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COMPARATIVE ANALYSIS OF SILKWORM EGG INCUBATOR DESIGNS AND THEIR CONTROL SYSTEMS

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Abstract. This thesis presents a comparative analysis of existing silkworm egg incubation methods and incubator control systems with particular attention to automation level, controlled microclimate parameters, sensing architecture, spatial uniformity, energy efficiency, and dependence on human intervention. The analysis covers traditional manually controlled incubation, temperature-only automatic incubators, temperature–humidity controlled laboratory systems, and multi-point digital monitoring solutions. The results demonstrate a clear technological transition from manual regulation toward integrated mechatronic control. Nevertheless, the reviewed solutions do not simultaneously provide coordinated temperature, relative humidity and CO_2 control, reduction of inter-layer microclimate non-uniformity, energy-efficient operation, and experimental validation. The identified integration gap substantiates the need for an energy-efficient mechatronic incubator in which microclimate parameters are measured in an integrated manner and spatial non-uniformity is reduced by periodic mechanical movement of egg-carrying disks.

Keywords: silkworm eggs, incubator, microclimate, temperature, relative humidity, CO_2 concentration, automation, mechatronic control, monitoring, energy efficiency.

1. Introduction

The successful incubation of silkworm eggs depends on maintaining a stable and sufficiently uniform microclimate throughout the working chamber. The principal technical requirements include keeping temperature, relative humidity and carbon dioxide concentration within appropriate ranges, coordinating these parameters through a unified control algorithm, and performing the process with minimum energy consumption. These requirements provide a common basis for objectively evaluating existing incubator designs.

Existing solutions can be classified according to their degree of automation and the number of controlled environmental parameters. Four principal groups are distinguishable: traditional manually controlled incubation methods; incubators that automatically regulate a single parameter, mainly temperature; systems that jointly control temperature and relative humidity; and modern incubators

equipped with multi-parameter digital monitoring or mechatronic control. This sequence reflects the general technological evolution from operator-dependent regulation toward integrated sensing and automation.

Despite this progress, several engineering problems remain unresolved. In particular, many systems do not measure CO_2 concentration, use only one temperature–humidity sensor, lack closed-loop control of all relevant variables, or do not compensate for spatial differences between layers. Therefore, the purpose of this study is to compare representative incubation systems using common technical criteria and to identify the scientific and engineering gap that should be addressed in the development of an improved mechatronic incubator.

2. Materials and Methods

A comparative analytical method was used. The systems were evaluated according to the following criteria: control method; controlled parameters; type and number of sensors; presence or absence of CO_2 measurement and regulation; spatial uniformity of temperature, humidity and airflow; possibility of periodically changing the spatial position of eggs; energy consumption and efficiency; level of automation and dependence on the operator; and the availability of continuous monitoring and data recording.

Four representative technological approaches were considered. The first was the traditional incubation room, in which temperature and humidity are periodically checked using instruments such as a thermometer and psychrometer, while heating, humidification and ventilation are manually adjusted. The second was the CN202949883U PLC-based incubation box, which automatically regulates temperature through an electric heater and a temperature probe. The third was the laboratory incubator developed by D. M. Subrata and co-authors, which uses an ATmega16 microcontroller, an SHT11 sensor, a nichrome heater, a Peltier cooling module and humidity-control devices. The fourth was the Duque-Torres monitoring system, in which nine DHT22 temperature–humidity sensors are distributed across the layers of a nine-level incubator and data are collected through a Raspberry Pi platform.

The systems were compared qualitatively and, where the source material provided numerical experimental data, quantitatively. Particular attention was paid to whether improvements in sensing and automation also solved the problems of CO_2 control, inter-layer uniformity, energy efficiency and autonomous closed-loop operation.

3. Results

The traditional incubation method is structurally simple and relatively inexpensive, but its performance strongly depends on human intervention. Temperature and humidity are observed periodically rather than continuously, CO_2 concentration is not measured, and heating, humidification and ventilation are not coordinated within a single control system. Because eggs are placed motionlessly on multi-level racks, natural convection and the positions of heat and moisture sources may create spatial gradients. Consequently, different layers can experience different thermal and humidity conditions, which may influence the uniformity of embryonic development.

The CN202949883U design represents the first level of automation. A temperature sensor transmits information to a PLC control panel, which switches an electric heater on or off to maintain approximately 25–26 °C. Compared with manual incubation, this reduces continuous operator involvement and improves temperature stability. However, relative humidity is not automatically measured or controlled, CO_2 concentration is not monitored, ventilation remains natural, and a single temperature probe cannot characterize the spatial temperature field. Therefore, automation of temperature alone does not eliminate inter-layer non-uniformity.

