

Article

Design and Performance Development of a Biomass-Fueled Herbal Steam Generation System Using *Melaleuca leucadendra* for Community Therapeutic Applications

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Abstract

Locally available biomass resources offer a sustainable pathway for supporting traditional health practices at the community scale. This study designed, developed, and evaluated a biomass-fueled herbal steam generation system using *Melaleuca leucadendra* leaves for community-based therapeutic applications in the U-Tapao River Basin, Songkhla Province, Thailand. The system was developed based on appropriate technology principles aligned with the Bio–Circular–Green (BCG) economic model, integrating a biomass combustion stove with a steam generation unit. Performance was assessed using the Water Boiling Test (WBT) to measure thermal efficiency, boiling time, and steam generation capacity. Results showed that the developed system significantly improved thermal efficiency and reduced boiling time compared with traditional methods ($p < 0.01$), attributable to enhanced combustion characteristics and heat transfer efficiency. Field trials across two herbal steam room configurations confirmed stable therapeutic temperatures of approximately 40 °C sustained over 30–35 min sessions. The system is technically feasible, energy-efficient, and practically viable for community-scale deployment. This work demonstrates that integrating renewable biomass energy with traditional herbal therapy can provide a replicable, sustainable model for local resource utilization and community-based economic development.

Keywords: appropriate technology; biomass combustion; community-scale energy; herbal steam generator; *Melaleuca leucadendra*; renewable energy systems; thermal efficiency



Academic Editor: Jun Cong Ge

Received: 29 May 2026

Revised: 30 June 2026

Accepted: 7 July 2026

Published: 10 July 2026

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1. Introduction

The application of herbal steam in traditional treatment has been known to offer medical benefits, especially in Southeast Asian cultures where the practice of herbal steaming

constitutes an important aspect in the holistic well-being practice. Herbal steam therapy is not only a way to relieve stress and breathing, but also lets the bioactive properties of vegetable infusions penetrate the skin and be used transdermally. A key facilitator to such therapy is the steam generation mechanism, which should act as a balance between effectiveness, safety, and herbal potency. Biomass energy, particularly from locally abundant species, is a sustainable source of energy that can be used to replace conventional fuels in resource-constrained and rural areas. *Melaleuca leucadendra* (cajeput tree), which is native to tropical and subtropical lands such as Thailand, is one of these potential resources. Leaves of the tree contain high concentrations of essential oils that have reported antiseptic and anti-inflammatory properties [1], and the biomass of the tree in the form of wood is a renewable and low-cost fuel source.

The essential oil of *Melaleuca leucadendra* is composed predominantly of oxygenated monoterpenes, particularly 1,8-cineole (eucalyptol), together with α -pinene, limonene, α -terpineol, and other volatile compounds. These constituents are responsible for the tree's characteristic aroma and have been widely associated with antimicrobial, anti-inflammatory, decongestant, and respiratory therapeutic effects. During herbal steam therapy, these volatile compounds are transferred into a steam phase and delivered to the treatment chamber through evaporation. Therefore, maintaining a stable steam temperature and continuous steam production is essential not only for thermal performance but also for the efficient release and transport of the bioactive constituents. This relationship highlights the importance of developing an energy-efficient steam generation system capable of providing consistent thermal conditions while preserving the effectiveness of the herbal treatment.

Though *Melaleuca leucadendra* is ecologically rich and has therapeutic importance, it is still lacking when it comes to integration with energy-efficient herbal steam generation. The existing herbal steaming technologies have a tendency to be either energy-intensive, fossil-based, or electricity-driven, and hence unfriendly to the natural environment [2]. Moreover, the older steamers that use biomass as a source of fuel are not energy efficient and steam controlled, hence their unstable thermal release, reduced extraction of herbs, and unnecessary fuel quantity [3]. Also, there are still constraints in real-time integration of smart control systems for regulating the temperature, steam flow, and the strength of herbal infusion of the tea. Such weaknesses limit the effectiveness and portability of herbal steam therapy in the wellness and pharmaceutical sphere.

