JASSU
Journal of Agrosociology and Sustainability
JASSU 3(2): 131–151
ISSN 3025-1362

Institute for Advanced Science,
Social and Sustainable Future
MORALITY BEFORE KNOWLEDGE

Analyze thermal behaviour and design performance of a passive vernalization-vertical farming system for tropical garlic production

Ahmad Arifuddin[1], Azzahra Al Fatikhana[1], Hasna-ur Rusyda Afifatul 'Ulya[1,*]
[1] *Bio-Agriculture Engineering Study Program, School of Life Sciences and Technology, Institut Teknologi Bandung, Bandung, West Java 45363, Indonesia.*
*Correspondence: 11423048@mahasiswa.itb.ac.id

Received Date: January 3, 2026 Revised Date: January 15, 2026 Accepted Date: January 28, 2026

ABSTRACT

Background: Indonesia exhibits a critical dependency on garlic imports, satisfying 96.8% of national demand (575,000 tons) and positioning the nation as the world's largest importer in the first half of 2024. This reliance undermines local competitiveness, necessitating urgent improvements in domestic productivity. However, cultivation is hindered by two primary constraints: limited arable land and the crop's high sensitivity to heat during vernalization. Vernalization, a cold-induced process (5°C–13°C) essential for transitioning vegetative buds to reproductive stages, presents a significant challenge in tropical climates. **Methods:** This study proposes a novel device integrating a pipe-based vertical cultivation system with a passive vernalization chamber. Utilizing evaporative cooling and locally sourced materials like clay and coconut fiber, it provides low-cost, energy-efficient operation. The device's performance and feasibility in tropical regions were evaluated through literature review of heat transfer and material properties. **Findings:** The analysis indicates that the integrating vertical cultivation with passive and active cooling mechanisms proposed system is theoretically capable of creating microclimate conditions conducive to garlic vernalization under tropical environments while significantly improving land-use efficiency through vertical cultivation. The estimated productivity enhancement is presented as a conceptual projection derived from spatial optimization rather than empirical yield measurements. This design optimizes land use and is projected to plant population density by up to 88,24% per hectare. **Conclusion:** Integrates verticulture with a hybrid cooling system utilizing zeer pot principles and Peltier modules, theoretically resolves Indonesia's land and climatic constraints by optimizing vernalization conditions, thereby serving as a sustainable, scalable strategy to reduce import dependency and strengthen national food sovereignty. **Novelty/Originality of this article:** The novelty of this research lies in the specific application of a cost-effective vernalization system within a vertical farming architecture designed for the tropics, offering an adaptive solution for sustainable national food sovereignty.

KEYWORDS: garlic; import; tropical; vernalization; verticulture.

1. Introduction

Garlic (*Allium sativum* L.) constitutes a vital food commodity, serving as a fundamental component in Indonesia's diverse culinary landscape (Hakim, 2015). Beyond its culinary utility, this commodity plays a pivotal role in macroeconomic stability, where its price sensitivity is heavily dictated by supply and demand dynamics. Such volatility directly impacts consumer purchasing power and household economics (Alqosasi, 2023), positioning garlic not merely as a daily ingredient, but as a critical indicator of national food security.

Cite This Article:
Arifuddin, A., Fatikhana, A. A., & 'Ulya, H.- ur R. A. (2026). Analyze thermal behaviour and design performance of a passive vernalization-vertical farming system for tropical garlic production. *Journal of Agrosociology and Sustainability*, *3*(2), 131-151. https://doi.org/10.61511/jassu.v3i2.2026.2719

While Indonesia currently meets domestic market demand for garlic, the supply of this commodity remains critically dependent on imports. Pusat Data dan Sistem Informasi Pertanian (2023) reported that in 2023; 575,000 tons accounting for 96.8% of national requirements were sourced via imports. Consequently, only 19,000 tons, or a mere 3.2% of the market share, consisted of locally cultivated garlic. This reliance is further corroborated by three distinct analytical metrics: the Trade Specialization Index (ISP), the Import Dependency Ratio (IDR), and the Degree of Import Openness (DKI). Between 2019 and 2023, Indonesian garlic exhibited an average ISP of -0.9, indicating low competitiveness in the global market. Concurrently, the average IDR stood at 90.64%, confirming that the vast majority of domestic supply is import-derived. Furthermore, the average DKI reached 3.18, implying that import expenditure for this commodity accounted for 3.18% of Indonesia's GDP during this period (Maharani et al., 2024). The magnitude of this dependency is also evident in Indonesia's significant contribution to global import volumes; the nation accounted for 24.39% of the world's total garlic imports between 2014 and 2018, peaking at 25.9% in the first half of 2024 (Ningsih et al., 2021).

The escalating reliance on garlic imports is intrinsically linked to relatively low domestic productivity. Further investigation is required regarding land availability and utilization suited to specific agroclimatic conditions, as well as the constraints affecting efficiency, particularly given the scarcity of arable land with high potential for garlic cultivation. Geographically, garlic is not inherently suited for widespread cultivation in tropical regions, as the crop thrives optimally in relatively cooler climates. Conversely, farmer interest in garlic cultivation has declined due to intensifying competition from imported products, which typically offer significantly lower prices and more stable supply chains. Given these circumstances, there is a critical need for viable cultivation technologies adaptable not only to highland regions but also to tropical lowlands, thereby supporting increased national production. During its development, garlic requires vernalization prior to entering the generative phase. Vernalization is defined as the induction of flowering in response to prolonged exposure to low temperatures.

This process functions by providing a flowering stimulus through low-temperature exposure above the freezing point. Bulbs subjected to vernalization yield generative shoots that subsequently develop into reproductive organs (Tunio et al., 2025). Typically lasting several weeks, this process requires an ideal temperature range of 5°C to 13°C; conversely, temperatures exceeding 15.5°C or dropping excessively low (between -13°C and 0°C) can inhibit flowering (Wu et al., 2016). While these conditions occur naturally in subtropical regions, they present a distinct challenge in tropical environments like Indonesia, which are characterized by relatively high average annual temperatures. According to data from Meteorology, Climatology, and Geophysical Agency (2024), ambient temperatures in Indonesia range from 26.45°C to 27.78°C, far exceeding the optimal range for vernalization. This situation is likely to be exacerbated by climate change; Meteorology, Climatology, and Geophysical Agency climate projections for the 2020–2049 period estimate that average temperatures in Indonesia will persist within the 27–28°C range, with a projected increase of 1.0°C to 1.15°C under Representative Concentration Pathway (RCP) 4.5 (moderate mitigation) and RCP 8.5 (high emission) scenarios. Such temperature elevations threaten to further impede successful vernalization in lowland areas, thereby limiting domestic garlic productivity and perpetuating import dependency.