A more advanced solution is the Subrata laboratory incubator. Temperature and relative humidity are measured with an SHT11 sensor and regulated by an ATmega16-based on/off controller. The system employs a nichrome heater and Peltier module for thermal regulation, while an ultrasonic humidifier and silica-gel-based moisture absorber are used for humidity control. Experimental results reported in the source show that temperature was maintained within 25.0–25.4 °C and relative humidity within 73.9–76.1%. The reported control accuracy was 99.6% for temperature and 98.5% for humidity. Simultaneous hatching increased from 55.5% under an uncontrolled room condition to 90% in the automatic incubator. These results confirm the benefit of coordinated temperature–humidity regulation. Nevertheless, the use of only one sensor, the absence of CO_2 monitoring, the stationary placement of eggs, and frequent switching among heating, cooling, humidifying and dehumidifying devices remain important limitations.

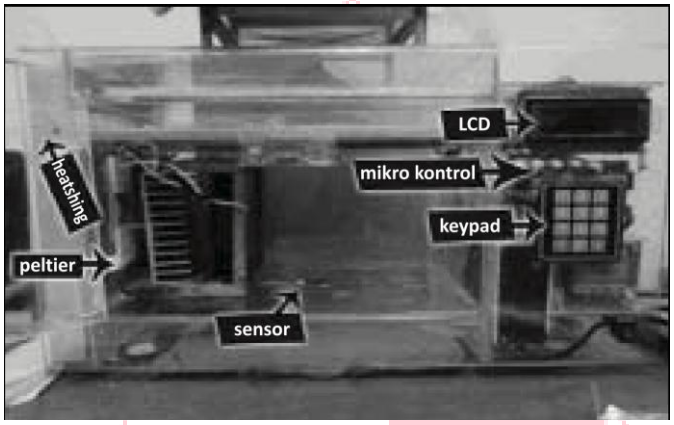


Figure 1. Laboratory silkworm incubator with automatic temperature and humidity control.

The Duque-Torres approach strengthens the sensing architecture. Nine DHT22 sensors, one on each incubator layer, make it possible to identify inter-layer differences in temperature and humidity, while a Raspberry Pi collects and stores data for remote monitoring. This multi-point architecture is useful for detecting spatial non-uniformity. However, the system mainly performs monitoring rather than complete closed-loop control. CO_2 is not measured, and the stationary arrangement of eggs means that detected spatial differences are observed but not mechanically eliminated.

Overall, the comparison demonstrates a consistent progression from manual operation to temperature automation, combined temperature–humidity control, and multi-point digital monitoring. At the same time, none of the reviewed solutions combines integrated multi-parameter sensing, CO_2 supervision, closed-loop regulation, mechanical equalization of inter-layer conditions and energy-efficient operation in one experimentally validated system.

4. Discussion

The comparative results indicate that increasing the number of sensors or automating individual parameters does not by itself guarantee a uniform and energy-efficient incubation environment. Traditional systems are limited primarily by operator dependence and the absence of continuous quantitative control. Temperature-only automation improves stability but leaves humidity, ventilation and gas concentration outside the control loop. Dual-parameter systems provide substantially better environmental regulation, yet they may still be limited by single-point sensing and increased energy consumption associated with alternating actuators. Multi-point monitoring reveals spatial differences, but monitoring alone does not remove those differences.

The central engineering issue is therefore integration. A more complete solution should coordinate temperature, relative humidity and CO_2 information while also addressing the spatial distribution of the microclimate. The source material proposes a different approach to inter-layer non-uniformity: instead of relying only on a large number of stationary sensors, the spatial position of eggs can be periodically changed by rotating the disks on which they are placed. Such mechanical redistribution may help equalize exposure to temperature, humidity and airflow and can support the use of an integrated multi-parameter sensor such as the SCD41 for simultaneous temperature, humidity and CO_2 measurement.

This approach changes the design problem from isolated parameter control to a mechatronic system problem involving sensing, actuation, mechanical motion, mathematical modeling, control synthesis and experimental optimization. Accordingly, the scientific contribution of the proposed research is not limited to a new incubator structure. It also includes mathematical modeling of the mechatronic incubation process, development of coordinated control, experimental optimization of constructive and technological parameters, and evaluation of energy and economic efficiency.

5. Conclusion

The comparative analysis shows that existing silkworm egg incubators have evolved from manually controlled rooms to increasingly automated and digitally monitored systems. Traditional incubation remains highly dependent on the operator and does not provide continuous or spatially uniform microclimate control. Temperature-only PLC systems reduce human intervention but do not regulate humidity or CO_2. Temperature–humidity systems significantly improve environmental stability and hatching uniformity, while multi-point monitoring systems reveal inter-layer variations more effectively. However, the reviewed solutions still leave an important integration gap: temperature, humidity and CO_2 control, spatial equalization, energy efficiency and experimental validation are not combined within one system.

Therefore, the development of an integrated energy-efficient mechatronic incubator is technically justified. Periodic rotation of egg-carrying disks offers a mechanical means of reducing inter-layer non-uniformity, while integrated sensing can provide coordinated information about temperature, relative humidity and CO_2. The identified direction provides a foundation for further mathematical modeling, control-system synthesis, experimental optimization and assessment of

the technological effectiveness of silkworm egg incubation under local operating conditions.

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