The latest developments have achieved significant steps towards addressing the most important issues in the context of sustainable herbal steam production and energy integration. New research [2,4] has shown novel strategies to help improve essential oil production and system efficiencies, i.e., lignocellulose pre-treatment and biomass-based technologies. Such advancements show a trend of expanding opportunities in the field of decentralized, environmentally friendly technologies that are friendly to local resources and adhere to the principles of a circular economy. These herbal steam systems provide the quality and safety of the processes performed, as introduced by automated and controlled herbal steam processes that enhance user safety and treatment reproducibility. Recent developments have shown that it is virtually possible to design the biomass-based hydrothermal system to extract essential oils, which gives hope that fuel combustion and herbal distillation may be integrated [5]. Developments in lignocellulose pre-treatment have also improved essential oils extraction yield from *Melaleuca leucadendra* leaves, thus providing new prospects in optimizing the efficiency of steam extraction [6]. In terms of energy, the emergence of biomass-based systems to construct combined heat and power (CHP) systems has emphasized the feasibility of a small-scale, distributed energy framework that utilizes nearby bioresources [7,8].

However, there remains a research gap in the development of locally adapted, low-emission herbal steamers combining improved thermal design and smart control of both combustion and therapeutic delivery with *Melaleuca leucadendra* as the fuel and herbal input in particular. Although some of the investigations have touched upon the fuel or the extracting element independently, not many of them have tried to investigate a combined system that can cover thermal efficiency, energy economics, and performance outcomes directed to the users in the background of the community wellness infrastructure. Moreover, rural businesses do not have access to low-cost and technologically suitable technologies that are in line with the concept of the circular economy to promote sustainable community health programs.

To overcome this gap, the current paper suggests designing and developing a herbal steam generator which uses *Melaleuca leucadendra* as the fuel as well as a therapeutic input. It is customized for the U-Tapao River Basin Community Enterprise, located in Songkhla, Thailand, and based on the principles of appropriate technology, with the addition of the intelligent features of the control to adjust steam parameters in real-time. Its performance was strictly tested with the Water Boiling Test (WBT) procedure and compared to a conventional system. In addition, operational efficiency, safety of the users, and the efficacy of treatment were further determined in field trials conducted in locally made steam rooms.

The main contributions of this study are as follows: (1) a new, more energy-efficient herbal steam generator, with *Melaleuca leucadendra* biomass fuel; (2) a hybrid combustion-infusion device that allows constant steam production; (3) a smart control system integration to provide extra flexibility and safety for users; and (4) a scalable model that also fits into the Bio–Circular–Green (BCG) economic targets of Thailand. This work combines the expertise of engineering design, ethnobotany, and community-based innovation, providing a potent contribution to the design of sustainable health technologies in rural areas.

2. Materials and Methods

2.1. Experimental Setup and Operating Principle

The biomass-fueled herbal steam system has three key parts (Figure 1): the biomass combustion unit (A), the steam generation unit (B), and the herbal steam chamber (C). The combustion unit (A) contains four major components, viz. the biomass stove (A1), the combustion chamber (A2), the ash clearance port (A3), and the pot support platform (A4). Rubberwood or *Melaleuca cajuputi* (white samet) biofuel is burned in the chamber (A2), producing heat and ash is cleared through the clearance port (A3). This heat is conveyed into the steam generation part (B), comprising a steam boiler (B1) and lid covering the boiler (B2), a heat chimney (B3), and a cylindrical type heat exchanger in honeycombed form (B4). The honeycomb pipe (B4) increases thermo exchange efficiency by transferring the heat directly to water, and it is possible to boil water rapidly and generate continuous steam. The steam passes through the outlet pipe (B5) and herbs through the herbal inlet pipe (B6). The system additionally has a temperature gauge (B7), an automatic water refill unit (B8), a float valve control (B9), and an auxiliary pipe in cylinder shape (B10). The steam produced in the boiler is directed to the compartment of herbal steam (C) through pipes B5 and B6 by the bottom center inlet. Such a setup allows the well-grained distribution of steam all over the chamber, which is beneficial to herbal therapy. The system is constructed to be energy-efficient, user-friendly and contextually important to local communities. With the help of the locally available biomass fuels, it will enhance the traditional wellness practices and sustainable health and economic development.