These suboptimal microclimatic conditions constitute a primary impediment to domestic productivity. Elevated temperatures characteristic of tropical regions significantly disrupt the vernalization process. In the absence of adequate vernalization, garlic plants tend to exhibit predominantly vegetative growth, failing to develop large, high-quality bulbs or failing to bulb entirely despite the fact that high temperatures may accelerate initial shoot emergence (Proietti et al., 2022). Furthermore, Indonesia's geographic profile restricts potential cultivation areas; garlic thrives principally on mountain slopes or at altitudes exceeding 800 meters above sea level (masl), whereas the vast majority of the Indonesian archipelago consists of lowlands (Ningsih et al., 2021). This scarcity of suitable arable land results in per-hectare productivity rates that are significantly lower than those of other nations. Consequently, such constrained productivity compels Indonesia to sustain its reliance on garlic imports to satisfy national food security requirements.

To address these challenges, this study proposes the integration of a passive cooling device responding to suboptimal tropical microclimates with a vertical farming system addressing the scarcity of arable land for garlic cultivation in Indonesia. The passive cooling mechanism relies on a synergy between thermal insulation and evaporative cooling. Thermal insulation minimizes heat transfer from the external environment, while evaporative cooling reduces the temperature of intake air via water evaporation within the media. Furthermore, the system incorporates the Peltier effect to further depress temperatures to the optimal range required for breaking garlic dormancy. This entire process operates with reduced electrical energy consumption, rendering it feasible for widespread implementation across tropical regions like Indonesia.

Consequently, it aligns with sustainable, low-energy agricultural principles and bolsters national food security through enhanced garlic production. Vertical farming is defined as an agricultural cultivation system arranged vertically or in tiered layers. This technique maximizes land-use efficiency, enabling a significantly higher planting density compared to conventional methods (Cahyanto & Murwanti, 2022). Additional advantages of vertical farming are evident from environmental, social, and economic stability perspectives. The system exhibits high flexibility, allowing for integration with existing agricultural technologies such as the Internet of Things (IoT) to further amplify garlic productivity (Siregar et al., 2022). Ultimately, the integration of these two systems aims to: reduce reliance on garlic imports; develop a unified cultivation system combining vernalization and growth phases within a single, tropically adaptive vertical structure; and utilize simple, eco-friendly materials for the system's structural and insulation components.

2. Methods

2.1 System design

The system design comprises two primary components: a passive cooling unit and a vertical farming structure. The passive cooling unit functions as a thermal insulator, drawing inspiration from the Zeer pot principle. This assembly utilizes two concentric clay vessels of differing dimensions, each with a wall thickness of 2 cm. The 3 cm annular gap between the vessels is filled with continuously moistened coconut fiber, while the lid is lined with recycled fabric. Subsequently, convective cooling is employed to reduce the internal temperature to below 13°C using a Peltier module, integrated with a thermostat to ensure the temperature does not drop below 5°C. Silica gel fragments are utilized to maintain low humidity levels, thereby preventing fungal decay of the garlic bulbs.

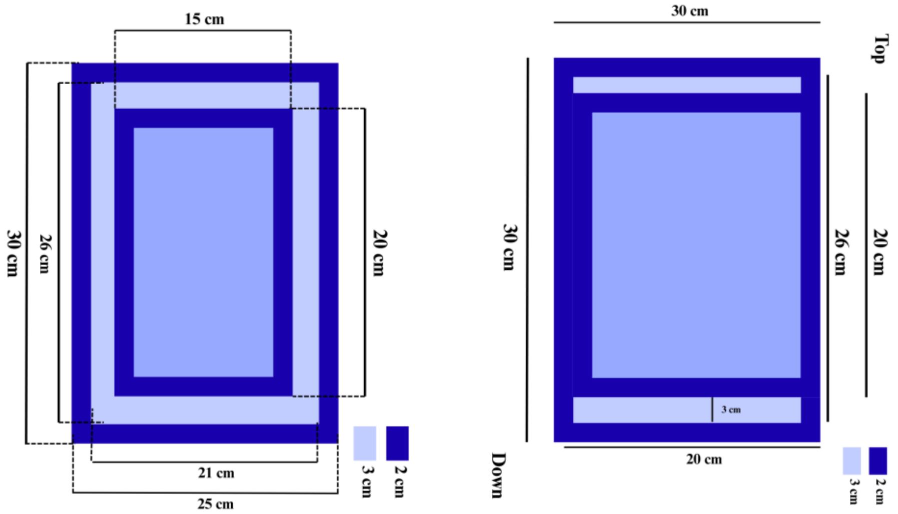

Fig. 1. Top view (left) and side view (right) of the vernalization chamber

The dimensional specifications include an outer vessel measuring 30 × 42 cm with a height of 10–15 cm, and an inner vessel of 25 × 37 cm, resulting in a net vernalization chamber area of 23 × 35 cm. This cooling apparatus is positioned directly on the ground surface, situated immediately beneath the vertical farming system. Concurrently, the vertical farming system is constructed using a primary framework of horizontal and vertical pipes, arranged in a tiered, rack-like configuration. The horizontal conduits, measuring 110 cm in length and 2.5 inches in diameter, feature 5 cm planting apertures spaced at 10 cm intervals along the pipe; these serve as the containment vessels for the soil-based growth medium. The pipes are stacked with a vertical inter-tier spacing of 50 cm, with the basal tier positioned 10 cm above ground level. The total structural height is established at 160 cm, ergonomically optimized to align with the average stature of Indonesian agricultural workers. The vertical support framework is configured in an inverted 'V' geometry with a length of 165 cm, where structural integration between vertical and horizontal components is achieved via 'Tee' pipe fittings. Furthermore, the system incorporates a modular design, enabling farmers to scale the cooling units by addition or removal in accordance with specific planting capacity requirements. This configuration affords farmers a cost-effective and environmentally sustainable garlic vernalization solution, offering a significantly more economical alternative to conventional compressor-based refrigeration systems.

2.2 Theoretical framework

This study was conducted through a literature review employing fundamental physics principles, specifically Fourier’s Law regarding heat transfer rates and electrical power alongside agronomic principles concerning productivity enhancement. The specific principles and governing equations utilized are as follows: Heat transfer across the structural walls occurs via two primary mechanisms: conduction and convection. The convective mechanism is governed by Newton’s Law of Cooling, which states.

$$q = hA\,(T_i - T_f) \qquad \text{(Eq. 1)}$$

Meanwhile, the conduction mechanism is governed by Fourier’s Law of Heat Conduction, which states:

$$q = -kA\frac{T_i - T_f}{L} \qquad \text{(Eq. 2)}$$

Consequently, the equation representing the heat transfer absorbed per unit area (pot surface) per unit time by the wall is derived as:

$$q = \frac{(T_i - T_f)}{\frac{1}{h_1A_1} + \frac{1}{h_1A_3} + (\frac{L_1}{k_1A_1}) + (\frac{L_2}{k_2A_2}) + (\frac{L_3}{k_1A_3})} \qquad \text{(Eq. 3)}$$

Subsequently, the equation expressing the heat transfer absorbed per unit area per unit time from the internal space (vernalization chamber) by the Peltier module is:

$$q = \frac{(T_i - T_f)}{\frac{1}{h_4A_4} + \frac{L_4}{k_4A_4}} \qquad \text{(Eq. 4)}$$

