and setup. It connects directly to the network, allowing users to set desired parameter values for turning it on/off. Additionally, it provides the convenience of saving parameter settings in case of a short circuit.

The KT100 features a high-quality sensor for temperature and humidity, ensuring precise measurements and efficient operation.

It is a reliable, lightweight, and convenient device with an ABS (Acrylonitrile Butadiene Styrene) plastic housing that can be embedded if desired.

The controller has a wide range of applications, including incubators, refrigerators, freezers, vivariums, terrariums, home fermentation and cooking industries, grain storage, machine rooms, and various other processes and rooms where temperature and humidity control is necessary.

KT100 has the following specification ●

Power Supply:110V-220VAC

i. Temperature control range: 0~100°C
ii. Humidity control range: 1~99%RH
iii. Control accuracy: 1°C / 1%RH
iv. Sensor: temperature humidity sensor
v. Output: Max 10A, power output directly
vi. Size:100mm(L)*55mm(W)*32mm(Depth)

Plate 3.3: Temperature and Humidity Sensor KT100

3.4.2 DC motor

A machine that converts that DC electrical power into mechanical power is known as a DC motor its work depends on the basic principle that when a current-carrying conductor is placed in a magnetic field, then a force is exerted on it and torque develops which converts electrical pulses into discrete mechanical movements. The use of this motor is to rotate/spin the egg tray for every six hours (depending on the coding) so the yellow egg will not stick between the eggshells.

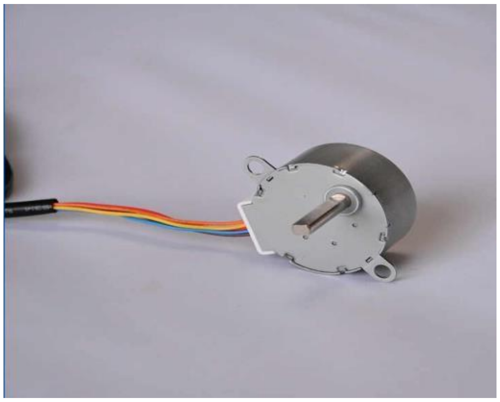

Plate 3.4: DC Motor

3.4.3 DC fan

A mechanical fan is a machine used to create flow within a fluid and typically a gas such as air. The fan consists of a rotating array element of vanes or blades that act on the fluid. The rotating assembly of blades and hub is known as an impeller or a rotor, or a runner, the major function of a fan in an incubator is to cool or circulate heat in the system. Thus egg incubator is used a 12v, 1.8w DC fan mounted at the back portion to ventilate the air inside the incubator for machine cooling.

Plate 3.5: Brushless DC Fan

3.4.4 Heating Element

In the developed incubator the source of heat was a 100w bulb powered by an electric or solar power voltage system. The heat outside the egg incubator is approximately 95°F. The light bulb emits heat energy if this energy is controlled, it's more than enough to incubate the eggs. Light has no apparent side effect on chick development during incubation.

Plate 3.6: 100W Incandescent Bulb

3.4.5 Egg Turner

The eggs' position and turning of eggs are very important during egg incubation. The proper egg position and turning of the eggs facilitate the position of developing embryos and ensure that nutrients are evenly distributed for embryonic development.

The positioning aspect of the eggs is critical to make the incubation process a successful one. This egg turner is capable of holding up to 36 eggs at a time. It also has a slot for the stepper motor to turn the egg tray from left to right. The position of the egg should be turned at least four to five times daily.

Plate 3.7: Egg tray turner

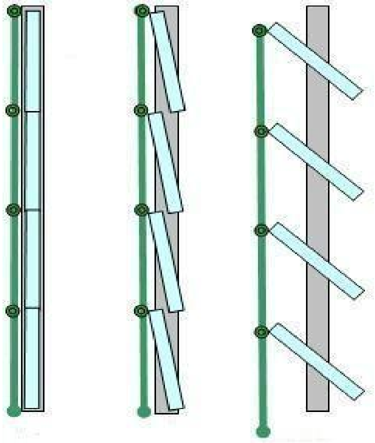

Figure 3.8: Schematic diagram of Egg-tray turner mechanism.