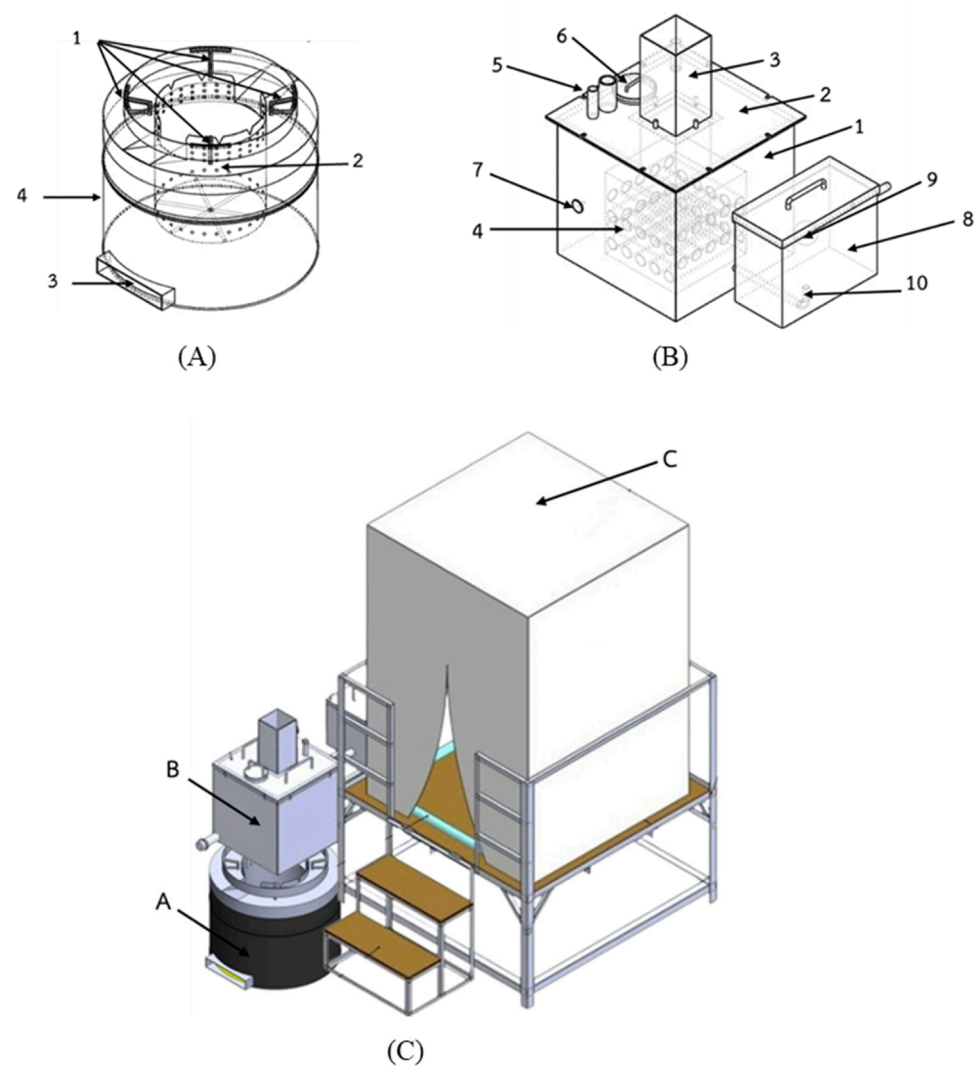


Figure 1. Design of the herbal steam treatment system consisting of (A) the biomass combustion unit, (B) the steam generation unit, and (C) the herbal steam chamber.