Where q is the heat flux / heat transfer rate (J/s), k is the thermal conductivity (W/m·K), A is the surface area (m^2), T_f is the final temperature (temperature measured after passing through the wall) (K), T_i is the initial temperature (temperature measured before passing through the wall) (K), L is the wall thickness (m), L_1 is the thickness of the outer clay pot (0.02 m), L_2 is the thickness of the coconut fiber insulation layer (0.03 m), L_3 is the thickness of the inner clay pot (0.02 m), T_1 is the ambient temperature (Indonesia average) (27°C or 300.15 K), T_4 is the target temperature at the Peltier module (5°C or 278.15 K), h_1 is the convective heat transfer coefficient of clay (0.7 W/m^2 K) (Sutcu et al., 2014), h_4 is the convective heat transfer coefficient of aluminum (59 W/m^2 K) (Khalif & Mousawi, 2016), k_1 is the thermal conductivity of clay (0.15 W/m K) (Dafalla & Samman, 2016), k_2 is the thermal conductivity of coconut fiber (0.05 W/mK) (Mahmud et al., 2023), k_4 is the thermal conductivity of aluminum (237 W/m K) (Zhang & Li, 2023), A_1 is the surface area of the outer pot (0.317 m^2), A_2 is the surface area of the coconut fiber layer (0.188 m^2), and A_3 is the surface area of the inner pot (0.17 m^2). Subsequently, the total heat absorbed or released by the system is determined by the following equation:

$$Q = m.C.\Delta T \qquad \text{(Eq. 5)}$$

Where Q is the heat absorbed or released (J), m is the mass of the air (kg), C is the specific heat capacity (kJ/kg·K), and ΔT is the temperature change (K). The time required for heat to traverse the wall is calculated using the following equation:

$$t = \frac{Q}{q} \qquad \text{(Eq. 6)}$$

Where t is the time required for heat to traverse the wall (s), q is the heat transfer rate (J/s), and Q is the heat absorbed or released (J). Next, the electricity consumption is calculated using.

$$W = P \times t \times n \qquad \text{(Eq. 7)}$$

Where W is the electrical energy consumption per component (Wh), P is the power rating of the component (Watt), t is the duration of usage (hours), and n is the quantity of devices (units). The last one, the enhancement in productivity is quantified using the following equation:

$$Potential\ Productivity\ Increase\ (\%) = \frac{Verticulture\ productivity - Current\ Productivity}{Current\ Productivity}) \times 100\% \qquad \text{(Eq. 8)}$$

Where Verticulture productivity (Kg/ha) is the plant population per hectare (verticulture) × average garlic bulb weight (Kg), and Current productivity (Kg/ha) is the plant population per hectare (conventional system) × average garlic bulb weight (Kg).

This study employs a library research methodology. The primary materials utilized include data and information derived from scientific literature, such as reference books and articles published in peer-reviewed journals. The gathered data were analyzed and presented descriptively to synthesize the key challenges encountered in realizing sustainable agriculture concepts in Indonesia.

3. Results and Discussion

3.1 Cooling principle of the zeer pot in the tropiverna system

The application of the zeer pot (pot-in-pot system) in the Tropiverna innovation was chosen because of its ability to provide a passive cooling mechanism that is simple, low-cost, and suitable for farmers in regions with limited access to electricity. This system relies on locally available materials, such as clay pots and coconut fiber, making it appropriate for deployment in rural and resource-constrained environments. Structurally, the zeer pot consists of an inner container placed inside a larger outer container, with the annular space between them filled with a porous medium, such as wet coconut fiber, which is continuously maintained at near-saturation conditions. The top opening of the system may be covered with an insulating layer or a moist cloth to further reduce direct heat exchange with the ambient environment.

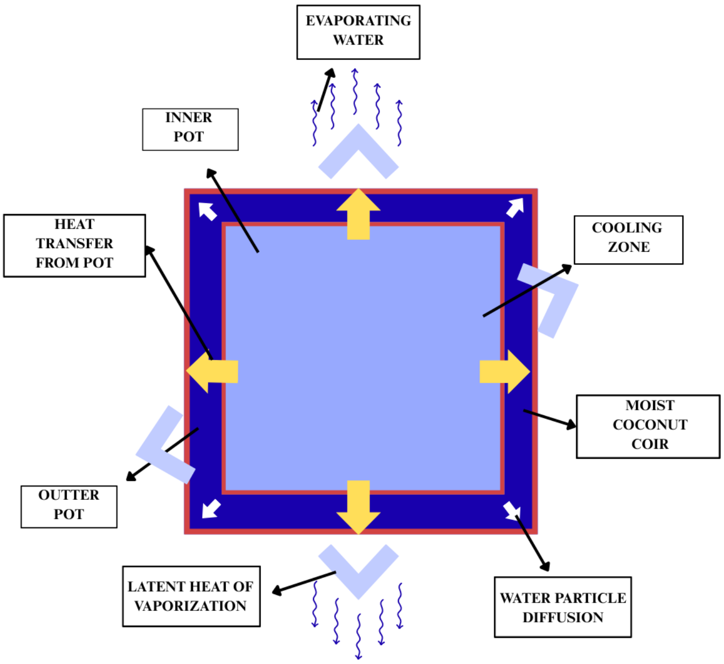

Fig. 2. Heat transfer in a zeer pot

As illustrated in Fig. 2, the cooling mechanism of the zeer pot is fundamentally governed by evaporative cooling coupled with heat and mass transfer processes. Water retained within the porous coconut fiber migrates toward the outer surface of the clay pot due to capillary action. When this water reaches the external surface, it evaporates into the surrounding air. The phase change from liquid to vapor requires latent heat of vaporization, which is absorbed from the pot walls and the air adjacent to the surface. As a result, heat is extracted from the inner container, leading to a reduction in the internal chamber temperature.

The effectiveness of this evaporative cooling process is strongly influenced by ambient conditions, particularly air temperature, relative humidity, and airflow. Under hot and relatively dry tropical conditions, the vapor pressure gradient between the moist pot surface and the surrounding air is enhanced, promoting higher evaporation rates. Convective heat transfer from the ambient air supplies the energy required for evaporation, while radiative heat exchange between the pot surface and the environment also contributes to the overall heat balance. These coupled heat and mass transfer mechanisms determine the magnitude of the cooling effect achieved inside the inner container (Rehman et al., 2020).

Furthermore, irreversible heat and mass transfer processes occurring within the system play a significant role in defining its thermal performance. Heat conduction through the clay walls, combined with thermal resistance introduced by the coconut fiber and water layer, moderates the rate at which external heat penetrates the inner chamber. The thermal conductivity of the clay material, the porosity and moisture content of the coconut fiber, and the effective surface area available for evaporation collectively influence the cooling efficiency, since porous materials exhibit complex heat transfer involving both solid conduction and internal fluid convection due to interconnected pores (Alabdaly, 2025). Consequently, the zeer pot functions not merely as a storage container, but as a passive thermal regulator that stabilizes the internal temperature by balancing heat ingress with evaporative heat removal.