B. Solar System

The parts of the Solar System division are listed below

1. Charge controller
2. Solar panel
3. Inverter
4. 12v 200ah battery

3.4.6. Solar Panel

A solar panel converts sunlight into electricity through photovoltaic (PV) cells.

Plate 3.9: Photovoltaic Cells

3.4.7 Charge Controller

The charge controller was an essential component in the solar-powered incubator. It regulates the voltage and current from the solar panels to the battery, preventing overcharging and over-discharging, which can damage the battery.

Plate 3.10: Charge Controller

3.4.8 Battery

A solar battery, also known as a solar storage battery, stores excess energy generated by solar panels for later use.

Plate 3.11: Dry Cell Battery.

3.5. Design Theory

3.5.1. Environmental and incubation set-points (control parameters)

I. **T_{inc} (Incubator temperature):** Target internal air temperature to maintain embryo development, typical set-point 37–38°C. (Used as target in control and ΔT calculations.)

II. **RH (Relative humidity)** : Target relative humidity (%) inside incubator (usually 50–65% during most of incubation; 70–75% during hatch). Affects evaporative cooling and water tray sizing.

3.5.2. Geometry and material parameters

I. **l, b, h (Length, Breadth, Height)** : Internal incubator dimensions (m). Used to compute internal **volume** $V = l \times b \times h$ and external surface area A for heat-loss. Example values appear in the report.

II. **d (wall thickness)** : Thickness of the incubator wall (m); used with thermal conductivity to compute thermal resistance.

III. **A (Surface area)** : Total external surface area (m^2) of the enclosure used in conduction heat loss $Q = U \cdot A \cdot \Delta T$.

3.5.3. Air and thermal properties

I. ρ_{air} (Air density) : kg/m^3 at the working temperature (e.g., 1.137 kg/m^3 at ~37.5°C used in your calculations). Used to compute mass of air inside ($M_a = \rho_{air} \cdot V$).

II. C_{air} (Specific heat capacity of air) : $J/(kg \cdot °C)$ ($\approx$ 1.005 $kJ/kg \cdot °C$). Used in $Q = M \cdot C \cdot \Delta T$ for heating the internal air mass.

III. K or k (Thermal conductivity of wall material) : $W/(m \cdot °C)$. Used with wall thickness to calculate thermal resistance $R = d/k$.

3.5.4. Heat transfer and loss parameters

I. ΔT (Temperature difference): $T_{inc} - T_{ambient}$ (°C). Drives conduction/convection heat loss through walls.

II. U (Overall heat transfer coefficient) : $\frac{W}{m^2\ °C}$ often computed as $1/R_{total}$. Used in wall heat loss: $Q_{loss} = U \cdot A \cdot \Delta T$.

III. H_{emb} (Embryo heat production) : Heat produced by embryo(s) (J) appears in energy balance models of egg temperature.

3.5.5. Egg-specific parameters

I. Egg thermal conductance / K_{egg}: $W/°C$ (or $W/(m^2 \cdot °C)$ depending on model). Used when computing egg temperature from incubator temperature and embryo heat.

II. Egg turning frequency: Number of turns per day (e.g., 4 turns/day as used in the project). A mechanical/design parameter affecting motor sizing and control logic.

3.5.6. Power and electrical system parameters

I. P_{heater} (Heater power): Watts (e.g., 100 W incandescent bulb used). Determines energy required to maintain T_{inc}.

II. P_{fan}, P_{motor} (Fan/motor power): Watts: used in daily energy budget and solar sizing.

III. Battery capacity (Ah, V): e.g., 12 V, 200 Ah battery used in the system. Convert to Wh:
IV. $E_{batt} = V \cdot Ah$. Used to compute autonomy (hours) = E_{batt} / average load.

V. I, V (current, voltage): Used for power calculations $P = V \cdot I$ and for battery runtime ($I = P/V$). The report shows example battery runtime calculation.

VI. Solar panel rating (W): Panel peak power (W): used to size PV so daily solar energy ≥ daily consumption plus battery charging losses.