2.2. Evaluation of Steam Production Efficiency in a Biomass-Based System

As an evaluation of the herbal steam generation system that was using local biomass, the Water Boiling Test (WBT) procedure was used. This evaluation involved recording of thermal efficiency, specific energy consumption, specific cost consumption, burning rate, firepower, boiling time, and steam production rate. The percentage of biomass furnace energy that could be effectively used was determined to assess thermal efficiency (the percentage of the biomass furnace energy that could effectively be used) as described in the process as follows Berrueta et al. [9]. It was calculated using the equation:

$$\eta = \left[\frac{4.186m_w(T_f - T_i) + 2260m_v}{f_d \times \text{LHV}} \right] \times 100 \quad (1)$$

where η represents thermal efficiency (in %), m_w is the mass of water (kg), T_i and T_f are the initial and final water temperatures ($^{\circ}\text{C}$), m_v is the mass of steam produced (kg), f_d is the mass of fuel used (kg), and LHV is the lower heating value of the fuel (kJ/kg).

Specific energy consumption (SEC) was determined as the amount of biomass energy required to produce one kilogram of steam, following the method of Jetter et al. [10]. It was calculated using the formula:

$$\text{SEC} = \frac{E_v}{m_v} \quad (2)$$

where SEC is expressed in MJ/kg, E_v is the energy used for water evaporation (MJ), and m_v is the mass of steam produced (kg).

Specific cost consumption (SCC) was calculated to determine the energy cost required to evaporate one kilogram of water. The formula used was:

$$SCC = \frac{C}{m_v} \quad (3)$$

where SCC is expressed in Baht/kg, and C is the total energy cost (Baht), at an exchange rate of 1 USD = 33 Baht.

The burning rate (BR) was measured as the rate at which fuel was consumed over time, based on the method by Oyelaran et al. [11]. It was calculated as:

$$BR = \frac{f_d}{\Delta t_m} \quad (4)$$

where BR is the burning rate (g/min), f_d is the mass of fuel used (g), and Δt_m is the combustion duration (min).

Firepower (P) was defined as the rate of energy consumption over time, following Huangfu et al. [12], and calculated by:

$$P = \frac{E}{\Delta t_s} \quad (5)$$

where P is expressed in kW, E is the energy used (kJ), and Δt_s is the combustion time (s).

The time to boil (BT) was measured as the time taken to boil 5 L of water and is an estimate in minutes. The rate of steam production was quantifiable as the weight of the steam produced over an hour, which was in kilograms per hour (kg/h).

In order to improve the performance of the systems, it went further to develop the local biomass-driven herbal steam generation system. It was retested on its performance through the Water Boiling Test technique, and its performance was statistically analyzed by means of mean and standard deviation. Hypothesis testing on statistical software was used to compare these values with the values of the conventional herbal steam system. The new and better biomass-fueled steam generation system was then fitted in the herbal steam room. The measured temperature and humidity within the chamber were analyzed so as to determine its appropriateness to the herbal steam therapy and to ensure that it was accustomed to the commonly accepted practices in Thailand.

