

THEORETICAL INTEGRATION OF SMART BUILDING, PASSIVE VENTILATION, AND IOT FOR ENERGY-EFFICIENT FOOD LABORATORIES

Andi Risnawati Ramli^{1*}, Nurul Qisti², Kastono³

Prodi Arsitektur Bangunan Gedung / Politeknik Dewantara, Palopo

Prodi Teknologi Rekayasa Pangan / Politeknik Dewantara, Palopo

Prodi Arsitektur Bangunan Gedung / Politeknik Dewantara, Palopo

E-mail: andirisnawatiramli82@mail.com^{1*}, nuqyss@mail.com², kastono@atidewantara.ac.id³

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Abstract

Tropical food laboratories face persistent challenges of high energy demand due to hot and humid climatic conditions throughout the year. These environments typically depend on mechanical cooling systems, resulting in substantial energy consumption and operational costs. This study develops a theoretical framework to improve energy efficiency by integrating passive design strategies, smart building principles, and Internet of Things (IoT)-based monitoring. The methodology combines literature review, secondary microclimate data from the Indonesian Meteorological Agency (BMKG) and observations at the Hasanuddin University food laboratory, as well as conceptual analysis. The compiled dataset indicates air temperatures between 12–38 °C, relative humidity of 51–95%, daily rainfall of 50–300 mm, and wind speeds ranging from 5–26 knots. Based on this data, a three-layer conceptual model is proposed: (1) passive design strategies, including orientation, cross ventilation, thermal mass, and daylighting; (2) IoT monitoring of temperature, humidity, lighting, and energy; and (3) adaptive control through if–then rules. The model demonstrates potential to reduce cooling loads, maintain thermal comfort, and serve as a foundation for further energy simulation in sustainable food laboratories.

Keywords: Smart Building, Passive Ventilation, Iot, Energy Efficiency, Tropical Food Laboratory.

INTRODUCTION

Food laboratories in tropical regions face significant energy challenges due to the need for stable indoor environmental conditions, particularly temperature and humidity, to ensure the quality of research activities and food material storage. In Indonesia, with its hot and humid climate throughout the year, such laboratories often rely on mechanical cooling systems, including air conditioners and dehumidifiers. While effective, these systems contribute to excessive energy consumption and high operational costs, creating concerns for sustainability in building operations [1]. Passive design strategies have been widely explored as an alternative to reduce energy demand in tropical climates. Studies indicate that design measures such as cross ventilation, natural daylighting, and the use of thermal mass can lower energy consumption by 30–50% [1]. Similarly, Alabid et al. confirmed that passive design measures are effective in reducing cooling requirements in tropical buildings without compromising thermal comfort [3]. These findings suggest that passive strategies can play a critical role in laboratory settings where environmental stability is essential.

In parallel, advancements in smart building concepts and Internet of Things (IoT) technologies offer new opportunities to improve energy efficiency. IoT-based systems enable real-time monitoring of environmental parameters such as temperature, humidity, illumination, and energy use. Zakka and Lee demonstrated that IoT-based monitoring enhances energy management and indoor environmental quality in smart buildings [2]. Furthermore, López et al. highlighted that sustainable IoT connectivity can act as a foundation for achieving long-term energy-efficient building operations [4]. Thus, the integration of passive design strategies with IoT-enabled monitoring and adaptive control systems presents a promising approach for food laboratories in tropical regions. The urgency of such integration is reinforced by the variability of Indonesia's tropical climate. Data from the Meteorological, Climatological, and Geophysical Agency (BMKG) for June–July 2025 indicate temperature ranges of 12–38 °C, relative humidity levels between 51–95%, daily rainfall between 50–300 mm, and wind speeds up to 26 knots [23], [24]. Frequent high rainfall and elevated humidity further complicate the microclimatic balance within laboratory

environments, increasing the energy demand for cooling and dehumidification. These conditions necessitate the development of adaptive and efficient building systems capable of responding dynamically to changing external conditions.

Although research on passive design strategies and IoT applications has been extensive, their combined application in the context of tropical food laboratories in Indonesia remains limited. Most prior studies have concentrated on residential or commercial buildings [1], [3], [4]. This gap indicates the need for integrative conceptual models tailored to the specific requirements of food laboratories, which must balance strict environmental controls with energy efficiency. The objectives of this study are threefold: (1) to analyze the relevance of passive design strategies and smart building elements in tropical food laboratories, (2) to develop an integrative conceptual model that combines architectural measures with IoT-based monitoring systems, and (3) to outline preliminary energy simulation scenarios based on microclimatic datasets. By employing a theoretical and conceptual approach, this research contributes to academic discourse on energy efficiency in tropical buildings and provides a practical foundation for sustainable laboratory design. Moreover, the study supports broader national and global agendas on sustainable development and energy transition, particularly in the building and food security sectors.

METHOD

This research employs a theoretical–conceptual approach designed to construct an integrative framework for energy efficiency in tropical food laboratories. The methodology consists of three main stages:

a. Literature Review

A comprehensive review of relevant national and international journal articles was conducted to identify principles of passive design, smart building concepts, and Internet of Things (IoT)-based monitoring systems. The literature provided the theoretical foundation for formulating an integrative model suitable for tropical building contexts.

b. Secondary Data Collection

Microclimate data were obtained from the Meteorological, Climatological, and Geophysical Agency of Indonesia (BMKG) and supported by direct observations at the Hasanuddin University food laboratory. The dataset included critical environmental parameters such as air temperature (12–38 °C), relative humidity (51–95%), daily rainfall (50–300 mm), wind speed (5–26 knots), and solar radiation levels. These parameters were selected due to their direct influence on building energy performance and indoor thermal comfort.

c. Conceptual Analysis and Modeling

The collected data were synthesized through conceptual analysis to develop a three-layer integrative model. The model consisted of:

- d. Passive design strategies, including building orientation, cross ventilation, the use of thermal mass, and daylighting techniques.
- e. IoT-based monitoring systems, incorporating sensors for temperature, humidity, illumination, and energy consumption.
- f. Adaptive control mechanisms, structured with simple if–then rules to support dynamic responses to changing environmental conditions.