3.5.7. Humidity / water parameters

m_{water} (Mass of water in tray): kg or L. Required to sustain RH through evaporation. Related to evaporative cooling term $H_{water\ losses}$ in the egg heat balance.

3.5.8. Control and safety parameters

I. Controller accuracy and set-point tolerances: e.g., KT100 control accuracy $1°C\ /\ 1\%RH$ (specs from the used controller). Use to state expected control error band.

II. Thermal cut-offs / safety margins: Over-temperature limits and surge protection values to protect eggs and electronics.

3.5.9. Performance Evaluation of Loaded Eggs on Each Tray

I. Fertility of Egg

Fertility of eggs = (number of fertile eggs) / (total number of eggs)

Number of fertile eggs = Total number of eggs – Number of infertile eggs Fertility of eggs

II. Hatchability of the Fertile Eggs

Hatchability of the fertile egg in the chamber = $\frac{\text{number of hatched eggs}}{\text{total number of fertile eggs}} \times 100\%$

III. Chick with Unabsorbed Yolk

Percentage of chicks with unabsorbed yolk = $\frac{\text{number of chicks with unabsorbed yolk}}{\text{total number of fertile eggs}} \times 100\%$

The chick with unabsorbed yolk was formed as a result of slow development at the last stage of incubation.

Dead in germ (early dead of embryo) was not recorded in any of the tray. All of the embryos in the fertile eggs reached the final stage (21st day). Some hatched; some were fully formed but unable to hatch, and some had unabsorbed yolk. Hatched eggs, late hatching, unhatched eggs and dead chicks are widely regarded as methods for evaluating the incubation process and indicating areas for improvement. The absence of dead germs in the developing embryo was due to the consistent power supply provided by solar power throughout the incubation period. The rate of evaporation of water in the humidifier container increased, resulting in an increase in the number of openings made. The increased rate of evaporation was due to the large number of developing embryos in the chamber, which absorbed more of the evaporated water. Although the temperature was maintained within the recommended range, there was significant heat loss during the process, resulting in temperature fluctuations. From discovery, it was observed that relative humidity is the most important element of incubation at the stage of hatching. Correct relative humidity is required for the chick to successfully emerge from the shell. If the relative humidity is low, the chick will find it difficult to pipe the shell and break it.

3.5.10 Notes on units, assumptions and sample equations

Temperature (°C), Length (m), Power (W), Energy (J or Wh).

Key formulas referenced later in calculations:

I. **Internal air heating:** $Q_{air} = M_a \cdot C_{air} \cdot \Delta T$.

II. **Heat loss through walls:** $Q_{loss} = U \cdot A \cdot \Delta T$, with U $(heat\ transfer\ coefficient) = i/R$ and R $(Thermal\ Resistance\ of\ the\ wall) = d/k$

III. **Battery runtime:** $\boldsymbol{I} = P/$; runtime (hours) = $Battery\ Ah\ /\ I$.

3.6. Design Calculations

To calculate the quantity of heat required inside the incubator, it is necessary to account for the heat needed to raise the temperature of the incubator's body, the eggs, the egg trays, the water, and the heat lost through the walls of the incubator.

3.6.1 Heat Loss

1. **The Volume of Air in the Incubator:**

$$V = lbh \tag{3.1}$$

$Length\ (l) = 0.51m$

$Breadth\ (b) = 0.48m$

$Height\ (h) = 1.0m$

$V = 0.51 \times 0.43 \times 1$

$= 0.2193m^3$

2. **Mass of Air, (M_a):**

The density of air(p) at 37.5°C is approximately 1.137kg/m³

$$M_a = p.V \tag{3.2}$$

$= 1.137 \times 0.2193$

$= 0.2493kg$

3. **.Heat Energy Required to Warm Air:**

$Specific\ heat\ capacity\ of\ (C) = 1.005kg^oC$

$Temperature\ differ(\Delta T)\ assuming\ 25^oC\ as\ ambient\ temperature) = 37.5 - 25$