Within the Tropiverna system, this cooling principle provides a critical foundation for maintaining the low temperature conditions required for garlic vernalization. By reducing reliance on continuous active cooling, the zeer pot contributes to energy efficiency and operational stability, particularly in tropical environments where ambient temperatures are consistently high. The passive cooling behavior described in this section also establishes the basis for subsequent analyses of heat transfer mechanisms and system performance discussed in later sections.

3.2 Thermal properties of system materials

The main materials of the pot, which are clay and coconut fiber, have specific characteristics that support the sustainability of this system. Clay has low thermal conductivity, so the rate of heat transfer from outside to inside the container is slower than other materials such as metal or glass, which are high conductors. Meanwhile, the coconut fiber layer plays an important role in maintaining constant moisture and assisting the water diffusion process, which enhances the cooling effect.

Table 1. Comparison of thermal conductivity in various materials

Material	Thermal conductivity (k, W/m·K)	Source
Clay	0.15	Dafalla & Samman (2016)
Cement	0.70 – 1.15	Bamogo et al. (2023)
Concrete	1.41 – 1.97	Bamogo et al. (2023)
Wood	0.08 – 0.09	Li et al. (2013)
Styrofoam	0.0377	Hasanzadeh et al. (2019)

Based on Table 1, it can be seen that clay has relatively low thermal conductivity, namely 0.41 W/m·K, compared to other materials such as cement (0.70-1.65 W/m·K) and concrete (1.41-1.97 W/m·K). This low conductivity value makes clay superior as the main material in the manufacture of zeer pots, because it is able to inhibit the rate of heat transfer so that the temperature inside the container remains lower and more stable. When compared to wood, which has a lower conductivity value of 0.10-0.20 W/m·K, wood is actually better at retaining heat, but its water-absorbing properties, susceptibility to decay, and lack of durability make it less than ideal for evaporation-based cooling systems (Ma'ruf, 2023). Meanwhile, styrofoam has a much lower thermal conductivity of 0.0377 W/m·K, making it theoretically excellent as a heat insulator. However, the main drawback of styrofoam is its fragile and non-porous mechanical properties, which do not support the evaporative cooling process, as well as its lack of environmental friendliness (Marlina et al., 2021). Considering technical aspects, material availability, and sustainability, clay is the best choice compared to wood or styrofoam because it offers a balance between sufficiently low thermal conductivity, durability, and porous properties that support the evaporative cooling system in zeer pots.

The limitation of evaporative cooling lies in high ambient humidity; thus, moisture-absorbing materials are employed to mitigate this. Silica gel possesses a high water adsorption capacity (up to 0.38 kg air/kg silica gel at 60% RH) and rapid adsorption kinetics (reaching near-saturation in approximately 980/seconds). When utilized as a 20% additive in $MgCl_2$ liquid desiccant, this composite material demonstrates a significant enhancement in dehumidification performance compared to pure $MgCl_2$. Quantitatively, this improvement is evidenced by an increase in moisture removal capacity up to $\Delta W = 0.00196$ kg/kg at a desiccant flow rate of 2 LPM, alongside a moisture removal rate of 0.00110 kg/s at an optimal air velocity of 7 m/s representing an approximate 22% increase over pure $MgCl_2$. Furthermore, dehumidification efficiency rises from approximately 35% at an air velocity of 5 m/s to 41.5% at 7 m/s. The $MgCl_2$ + 20% silica gel composite exhibits an efficiency roughly 22% higher than pure $MgCl_2$ under maximum air velocity conditions. Regarding desiccant flow rates, the highest system efficiency is achieved at 2 LPM, reaching 67%, confirming that the optimal silica gel fraction combined with precise operating conditions is crucial for enhancing overall dehumidification performance (Ahrestani et al., 2023; Ajay et al., 2025).

3.3 Principle of the thermoelectric peltier module in the vernalization chamber

Peltier thermoelectric modules work based on the Peltier effect, a thermodynamic phenomenon in which a temperature difference is generated at the junction of two different conductors when an electric current is passed through them. Fundamentally, Peltier modules consist of a pair of n-type and p-type semiconductors connected in series. When a DC electric current is passed through, electrons in the n-type semiconductor and holes in the p-type semiconductor move from one side to the other, carrying kinetic energy. This movement of charge carriers causes heat energy to be absorbed on one side (the cold side) and released on the other side (the hot side). The cooling efficiency (Coefficient of Performance/COP) of a Peltier module is generally influenced by the temperature difference between the two sides, the magnitude of the electric current, and the quality of the semiconductor material (Enescu & Virjoghe, 2014; Balasubramanian, 2020).

At the microscopic level, this cooling mechanism is governed by charge carrier diffusion across p–n junctions. As carriers traverse interfaces between dissimilar materials, changes in their average energy lead to heat exchange with the crystal lattice. When carriers gain energy while crossing the junction, heat is absorbed, producing a cooling effect, whereas energy loss results in heat release on the opposite side (Galphade & Chhantbar, 2025). Through this solid-state process, thermoelectric modules enable direct heat pumping without mechanical components or refrigerants, allowing rapid and precise temperature control.

In the context of garlic vernalization, maintaining a stable low-temperature environment, typically in the range of 0–10 °C, is essential to induce dormancy release and subsequent bulb development. The localized and controllable cooling provided by Peltier modules makes them particularly suitable for small-scale and controlled-environment agricultural systems, such as vertical or chamber-based cultivation. By adjusting the electrical input, cooling intensity can be finely regulated to maintain temperatures within the optimal vernalization range, ensuring uniform thermal exposure across the planting medium (Pratama & Saraswati, 2023).

From a thermal response perspective, the Peltier module is also critical in regulating transient temperature fluctuations within the chamber. When internal temperatures exceed a predefined threshold, activation of the thermoelectric module enables rapid heat extraction, counteracting incoming environmental heat flux. This behavior reflects the transient cooling characteristics of thermoelectric systems, where short-term temperature response is strongly influenced by electrical input and device dynamics (Wu et al., 2024). Such dynamic operation forms the basis for the transient thermal analysis discussed in subsequent sections, particularly in evaluating system response time and operational stability.

3.4 Design of the vernalization cooling system

The cooling system for this vernalization chamber is designed using Peltier thermoelectric modules as the core of the cooling mechanism. The Peltier modules are strategically placed at the bottom of the vernalization chamber cover, with the cold side (which absorbs heat) facing the chamber and the hot side (which releases heat) facing outward. This configuration ensures that heat extracted from the internal space is directly transferred toward the external environment without interfering with the planting area inside the chamber (Aziz et al., 2017). To increase cooling effectiveness, the cold side of the Peltier is connected to an aluminum plate. The use of this aluminum plate aims to expand the contact surface area and increase the convection rate, so that heat from inside the vernalization chamber can be absorbed more efficiently and distributed to the cold side of the Peltier. This aligns with previous studies showing that optimized heat spreaders and aluminium sinks significantly improve heat dissipation and overall cooling performance in thermoelectric systems (He et al., 2024). In addition, the aluminum plate acts as a heat spreader that reduces local temperature gradients and minimizes thermal contact resistance between the air in the chamber and the thermoelectric module. This design helps ensure a more even temperature distribution within the vernalization chamber, thereby ensuring and predicting consistent vernalization conditions for garlic.