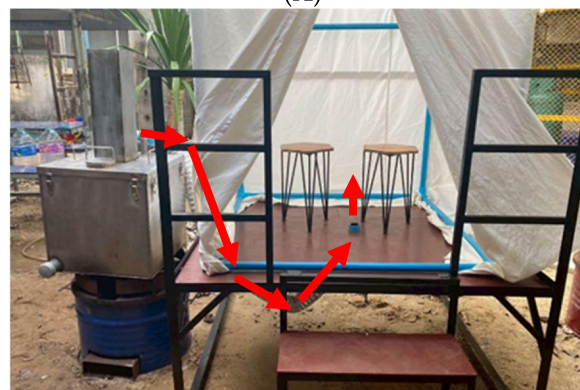
3. Results and Discussion

According to a field study conducted in the U-Tapao River Basin Community Enterprise area, in Bang Klam District, Songkhla Province, Thailand, the area has been characterized by a high level of biodiversity, especially with the proliferation of *Melaleuca cajuputi* trees, commonly referred to as white samet [13]. These trees are spread over thousands of square yards and are an unusual ecological aspect of the region. They have leaves that contain essential oil and provide therapeutic benefits which can be used in herbal steam application, representing an important traditional wellness strategy in Thai culture.

Although these trees are plentiful, there has been limited usage as a consequence of poor development. The research team developed an indigenous, locally built herbal steam plant by utilizing sources of locally available biomass. The system was developed as an innovative model combining the therapeutic power of *Melaleuca cajuputi* and other native herbs while encouraging sustainable energy consumption. The system comprises a biomass combustion stove, as shown in Figure 2A,B.



(A)



(B)

Figure 2. Configuration of the herbal steam room: (A) external view of the herbal steam chamber and (B) internal view of the herbal steam chamber. The red arrow indicates the direction of steam flow from the biomass-fired boiler through the steam delivery pipe into the herbal steam room.

This is an instance of appropriate technology, which means that it is easy, cheap, and suited to local conditions. In addition, it triggers economic development in the community. The system allows the local population to receive additional income, to raise the level of livelihood in households, and to enhance community enterprise forms by exploiting a large natural resource in the region and selling this as a value-added wellness product. It is also strategic under the concept of Bio–Circular–Green (BCG) economy in terms of environmental sustainability, resource efficiency, and self-reliance. Finally, the execution of the present project proves the idea that the interdisciplinary research which unites engineering, botany, and community involvement can foster effective innovations that benefit not only the ecological landscape but also socio-economic aspects.

3.1. Performance Testing of the Herbal Steam Production System Using Local Energy

The thermal performance of the developed biomass-powered herbal steam production system was evaluated using the Water Boiling Test (WBT), a standardized protocol widely employed to determine the thermal efficiency and energy performance of biomass combustion systems [14]. The experiment was designed as a controlled comparative study in which the developed herbal steam production system served as the experimental unit, while the conventional herbal steam furnace commonly used by the local community was employed as the control system.

The control system consisted of a traditional furnace fabricated from one-half of a 200 L steel drum with a diameter of 60 cm and a height of 45 cm (Figure 3). This design

represents the conventional herbal steam production system currently used in community-based herbal steam practices. Both the developed system and the control system were operated under identical experimental conditions using oven-dried rubberwood as the biomass fuel. Each experimental run employed 7 kg of fuel, while the water volume, herbal steam chamber, operating procedures, and ambient environmental conditions were kept constant throughout all experiments to ensure a fair and reliable comparison.



Figure 3. Local stream boiler (control).

Figure 3 shows a traditional community herbal steam furnace used as the control system. The furnace was fabricated from one half of a 200 L steel drum (60 cm in diameter and 45 cm in height). Both the developed and control systems were fueled with 7 kg of oven-dried rubberwood under identical experimental conditions.

To comprehensively evaluate the energy utilization and steam generation performance of both systems, seven performance indicators were determined: thermal efficiency (η), specific energy consumption (SEC), specific cost consumption (SCC), burning rate (BR), thermal power output (P), boiling time (BT), and steam production rate. Thermal efficiency was calculated as the ratio of useful heat transferred to the water to the total energy released from the biomass fuel, whereas SEC and SCC were used to assess the energy and economic requirements for steam production. Burning rate and power output were employed to characterize combustion performance, while boiling time and steam production rate were used to evaluate the effectiveness of steam generation.