$$= 12.5^{o}C$$

$$Q = M.\,C.\,\Delta T \quad (3.3)$$

$$= 0.2493 \times 1.005 \times \Delta T$$

$$= 3.14kj$$

4. **Heat Loss Through Walls:**

The incubator is made of wood, lined with aluminium foil

$Thermal\ Conductivity\ (k) = \frac{0.13W}{m.k}$

$Wall\ thickness\ (d) = 0.02m$

$Total\ surface\ area\ of\ the\ incubator$

$$A = 2(l.\,b) + 2(l.\,h) + 2(b.\,h) \quad (3.4)$$

$$A = 2(0.51\ 0.43) + 2(\ 0.51 \times 1) + (0.43 \times 1)$$

$$= 0.4386 + 0.86 + 1.02$$

$$= 2.32m^2$$

$$Q = U.\,A.\,\Delta T \quad (3.5)$$

$$U = heat\ transfer\ coefficient = \frac{i}{R} \quad (3.6)$$

$R = Thermal\ Resistance\ of\ the\ wall$

$$= \frac{d}{k}$$

$= Thickness\ of\ the\ material/\ Thermal\ conductivity$

i) Wood layer

$d_{wood} = 0.02m$

$k_{wood} = 0.13 W/m.\ k$

$R_{wood} = d_{wood}/k_{wood}$

$= 0.02 / 0.13 = 0.1538 m^2k/W$

ii) Aluminium foil layer

$d_{foil} = 0.0002m$

$k_{foil} = 235W/m.\ k$

$R_{foil} = d_{foil}/k_{foil}$

$= \frac{0.0002}{235}$

$= 8.8 \times 10^{-7} m^2k/W$

iii) Convective heat transfer (Inside and Outside air layers)

$Inside\ Convec(h_{inside}) = 10W/(m\char`^2\ k)$

$Outside\ Convec(h_{outside}) = 10W/(m\char`^2\ k)$

$$R = \frac{1}{h} \tag{3.7}$$

$R_{insi} = \frac{1}{h_{inside}}$

$= 1/\ 10$

$= 0.1m^2k/W$

$R_{outside} = 1/h_{outside}$

$= 1/10$

$= 0.1m^2k/W$

$iv)\ Overall\ thermal\ resistance\ (R_{total})$

$The\ total\ thernal\ resistance\ is\ the\ addition\ \ of\ the\ resistances$

$R_{total} = R_{inside} + R_{wood} + R_{foil} + R_{outside}$

$= 0.1 + 0.1538 + 8\ 51 \times 10^{-7} + 0.1$

$= 0.3538 m.\ k/W$

$\boldsymbol{v})Overall\ heat\ transfer\ coefficient(v)$

$The\ overall\ heat\ transfer\ coefficient$

$U = \frac{1}{R_{total}}$

$= \frac{1}{0.3538}$

$= 2.83 \frac{W}{m^2k}$

$Q_{loss} = V\ A\ \Delta T$

=

2.83×2.32×

12.5 =

82.07W

$Assuming\ Aluminium\ foil\ insulation\ accounts\ for$ 30% $heat\ loss\ reduction\ due\ to\ insulation.$