This stepwise approach was designed to provide a conceptual basis for future simulation scenarios, allowing comparative analysis between baseline conditions, passive design-only interventions, and integrative strategies combining passive and IoT systems.

RESULTS AND DISCUSSION

The outcomes of this study consist of three main elements: a compiled microclimate dataset, the development of a three-layer conceptual model, and an outline of preliminary energy simulation scenarios.

a. Microclimate Dataset

The secondary climatic data obtained from BMKG and complemented by laboratory observations revealed the following ranges:

- 1) Air temperature: 12–38 °C
- 2) Relative humidity: 51–95%
- 3) Daily rainfall: 50–300 mm
- 4) Wind speed: 5–26 knots
- 5) Solar radiation: higher than average baseline conditions

These parameters were identified as critical factors influencing thermal comfort, material stability, and energy demand in tropical food laboratory environments.

Table 1 Microclimate dataset

No	Parameter		Data Source	Range/Value	Relevance
1	Air	Temperature	BMKG, Hasanuddin University	12–38	Determines thermal comfort
2	Relative	Humidity	BMKG, Hasanuddin University	51–95	Influences food material stability
3	Rainfall (mm/day)		BMKG	50–300	Adds humidity and cooling load
4	Wind Speed (knots)		BMKG	5–26	Key for cross ventilation
5	Solar Radiation		BMKG	Above normal	Adds heat load → shading and thermal mass

b. Three-Layer Conceptual Model

Analysis of the dataset produced an integrative model comprising three layers:

- 1) Passive design strategies: building orientation, cross ventilation, thermal mass application, and natural lighting.
- 2) IoT monitoring systems: sensors for temperature, humidity, illumination, and energy performance.
- 3) Adaptive control mechanisms: management rules based on if–then logic to dynamically adjust building performance.

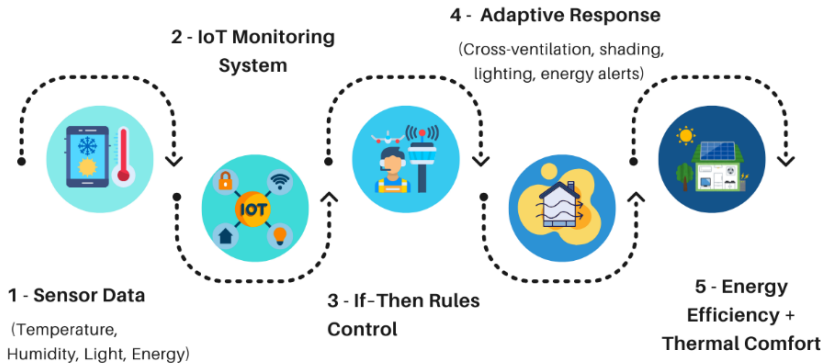


Figure 1 Conceptual model diagram of passive design and IoT integration for tropical food laboratories.

c. Energy Simulation Outline

An initial framework for energy simulation was formulated, consisting of three scenarios:

- 1) Baseline scenario: reflecting current laboratory conditions reliant on mechanical cooling.
- 2) Passive-only scenario: incorporating passive design measures without IoT support.
- 3) Integrative scenario: combining passive strategies with IoT-based adaptive monitoring and control.

This stepwise outline is expected to provide a foundation for subsequent quantitative analyses of energy savings and thermal comfort performance in tropical food laboratories.

The findings of this study reaffirm that passive design strategies remain highly effective in reducing building energy loads in tropical climates. Measures such as cross ventilation, thermal mass utilization, and daylighting have been reported to lower cooling energy demands by up to 30–50% [1], [3]. In the context of food laboratories, which require stable indoor environments, the application of these strategies provides a promising alternative to mechanical cooling systems.

The integration of passive approaches with Internet of Things (IoT)-based monitoring represents the main novelty of this research. Real-time environmental sensing and adaptive control through simple if–then rules enable laboratories to respond dynamically to microclimatic fluctuations. This result is in line with previous findings that IoT technologies can enhance energy management and indoor environmental quality [2], [4].

Thus, the proposed three-layer conceptual model—comprising passive design, IoT monitoring, and adaptive control—offers a specific framework tailored to tropical food laboratories. Unlike prior studies focusing on residential or office buildings, this research highlights the potential of integrated strategies to reduce cooling loads

while maintaining thermal comfort. This outcome demonstrates both academic relevance and practical value for advancing energy-efficient and sustainable food laboratories in Indonesia.

CONCLUSION

This study developed a conceptual model for improving energy efficiency in tropical food laboratories through the integration of passive design strategies and Internet of Things (IoT)-based monitoring. The results include a compiled microclimate dataset, a three-layer conceptual framework, and an outline of preliminary energy simulation scenarios. The findings confirm that passive measures such as orientation, cross ventilation, thermal mass, and daylighting can reduce cooling energy loads, while IoT-based monitoring and adaptive control enhance efficiency by enabling real-time responses to environmental fluctuations.

The novelty of this research lies in offering an integrative model specifically tailored to food laboratories in tropical regions, addressing a gap in previous studies that largely focused on residential and commercial buildings. This framework provides both theoretical contribution to the literature on energy-efficient tropical buildings and practical value as a foundation for future simulation and implementation. Furthermore, it supports national agendas on sustainable development and energy transition, particularly in the building sector and food security.

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