Each experiment was conducted in triplicate under identical operating conditions, and the results are reported as mean values. Statistical comparisons between the developed herbal steam production system and the conventional control system were performed using an independent-samples *t*-test with a significance level of $p < 0.05$. The overall experimental framework and the evaluated thermal performance parameters are illustrated in Figure 4.

The statistical analysis demonstrated that the developed herbal steam production system significantly improved several key performance indicators compared to the traditional community system. Significant differences ($p < 0.01$) were observed for thermal efficiency, specific energy consumption, specific cost consumption, boiling time, and steam production rate. The developed system achieved higher thermal efficiency, indicating more effective conversion of biomass energy into useful thermal energy for steam generation. Simultaneously, the lower SEC and SCC values indicate that less fuel and lower operating costs were required to produce the same amount of steam, thereby improving the overall energy and economic efficiency of the system. Furthermore, the reduced boiling time together with the increased steam production rate demonstrates that the developed system

can generate herbal steam more rapidly and continuously, making it more suitable for practical community healthcare applications.

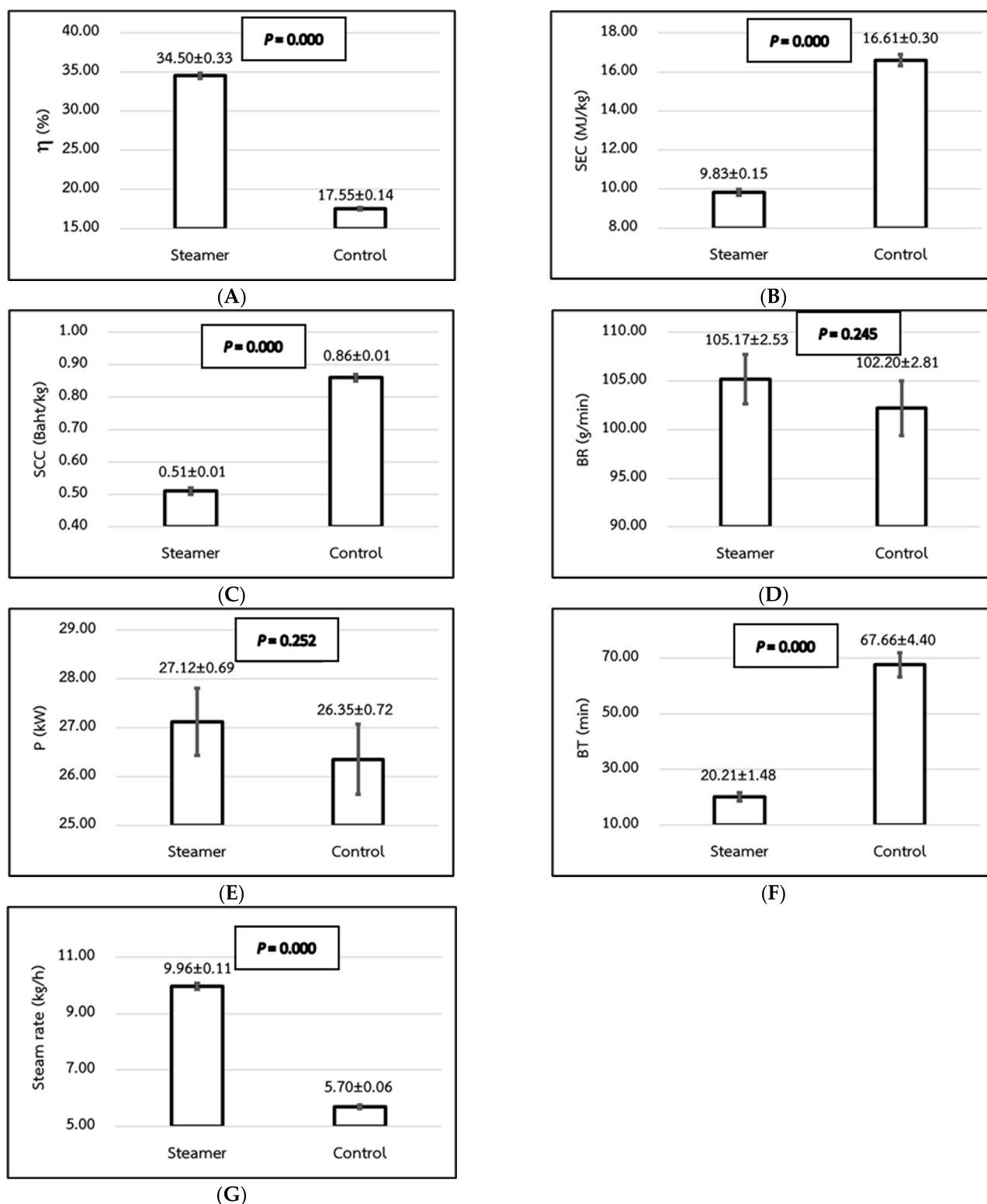


Figure 4. Comparison of thermal performance indicators between the developed biomass-fueled herbal steamer and the traditional control system: (A) thermal efficiency (η), (B) specific energy consumption (SEC), (C) specific cost consumption (SCC), (D) burning rate (BR), (E) power output (P), (F) boiling time (BT), and (G) steam production rate.

These improvements are primarily attributed to the optimized thermal design of the developed herbal steam production system. The enlarged heat transfer area between the combustion chamber and the water reservoir, together with the improved steam flow pathway and reduced heat losses, promote more efficient heat transfer from the biomass combustion chamber to the water. Consequently, a greater proportion of the released thermal energy is converted into steam instead of being dissipated to the surrounding environment.