$Q_{\text{loss adjusted}} = Q_{loss} \times 0.7$

$= 82.03 \times 0.7$

$= 57.42W$

5. $\boldsymbol{Heat\ required\ to\ warm\ up\ the\ wooden\ rack}$

$Density\ of\ (p_{wood}) = 600 kg/m^3$

$Specific\ heat\ capacity\ of\ wood = 2.1 kj/kg^0k$

$Specific\ heat\ capacity\ of\ steel = 0.5kg/kg^0k$

$By\ assumption$

$Wooden\ frame = 0.5kg\ per\ rack$

$Metal\ mesh = 0.2kg\ per\ rack$

$For\ all\ 3\ racks$

$Total\ wooden\ mass = 3 \times 0.5$

$= 1.5kg$

$Total\ metal\ mass \quad = 3 \times 0.2$

$= 0.6kg$

6. $\boldsymbol{Heat\ energy\ for\ tge\ wooden\ rack}$

$Q_{wood} = M_{wood} \times C_{wood} \times \Delta\ T$

$= 0.6 \times 0.5 \times 12.5$

$= 3.75kJ$

7. $\boldsymbol{Heat\ required\ by\ eggs}$

$Q_c = M_c \times C_c \times \Delta T$

$Mass\ of\ idle\ size\ eggs = 0.06kg$

$Since\ 3\ crates = 90\ eggs$

$Specific\ Heat\ capacity\ of\ eggs$

$= 3.182kJ/kg^0K$

$Q_c = 0.06 \times 3.182 \times 12.5 \times 90$

$214.785kJ$

8. *Heat required by water*

$Assuming\ 1\ litre\ of\ water\ (humidity\ system)$

$Specific\ heat\ capacity\ of\ water = 4.187 kj/kg^0K$

$Q_{water} = 1\ X\ (4.187)\ (12.5)$

$= 52.338W$

9. *Heat required to warm body of machine*

$Q_b = M_b \times C_b \times \Delta T$

$M_b = V_bP$

$M_b = Area\ of\ box \times thickness \times density$

$= 2.32 \times 0.02 \times 600$

$= 27.84kg$

$Specific\ heat\ capacity\ of\ wood = 2.1kj/kg^0K$

$Q_b = 27.84 \times 2.1 \times 12.5$

$= 730.8kJ$

10.

Total Q for turning equipment

$Q_{eq} = Q_b + Q_c + Q_{water} + Q_{wood} + Q_{metal} + Q_{air}$

$= 730.8 + 214.785 + 52.338 + 39.375 + 3.757 + 3.14$

$= 1044.188kJ$

11. *Electric Power Required*

$$P = Q/t \tag{3.8}$$

$$= \frac{1044.188 \times 10^3}{24 \times 60 \times 60}$$

$$= 12.1W$$

12. $\boldsymbol{Total\ Power}$

$Q_{total} = 12.1 + 57.42$

$= 69.5W$

$Adding\ a\ factor\ of\ safety\ of\ 20\%$

$Q_{total} = 69\ 5W \times 1.2$

$= 83.41W$

$To\ meet\ the\ heating\ requirement\ of\ 83.41W,\ one\ 100\ W\ bulb\ would\ be\ used$

3.6.2. Charging Time

To calculate the charging time for a 200Ah battery using a 300W solar panel and a 60A charge controller, let's break down the information provided:

$Solar\ Panel\ Power\ (P) = 300W$

$Battery\ voltage\ (V) = 12V\ Current =$

$Power\ /\ Voltage$

$For\ a\ 12V\ battery:$

$I = 300/12 = 25A$

$Battery\ Capacity = 200Ah$

$Solar\ Panel,\ I = 25A$

$Using\ the\ formula\ for\ charging\ time:$

$Time = Battery\ Capacity\ /\ Solar\ Charging\ Current$

$Time$ = 200 / 25 = 8 $hours$

3.6.3. Additional Considerations

1. Charging Efficiency: Real-world charging systems are not 100% efficient. Assuming around 80-90% efficiency, the time might increase to about 9-10 hours.
2. Sunlight Hours: The charging time depends on available peak sunlight hours. If there are only 5 hours of peak sunlight, for instance, the battery will only get partially charged each day.
3. Battery Depth of Discharge (DoD): If the battery isn't fully discharged, it will take less time to reach full capacity.

3.6.4. Discharge Speed

To calculate how long 200Ah battery will last powering the incubator over night:

$Heating\ Bul = 100w$

$Dc\ fan \quad = 40w$

$Dc\ Motor \quad = 10w$

Tot Power $= 100 + 40 + 10$

$= 150w$

$P = iv$

$I = p/v$

$= 150/12$

$= 12.5A$

$T = 200/12.5$

$= 16hrs$

Battery is capable of running the incubator 16hours nonstop without recharge

3.7. Cost Analysis

$12v\ battery\ (200ah) = 300{,}000$

$300w\ solar\ panel = 50{,}000$

$Charge\ Controller = 50{,}000$

$1kva\ Sine\ wave\ inverter = 60{,}000$

$Dc\ fan, KT100\ controller, DC\ motor = 50{,}000$

$Lampholder, wires, Wood, net, screw$ and $bolt = 10{,}000$

CHAPTER FOUR

RESULTS AND DISCUSSION

4.1 Results and Discussions

Several tests were conducted in order to verify the effectiveness and correct operation of the constructed solar powered automatic egg incubator. These tests were carried out with the aid of the temperature sensor to determine the effectiveness of the heating elements (two AC bulbs) and how the system responds to the input signal from the sensor. It was also to determine the positioning of the heating elements so as to ensure even distribution of temperature in the incubator. The heating elements were positioned opposite each other to ensure that every corner of the incubator receives equal heating. When temperature was below the specified value, the heater turned on while, when the temperature was above the specified value the heater went off and the fan came on.A mean average of 37.36°C and 62.38% for temperature and humidity respectively was obtained when checked at certain intervals. This showed that the system is effective for egg incubation because

(Abiola, (2014)) stated that temperatures of between 36°C to 38°C and relative humidity of 50 – 70% and 70 – 75% at the last three days of the incubation period are needed for effective incubation and hatching of eggs.

To ensure optimal incubation, the apparatus has an automated turning mechanism that rotates the eggs every two hours and fifty minutes. The specimen eggs hatched between the 19th and the 21st day of incubation, which is consistent with Dalangin and Ancheta's (2018) findings that hatching takes place between the 18th and 22nd day of incubation in their study. Notably, a significant majority of eggs hatched on the 20th day. The hatch rate of the device was assessed through actual incubation tests using eggs from three distinct batches, each with varying specimen egg quantities. These eggs were confirmed to be fertilized, as attested by the cooperating owners who provided them for the study. The hatchability rate for fully hatched chicks using the incubator stood at 76.36%, with 7.35% of eggs partially hatched and 17% remaining unhatched. In comparison to literature, where average hatchability rates ranged from

27% to 75% in previous studies (Iqbal et al., (2014); Mansaray and Yansaneh, (2015); Okonkwo and Chukwuezie, (2012); Othman et al., (2014)), the incubator's performance surpassed the average. The high hatch rate is attributed to consistent egg turning and the provision of optimal incubation conditions. Eggs used were sourced from hens with known high hatchability rate, as confirmed by the contributing farmers. The average weight of chicks a few hours after hatching was determined to be 40.8g, falling within the range reported by Deaton et al. (1979), who stated that chick weights at one day old varied between 32.2g and 42.6g. This recorded chick weight aligns with findings from previous research.

The results obtained from the performance evaluation done on the developed incubator are the incubating temperature and humidity as well as the ambient temperature. After the completion of incubation, the efficiency of the incubator was also determined based on the percentage hatchability. The results obtained are presented as follows:

4.2 Effect of Ambient Temperature on the Interior Temperature of the Incubator

The ambient temperature has great influence on the interior temperature of the incubator which made the interior of the incubator not having a constant temperature throughout the period of incubation but the interior temperature of the incubator was still maintain within the recommended range of 36°C to 38°C with the help of the thermostat. This same observation was reported by Adewumi (2006).

4.3. Discussion of Result (Humidity variation, Heat loss, Control performance)

The relative humidity maintained within the incubator throughout the incubation period exceeded the process's minimum requirement of 50%. The humidity value varied from day to day, however there were significant differences on days 3, 7, 11, 14, and 19. There were days where the humidity increased or decreased steadily, as well as days when the humidity was quite consistent. The variation in humidity over time could be accounted for by the changing air conditions surrounding the incubator.

Air was brought in from the surroundings to cool the incubator when the temperature increased above 37.5°C, which had a significant impact on the incubation conditions. Temperature values change throughout the incubation phase. On some days, incubation temperatures were below 36°C for extended periods. Although this was not ideal for the incubation process, it is still preferable than the period when the incubation temperature exceeded 37.5°C.

Incubating at temperature higher than 37.5°C is harmful to the embryo. This was of greater concern during the experiment as it may greatly affect the performance of the incubator. The percentage of egg hatched was higher compared to those obtained during preliminary study.