Meanwhile, to overcome the heat generated on the hot side, an ultra-thin coated PVC heatsink is placed on top (Dizaji et al., 2024). This heatsink functions to transfer the heat released by the Peltier to the surrounding environment, thereby preventing heat buildup that can reduce the cooling performance of the Peltier module itself. Although PVC has a lower thermal conductivity compared to metallic heatsinks, its lightweight structure, corrosion resistance, and adequate surface area make it suitable for low temperature gradient applications where compactness and material efficiency are prioritized.

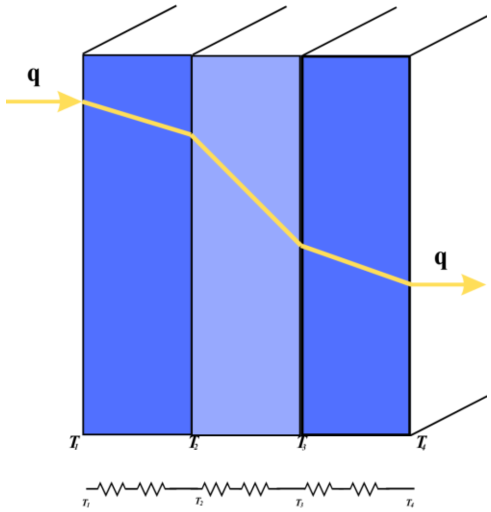

Fig. 3. Schematic of heat transfer through three surfaces

From a thermal design perspective, the cooling system can be conceptualized as a series of heat transfer layers, starting from the internal chamber air, passing through the aluminum plate and the Peltier module, and finally dissipating to the ambient environment via the heatsink. Each layer contributes a specific thermal resistance that collectively governs the steady-state heat flow across the system. The schematic of heat transfer through three surfaces can be seen in Fig. 3**.**

As illustrated in Fig. 3, heat flux originating from the warmer external environment is transmitted sequentially across three distinct surfaces before reaching the internal chamber, with each interface introducing a temperature drop due to thermal resistance. This behavior is consistent with multilayer heat transfer theory, where the presence of successive conductive and convective resistances reduces the net heat flow entering a controlled space (Yuan et al., 2022). Such a layered heat transfer pathway demonstrates how the system design intentionally attenuates environmental heat ingress before it reaches the active cooling interface. By reducing the thermal load imposed on the Peltier module, this configuration enhances overall operational stability and prevents excessive transient demand on the thermoelectric cooler, a principle also emphasized in recent studies on thermally managed enclosure systems (Wu et al., 2024). This design oriented thermal configuration provides the foundation for the heat transfer mechanisms analyzed in the subsequent section, where conduction and convection processes are quantified to evaluate system thermal performance.

3.5 Heat transfer mechanisms in the tropiverna system

In the Tropiverna system, it is specifically designed to resist heat transfer from the external environment, with the aim of maintaining the stability of the medium temperature so that it remains in accordance with the physiological needs of garlic during the vernalization phase. For this purpose, thermal analysis is carried out based on two main heat transfer schemes, namely conduction and convection. The convection mechanism was analyzed using Newton's Law of Cooling. Convection occurs in two main zones: first, between the external environment and the outer surface of the outer pot, where the surrounding air becomes a fluid medium that interacts with the pot wall. Second, between the inner pot surface and the internal environment in the form of an internal space (vernalization space). In both conditions, the heat flow transferred through convection is directly proportional to the temperature difference, the convective heat transfer coefficient, and the surface area (Cengel & Ghajar, 2020). Theoretically, this system has a convective heat transfer value of 1.5749 J/s, which indicates that this system is capable of resisting heat entering from the environment (fluid) into the outer surface of the pot. From a thermal behavior perspective, the relatively low convective heat transfer value indicates that the temperature gradient between the tropical environment and the system boundary is effectively suppressed. This suppression reduces the intensity of heat exchange through natural convection, thereby limiting the rate at which environmental heat penetrates the system (Liu et al., 2025). In tropical climates, where ambient air temperatures are relatively high, controlling convective heat transfer at the outer surface is essential to prevent excessive thermal loading on the internal vernalization chamber.

Conduction is analyzed by referring to Fourier's Law of Heat Conduction. Conduction occurs along the path of the pot material, which is designed with three different layers. Each layer has a different thermal conductivity, which affects the amount of heat flow transferred from the outer layer to the inner layer (Wang et al., 2017). With a combination of low-conductivity materials, this system functions as multilayer insulation that can slow down the propagation of environmental heat into the internal space (vernalization chamber). Thus, the three-layer pot design is not merely a structural aspect, but a thermal engineering strategy to resist heat flow and maintain internal temperature stability. Theoretically, this system has a conduction heat transfer value of 0.9592 J/s, which indicates that it is capable of resisting heat entering from the environment (fluid) into the outer surface of the pot.

The combined resistance to convective and conductive heat transfer plays a critical role in maintaining temperature stability during the garlic vernalization phase. Stable low-temperature conditions are essential to trigger physiological responses related to dormancy breaking and bulb differentiation (Filyushin et al., 2023). By minimizing external heat intrusion, the Tropiverna system reduces temperature fluctuations within the chamber, thereby providing a more controlled and uniform thermal environment for garlic cultivation in a vertical farming configuration. The passive heat transfer resistance mechanisms described in this section are closely linked to the active cooling system discussed in Section 3.4. By suppressing conductive and convective heat gains from the environment, the thermal load imposed on the Peltier thermoelectric module is significantly reduced. This synergy between passive insulation and active cooling enhances the overall thermal performance of the Tropiverna system and improves energy efficiency, particularly under tropical operating conditions.

3.6 Thermal response and operational dynamics of the cooling system

The total heat transfer rate ($\dot{Q}$) resulting from combined conduction and convection mechanisms is expressed as heat flux per unit area using the fundamental heat transfer equation (W). This total heat transfer rate represents energy transferred per unit time (J/s), indicating the amount of thermal energy entering the system each second. To evaluate the thermal response of the system, the total heat energy absorbed is calculated up to the point at which the system undergoes a specified temperature increase. This rate quantifies the environmental heat load that penetrates the Tropiverna system, primarily through the porous medium of the coconut husk and the ceramic boundaries of the Zeer pot. As discussed in Section 3.5, the conduction (Eq. 2) and convection (Eq. 3) mechanisms govern the rate at which thermal energy penetrates the Tropiverna system from the external environment. These heat transfer processes determine the magnitude of thermal energy accumulation within the internal space prior to active cooling. Therefore, the thermal response of the system can be understood as a time-dependent consequence of heat transfer resistance(R_{th}) and internal energy storage, which together define how quickly the system approaches the cooling activation threshold (T).