In contrast, no statistically significant differences ($p > 0.05$) were observed for the burning rate and thermal power output between the two systems. This finding is expected because both systems employed the same biomass fuel type, fuel loading (7 kg of oven-dried rubberwood), and combustion chamber configuration. Therefore, these parameters are primarily governed by the intrinsic combustion characteristics of the biomass fuel rather than by the design of the steam generation unit. The developed system mainly enhances the utilization of the generated thermal energy rather than altering the combustion process itself.

Overall, the results demonstrate that the developed biomass-powered herbal steam production system provides superior thermal efficiency, lower energy consumption, shorter steam generation time, and higher steam production capacity than the conventional community herbal steam system. These findings highlight the potential of the developed technology as an energy-efficient, cost-effective, and environmentally sustainable herbal steam production system suitable for community healthcare facilities and the promotion of locally appropriate energy technologies [15].

3.2. Effects of Integrating a Local Biomass-Powered Herbal Steam System into Community Herbal Business Promotion

The herbal steam rooms were also built in two different sets of formats, with varying capacities for users. Type A, which is $110 \times 110 \times 220$ cm, is a two-person steaming chamber used during the steam processing of herbs. Conversely, Type B ($90 \times 90 \times 165$ cm) is used by an individual person. Figure 2 shows the structural layouts of the two types of rooms.

In order to determine the feasibility of the system operation, the herbal steam generating unit driven by local biomass was tested in the real usage environment with both sizes of the steam room. In both trials, 60 L of water was boiled with the help of rubberwood, which weighed 5.32 kg. The quantitative indicators of the performance were systematically logged with each interval of 5 min, as illustrated in Tables 1 and 2. According to the performance analysis conducted at the operating temperature of 40°C which is deemed superior in herbal steam therapy, the results show that room Type A can be used by two persons in a time range of about 35 min during steaming, whereas room Type B is suitable for a single person in approximately 30 min of steaming.

Table 1. Results of temperature measurements inside the herbal steam room (dimensions: $110 \times 110 \times 220$ cm).