4.4.Findings

The prototype demonstrates a functional low-power solar-driven incubator that maintained mean internal conditions near recommended ranges and produced strong hatchability for its class (mean internal temp & RH recorded; hatchability: high fully-hatched rate).

I. Performance summary: Mean internal conditions and hatch outcomes were within acceptable ranges (reported mean temp/RH and hatch rates).

II. Control behavior: Thermostat and control logic kept temperatures mainly within the 36–38 °C window, although occasional short excursions occurred.

III. Humidity dynamics: RH varied across incubation stages (notable shifts on key days) and contributed to some late-stage hatching issues.

IV. Mechanical subsystems: Automated egg-turning and heater/fan control operated reliably and are linked to the observed hatchability.

V. Energy & sizing note: System uses a 12 V, 200 Ah battery with PV/charge controller for off-grid use; PV/battery sizing should be reviewed for longer autonomy or higher heating loads.

Recommended short-term improvements: Improve insulation to reduce heat loss, consider thermal storage (PCM) to smooth temperature, refine stage-based RH control, and reassess PV/battery sizing to increase robustness.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusions

In this project, a Solar-Powered Egg Incubator system for poultry eggs (120 eggs at full capacity) was designed and constructed, simulating the natural incubation environment. It is run on renewable energy sources, such as solar energy, which is abundant in Nigeria, as well as the grid. This study has also proven the effectiveness of solar power for low energy consumption applications (such as in agribusiness) to cut down the operational cost and make it possible for those who do not have access to the grid to incubate without grid dependence successfully.

The choice of materials for this solar-driven incubator balances thermal performance, durability, manufacturability and cost to deliver reliable field operation. Priority was given to low-thermal-conductivity, high-insulation panels for the enclosure (to reduce heater duty cycle and battery draw), structurally stable framing that resists warping and moisture, and food-safe, non-toxic internal surfaces where eggs contact the tray. Where thermal smoothing is required, incorporating a phase-change material (PCM) was recommended because it increases thermal inertia and reduces temperature excursions, but only when justified by lifecycle cost and maintainability. Exterior components (fasteners, hinges, PV mounts) were specified as corrosion-resistant and UV-stable to ensure longevity in outdoor conditions, while electronic housings and cable glands were chosen to protect sensors, controllers and batteries from dust and moisture. Throughout, preference was given to readily available, locally sourceable materials and modular subassemblies to simplify repairs and scale production—trading higher upfront material cost in a few places (insulation, PCM, stainless fasteners) for lower operational cost, improved hatch reliability, and greater field robustness.

Fabricating and assembling the incubator involved constructing a well-insulated enclosure, installing the egg tray with its automated turning mechanism, and positioning the heater, fan, and sensors to ensure even airflow and accurate temperature–humidity control. The electronic components—controller, relays, battery, and charge controller—were mounted in a protected compartment with clean, labelled wiring for safety and easy maintenance. The PV panel and battery system were connected through weather-proof fittings, and all internal seams were sealed to prevent heat loss. Once assembled, the unit was calibrated and tested for temperature stability, humidity response, turner reliability, and overall energy performance to confirm readiness for operation. The power consumption of the incubator is on the low end making it very cost effective to use. Test results were used to evaluate the system's performance, and the system's portability, sensitivity, dependability, and operational simplicity demonstrated that it could be a useful tool to farmers in chicken (poultry livestock) production. Also, variation, control and monitoring of the incubator parameters can easily be done by users of the system. With these findings, the aim and objectives of the research has been achieved.

5.2 Recommendations

From the designed and fabrication of the solar-powered egg incubator, the following recommendations can be made:

The egg roller mechanism can be well adapted in conveyor systems in batch processing environments.

The use of high-quality insulation materials should be recommended to minimize heat loss and maintain stable temperatures within the incubator. This could include using materials like foam board insulation or double-glazed windows to improve thermal efficiency.

There should be an inclusion of a battery backup system to store excess solar energy generated during the day for use during periods of low sunlight (rainy seasons) or at night. This ensures uninterrupted operation of the incubator even in adverse weather conditions or unforeseen issues with the solar connection.

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