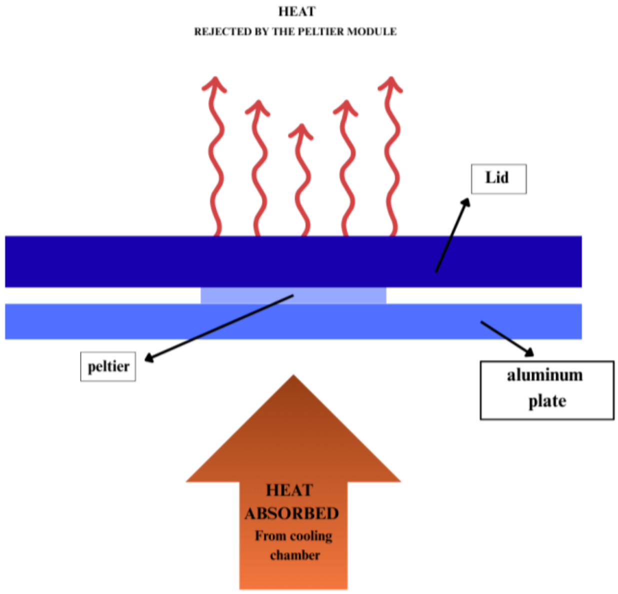

Fig. 4. Peltier heat transfer schematic

The evaluation of thermal response account the mass of the medium (m), its specific heat capacity (C_p), and the temperature gradient (ΔT) experienced before the thermoelectric (Peltier) device is triggered. Theoretically, the heat energy absorbed by the system is 95.073 J. The calculated absorbed heat energy of 95.073 J represents the thermal inertia of the system, reflecting its capacity to temporarily store incoming heat before a noticeable temperature rise occurs. A higher thermal energy storage capacity implies that the system can tolerate a longer delay before reaching the temperature threshold that triggers the cooling mechanism. In the context of garlic vernalization, this buffering effect is advantageous, as it contributes to maintaining short-term temperature stability despite continuous external heat exposure in tropical climate.

Based on the amount of energy absorbed, the time required for heat to infiltrate the internal space is calculated using the relationship between the total absorbed heat energy and the heat transfer rate. In accordance with transient heat transfer analysis, the estimated system response time ($\boldsymbol{\tau}$) is defined by the ratio of stored thermal energy to the rate of heat input. From a transient heat transfer perspective, the system response time reflects the dynamic balance between heat accumulation and heat removal. During the initial phase, the internal temperature rises gradually as thermal energy accumulates within the medium. Once the activation threshold is reached, the Peltier module begins to initiate operation, shifting the system from a heat accumulation regime to a heat extraction regime.

This dynamic transition highlights the role of the Peltier device as a temperature regulator rather than a continuous cooling source. This result indicates the duration required for the internal temperature to rise to the activation threshold of the Peltier cooler, after which the device operates to reduce the system temperature to the desired level. As illustrated in Fig. 4, heat absorbed from the vernalization chamber is conducted through an aluminum plate and transferred to the cold side of the Peltier module. The absorbed thermal energy is then transported across the thermoelectric junction and rejected at the hot side, where it is dissipated to the surrounding environment. This directional heat flow ensures that thermal energy accumulated during the pre-activation phase is effectively removed, enabling the system to return to the target temperature range required for vernalization. The interaction between heat transfer rate, thermal energy storage, and cooling activation time defines the operational dynamics of the Tropiverna cooling system. A controlled response time prevents abrupt temperature fluctuations, thereby promoting a stable thermal environment within the chamber. Such stability is particularly important for garlic vernalization, as gradual temperature regulation supports consistent physiological responses and uniform development across planting units in a vertical farming system.

3.7 Energy efficiency implications and operational dynamics

Theoretically, based on the governing heat transfer equations, the time required for the system to reduce the internal chamber temperature from 10°C, which represents the upper operating threshold of the Peltier device, to 5°C, defined as the lower cutoff temperature, is estimated to be approximately 60.37 s. Conversely, the time required for environmental heat gain to raise the chamber temperature back to the upper threshold is calculated to be around 22.52 s. This disparity indicates that heat ingress from the surrounding environment occurs relatively rapidly compared to the active cooling process. Under this simplified theoretical condition, the Peltier module would be required to operate almost continuously over a 24 hour period to maintain the target temperature range within the vernalization chamber.

However, in practical operation, the thermal behavior and energy efficiency of the system are influenced by multiple internal and external factors that are not fully captured by the theoretical model. The performance of thermoelectric cooling systems is known to vary with operating parameters such as hot- and cold-side temperatures, thermal contact resistances, and heat sink characteristics, all of which directly affect heat transfer rates and overall efficiency (Ameer et al., 2025). In addition to these factors, the theoretical analysis also neglects secondary heat dissipation mechanisms that may occur during real operation. One such mechanism is evaporative cooling at the outer surface of the system, where water evaporation absorbs latent heat from the surrounding environment and effectively lowers the net thermal load entering the chamber. Consequently, the cooling demand imposed on the Peltier module may be reduced, allowing the system to operate with a lower duty cycle and enabling intermittent rather than continuous cooling.

In addition, environmental parameters such as ambient humidity, wind speed, and airflow patterns play an important role in determining convective and conductive heat transfer rates. Variations in these parameters can either enhance or suppress heat ingress into the system, depending on the prevailing microclimatic conditions surrounding the Tropiverna unit. Previous studies have shown that changes in humidity and airflow significantly affect convective heat transfer coefficients, thereby altering heat exchange behavior at the surface–air interface (Kočí et al., 2025). Under conditions of elevated wind speed, for example, convective heat transfer at the external surface may increase, which can accelerate heat gain when the ambient air temperature is relatively high. At the same time, differences in water vapor partial pressure between the internal and external environments can promote coupled heat and mass transfer processes, particularly when moist air interacts with cooling surfaces. Together, these mechanisms complicate the thermal response of the system and contribute to fluctuations in cooling energy demand, making overall performance highly sensitive to short-term environmental variations.

Furthermore, the insulation material used in the Tropiverna system, namely coconut fiber, exhibits significant porosity that alters its thermal behavior compared to conventional insulation materials. Unlike dense solid materials, porous media allow heat transfer not only through solid conduction but also through internal convection within air filled pores. The presence of interconnected pores enables air movement within the insulation layer, which may promote localized convective currents under certain temperature gradients, leading to enhanced heat transfer through the medium (Ranjbarzadeh & Sappa, 2025). Depending on airflow conditions within the insulation layer, this internal convection may either increase or reduce the net heat flux entering the chamber. Consequently, the effective insulating performance of coconut fiber cannot be fully represented by a single thermal conductivity value and must be understood as a dynamic property influenced by environmental and operational conditions.