Time (min)	Temperature in the Steam Room at Various Height Positions		
	Floor	30 cm	60 cm
0	38.1	37.5	35.1
5	38.2	38.0	35.5
10	38.5	38.1	35.8
15	38.9	38.5	36.6
20	38.5	38.2	36.5
25	38.9	38.4	36.3
30	38.9	38.4	36.5

Table 2. Temperature measurement results within the herbal steam chamber measuring 90 × 90 × 165 cm.

Time (min)	Temperature in the Steam Room at Various Height Levels		
	Floor	30 cm	60 cm
0	33.9	33.6	32.8
5	34.6	34.6	33.2
10	35.8	35.8	33.9
15	36.4	36.2	34.1
20	37.3	36.7	34.2
25	37.7	36.8	34.4
30	40.2	33.9	33.6

4. Conclusions

This study demonstrated the successful development and field implementation of a biomass-fueled herbal steam generation system for community-based therapeutic applications in the U-Tapao River Basin Community Enterprise. The system utilizes locally available biomass resources together with *Melaleuca cajuputi* leaves and other indigenous herbs, thereby supporting renewable energy utilization while preserving traditional herbal steam therapy practices. *Melaleuca cajuputi* leaves contain volatile essential oils, particularly 1,8-cineole (eucalyptol), together with α -pinene, limonene, and other terpenoid compounds that are commonly associated with the characteristic aroma and traditional therapeutic properties of herbal steam treatment. An efficient steam generation process, therefore, facilitates the transfer of these volatile constituents into the treatment chamber during operation. Performance evaluation based on the Water Boiling Test (WBT) demonstrated that the developed steam generation system achieved higher thermal efficiency, lower specific energy consumption, lower operating cost, and greater steam production capacity than the conventional steam generation system under identical operating conditions. These performance improvements are associated with the engineering design of the developed system, including the incorporation of an enlarged heat exchange surface and a more effective heat transfer pathway between the combustion chamber and the steam generation unit. Since both systems employed similar combustion stoves and identical rubberwood fuel, no statistically significant differences were observed in the burning rate or thermal power output.

Field validation using both single-user and dual-user herbal steam rooms confirmed that the generated steam could maintain suitable operating temperatures and treatment durations under practical community conditions. These findings demonstrate that the developed system is technically feasible for community-level implementation and has the potential to improve energy-utilization efficiency while supporting local wellness enterprises and traditional healthcare services.

Overall, the developed biomass-fueled herbal steam generation system provides a practical approach for integrating renewable biomass energy with traditional herbal therapy within the framework of the Bio–Circular–Green (BCG) economy. The system promotes the efficient utilization of local biomass resources while supporting environmental sustainability and community development. Future work should investigate detailed heat transfer mechanisms through computational simulation, long-term operational performance, economic feasibility, and clinical evaluation of herbal steam therapy to further enhance system performance and broaden its practical applications.

Author Contributions: Conceptualization, W.S. and S.W.; methodology, W.S., P.K., N.P. and S.W.; validation, W.S., S.W. and R.K.; formal analysis, W.S., S.W. and M.M.; investigation, W.S., S.W., J.R.

and M.M.; data curation, W.S., S.W., J.R. and M.M.; writing—original draft preparation, S.W., J.R., T.K. and M.M.; writing—review and editing, J.R., T.K. and M.M.; visualization, W.S., P.K., N.P. and S.W.; supervision, W.S. and S.W.; project administration, W.S. and S.W.; funding acquisition, S.W. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the Thailand Science Research and Innovation (TSRI) through the National Science, Research and Innovation Fund (NSRF) under the Fundamental Fund, Fiscal Year 2024, Project No. 192768, Contract No. FRB670020/0172.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Acknowledgments: We thank the Fundamental Fund Support Budget for the Fiscal Year 2024, provided by the Science, Research, and Innovation Promotion Fund under the Office of the National Higher Education, Science, Research and Innovation Policy Council using the Area Development Capital Administration and Management Unit.

Conflicts of Interest: The authors declare no conflicts of interest.

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