In addition to conductive and convective heat transfer, radiative heat transfer may also contribute to the overall thermal load of the system, particularly under tropical climatic conditions. Long wave radiation exchange between the chamber surface and surrounding objects is governed by surface emissivity and temperature differentials, such that surfaces with higher emissivity can absorb or emit greater amounts of thermal radiation and thereby influence the net heat balance of the system (Acikgoz, 2015). Although radiative heat transfer is often neglected in simplified theoretical models, its contribution may become significant when the chamber is exposed to direct solar radiation or surrounded by warm external structures. Under such conditions, radiative heat gains can increase the cooling load imposed on the system. In addition, the thermal mass of materials stored within the vernalization chamber, including the planting media and garlic bulbs, further affects cooling energy demand, as larger thermal masses require greater energy input to achieve and maintain temperature changes over time. Together, these radiative effects and thermal storage characteristics add complexity to the system's thermal response beyond that predicted by purely conductive and convective models.

Overall, simplified theoretical models tend to underestimate the combined effects of conduction, convection, radiation, and mass transfer occurring simultaneously under real operating conditions. By treating these mechanisms independently or neglecting certain contributions, such models fail to capture the complex thermal interactions present in the Tropiverna system. As a result, theoretical predictions may appear overly pessimistic and may not accurately reflect actual system performance during field operation. The interaction between passive cooling mechanisms, such as evaporative cooling and insulation, and active thermoelectric cooling introduces dynamic behavior that is difficult to capture analytically. Consequently, experimental validation and real time operational measurements are essential to fully assess the energy efficiency, thermal stability, and operational behavior of the Tropiverna cooling system under tropical conditions.

3.8 Application of vertical cultivation and its impact on productivity

The implementation of vertical cultivation (verticulture) in garlic production is strongly associated with increased productivity per unit of land area. Under conventional open-field conditions, only approximately 60–70% of a one-hectare plot is effectively utilized for planting, as the remaining area is allocated to drainage channels, pathways, and inter-bed spacing. Standard planting distances for garlic range from 12.5 × 12.5 cm for larger cloves to 10 × 10 cm for smaller cloves (Titisari et al., 2019). Assuming a planting hole width of 5 cm and an inter-plant distance of 10 cm, each garlic plant occupies approximately 0.225 m^2 in conventional systems. In contrast, a pipe-based vertical cultivation system substantially reduces spatial requirements, with each plant requiring only about 0.17025 m^2. Although vertical systems require wider planting holes to accommodate pipes or containers, the inter-tray or inter-row spacing can be reduced to as little as 0–5 cm, representing a reduction of more than 50% compared to conventional systems. This spatial optimization theoretically increases plant population density by up to 88,24% per hectare. Such intensification is particularly advantageous for land-limited environments, including urban rooftops, residential yards, peri-urban agriculture zones, and controlled environments such as greenhouses, thereby expanding garlic cultivation opportunities beyond traditional rural farmland.

Beyond land-use efficiency, the verticulture system demonstrates additional benefits related to sustainability and resource optimization. The system is highly adaptable and can incorporate organic and locally available materials, such as coconut husk fiber used in the secondary wall of the cooling system, which may also be substituted with sand, rice husks, or other porous organic media possessing low thermal conductivity. Furthermore, vertical cultivation promotes waste reduction and circular resource use through the repurposing of discarded materials, including used PVC pipes, bamboo structures, and old planting containers. However, despite its potential to enhance domestic garlic production and reduce import dependency, the application of verticulture requires careful recalibration of nutrient and pesticide management. This necessity arises from the limited volume of growth media in container-based systems compared to conventional soil-based cultivation. In open-field conditions, larger soil volumes allow excess nutrients and agrochemical residues to dissipate through runoff or leaching into deeper soil layers, reducing the risk of accumulation (Nuruzzaman et al., 2025). Conversely, in vertical systems with restricted substrate capacity, applying identical chemical concentrations may result in nutrient buildup and increased risk of phytotoxic effects (Sachdeva et al., 2025). Therefore, precise input management is essential to maintain plant health, optimize productivity, and ensure long-term environmental sustainability of vertical garlic cultivation systems.

3.9 Economical impact and feasibility

Efendi et al. (2020) reported that seed bulb diameter sizes of 0–0.35 cm in the *Lumbu Hijau* variety had no significant effect on the diameter and height of the harvested bulbs, yielding bulb diameters of 4.63–4.74 cm and bulb heights of 4.32–4.58 cm. Based on these dimensions, the volume of a single garlic bulb is estimated at 76.55 cm^3. Regarding the same variety, the Center for Library and Agricultural Technology Dissemination (2019) stated that the clove count ranges from 13 to 20 cloves per bulb. Consequently, a single vernalization chamber with a volume of 2,816 cm^3 can accommodate approximately 36.79 bulbs or 588 garlic cloves.

Peltier modules indeed incur higher operational costs due to their low energy efficiency. Modern vapor compression refrigerators possess a Coefficient of Performance (COP) that can reach 2.4, indicating the capability to transfer approximately 2.4 times more heat than the electrical energy consumed (Ali et al., 2025). Conversely, Peltier modules typically exhibit a significantly lower COP, ranging from 0.67413 for single thermoelectric configurations to 0.85285 for double thermoelectric systems (Darwin et al., 2022). This implies that to achieve an equivalent temperature reduction, Peltier systems require greater power consumption, directly resulting in higher monthly operational costs. The commonly utilized TEC1-12706 Peltier module has a maximum power consumption of approximately 60 Watts during operation. Assuming the system runs continuously for 24 hours, the daily energy consumption is approximately 1.44 kWh.

Based on an electricity tariff of IDR 1,444.70/kWh, the monthly operational cost of the Peltier system is estimated to reach IDR 62,411.04. In comparison, a small refrigerator with a volume of 40–50 liters have a power rating of approximately 55 Watts. Assuming continuous 24-hour operation, the daily consumption is estimated to be between 1.5 and 2.5 kWh, equating to approximately IDR 65,011.5 per month. Consequently, without accounting for the duty cycle inherent in refrigerators, the operational cost of the Peltier system may appear lower per unit compared to the more efficient compression refrigerators. Furthermore, regarding manufacturing costs, the Peltier system offers a significant advantage. The TEC1-12706 Peltier module, serving as the core component, is highly affordable, priced at approximately IDR 30,000. The total fabrication cost, including the heatsink and aluminum plates, ranges between IDR 200,000 and IDR 250,000. In comparison, the market price for a commercially available small refrigerator or mini-fridge with a 4-liter capacity ranges from IDR 550,000 to IDR 2,000,000.

3.10 System limitations and development potential

Implementation studies on storage and on-farm facilities demonstrate that evaporative cooling structures are effective in reducing temperatures and extending the shelf life of horticultural products in hot and arid regions (Basediya et al., 2013). This technology is suitable for lowering micro-temperatures toward the ranges conducive to the physiological process of vernalization; however, its efficacy diminishes in high-humidity climates. Consequently, modifications such as two-stage evaporative systems, desiccant pre-cooling, or integrated controlled ventilation are required for humid tropical conditions. However, the current Tropiverna design has not yet incorporated advanced configurations such as two-stage evaporative cooling or desiccant based precooling. These technologies are therefore identified not as existing system features, but as necessary future modifications to address the inherent performance limitations of evaporative cooling under humid tropical conditions.

Considering the limitations of evaporative cooling in humid tropical climates, a critical review of the theoretical modeling approach used in the system's performance analysis is necessary. Clay pots can reduce temperature through the mechanism of evaporative cooling. In this process, sensible heat from the air is transferred and converted into latent heat to evaporate water that seeps through the pores of the pot wall. This indicates that the pot does not merely act as a passive insulator, but also functions as an active cooling system whose performance is influenced by environmental conditions such as air temperature and humidity, as well as water availability. This dual role has important implications for system modeling, as treating the clay pot solely as an insulating boundary may oversimplify the actual thermal behavior of the system.

Experimental studies have shown that the water temperature inside the pot can be lower than the ambient temperature, particularly when the air flow velocity increases (Harish & Krishne, 2014). Recent studies conducted in tropical regions have further revealed that cooling effectiveness strongly depends on ambient humidity levels. Under dry air conditions, temperature reductions of more than 10°C can be achieved, whereas in high-humidity environments, the resulting temperature reduction is generally less than 4°C (Saagoto & Chowdhury, 2025). This indicates that although clay pot-based evaporative cooling is physically effective, its performance remains highly sensitive to ambient humidity, which limits its ability to consistently achieve vernalization temperatures in tropical environments.

The proposed Tropiverna system relies on simplified thermal assumptions that may not fully capture complex real-world interactions. In particular, the theoretical model relies on conservative natural convection assumptions, which may underestimate the actual cooling rate. Therefore, this thermal model focuses on heat transfer effects, but does not consider mass transfer resistance caused by high environmental humidity. As a result, the predicted cooling performance represents a lower bound estimation rather than an exact operational outcome.

In practice, airflow velocity, specifically forced convection, significantly enhances performance. Although increased airflow elevates the convective heat transfer coefficient, its more critical contribution lies in mass transfer processes. It continuously removes the saturated vapor boundary layer from the porous surface, thereby maintaining the vapor pressure deficit required for sustained evaporation. However, Rehman et al. (2020) observed that these efficiency gains exhibit diminishing returns beyond wind speeds of 3 m/s, presenting a trade off where higher velocities significantly increase water consumption without proportionally reducing the inner temperature.

Even so, this potential is thermodynamically constrained by tropical humidity. As ambient relative humidity approaches saturation above 75%, the capacity for air to absorb water vapor diminishes regardless of wind speed. Recent reviews on evaporative cooling indicate that while temperature reductions of 10–15°C are possible in arid regions, reductions in humid tropical environments are typically limited to 3–5°C (Basediya et al., 2013). Consequently, while wind dynamics improve efficiency beyond the model's prediction, the local humidity imposes an intrinsic limit on the achievable minimum temperature. These findings highlight that future development of the Tropiverna system should prioritize hybrid cooling strategies and improved airflow management to overcome climatic constraints while maintaining energy efficiency and water-use sustainability.

4. Conclusions

Tropiverna (tropical vernalization) integrates passive vernalization systems with verticulture to address the two primary obstacles to garlic cultivation in Indonesia, namely limited land availability and tropical temperatures that are unfavorable for the vernalization process. The design of this passive cooling system, which utilizes Zeer pots, coconut fiber, and Peltier modules, is theoretically demonstrated to be capable of creating microclimate conditions conducive to breaking garlic dormancy. This approach offers a low-cost implementation pathway while utilizing eco-friendly and locally available materials. Concurrently, the application of verticulture significantly enhances spatial efficiency, with theoretical projections indicating a substantial increase in productivity per unit area compared to conventional cultivation systems. Consequently, Tropiverna represents an adaptive cultivation strategy for tropical environments that not only addresses climatic and spatial constraints but also supports national food sovereignty by reducing import dependency and promoting sustainable, energy-efficient agricultural practices that are potentially replicable across diverse regions.

Acknowledgement

The authors express their profound gratitude to the mentors and institutions whose guidance facilitated the conceptualization of the 'Tropiverna' innovation. Special recognition is extended to technical colleagues for their invaluable discussions and critical insights during the development of the thermal models; specifically, their feedback was instrumental in applying Fourier's Law and Newton's Law of Cooling to analyze heat transfer within the vernalization chamber. We also acknowledge the contributors who assisted in statistical data compilation and the preparation of technical schematics for the heat transfer and verticulture systems, which greatly enhanced the manuscript's clarity. Furthermore, we are grateful for the linguistic refinement and constructive suggestions provided during the review process. The authors remain solely responsible for any remaining errors or omissions.

Author Contribution

Conceptualization, A.A.; Methodology, A.A.; Formal Analysis, A.A.; Writing – Original Draft Preparation, A.A.; Writing, A.A.F.; Visualization, A.A.F.; Validation, A.A.F.; Writing – Review & Editing, H.U.R.A.U.; Investigation, H.U.R.A.U.; Project Administration, H.U.R.A.U.

Funding

This research received no external funding.

Ethical Review Board Statement

Not available.

Informed Consent Statement

This research does not involve humans.

Data Availability Statement

Not available

Conflicts of Interest

The authors declare no conflict of interest.

Declaration of Generative AI Use

In the preparation of this manuscript, the authors utilized Gemini, ChatGPT, and DeepL Translate primarily for linguistic refinement, grammatical enhancement, paraphrasing, and the optimization of academic tone. These tools were employed solely to improve clarity, coherence, and readability, without generating original scientific ideas, data, or interpretations. Following the AI-assisted editing process, the authors conducted a comprehensive review, critical evaluation, and manual revision of the entire manuscript to ensure conceptual accuracy and consistency. Consequently, the authors maintain full accountability for the manuscript's intellectual integrity, originality, and the accuracy of the final content.

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Biographies of Authors

Ahmad Arifuddin, Undergraduated student at Bandung Institute of Technology, majoring in Agricultural Engineering with a specialization at agricultural technology, with research interest in agricultural biomass valorization and sustainable agriculture.

- Email: 11423057@mahasiswa.itb.ac.id
- ORCID: N/A
- Web of Science ResearcherID: N/A
- Scopus Author ID: N/A
- Homepage: N/A

Azzahra Al Fatikhana, currently a student at Bandung Institute of Technology. As of 2025, Zahra is currently in the fifth semester, enrolling in agricultural engineering, focusing on sustainable agriculture.

- Email: 11423022@mahasiswa.itb.ac.id
- ORCID: N/A
- Web of Science ResearcherID: N/A
- Scopus Author ID: N/A
- Homepage: N/A

Hasna-ur Rusyda Afifatul 'Ulya, currently a student at Bandung Institute of Technology. As of 2025, Hasna is currently in the fifth semester, enrolling in agricultural engineering, focusing on plant breeding technology and sustainable agriculture.

- Email: 11423048@mahasiswa.itb.ac.id
- ORCID: N/A
- Web of Science ResearcherID: N/A
- Scopus Author ID: N/A
- Homepage: N/A