Energy Management of a Solar-Biogas-Electric Hybrid Dryer for Animal Manure Processing

Arthit Sawatdiraksa
Faculty of Agriculture, Rajamangala University of Technology Srivijaya Thung Yai Campus, Nakhon Si Thammarat, Thailand
Arthit.s@rmutsv.ac.th

Pennung Inthararak
Faculty of Engineering, Rajamangala University of Technology Srivijaya, Songkhla, Thailand
Pennung.i@rmutsv.ac.th

Jaruwat Jareanjit
Faculty of Engineering, Rajamangala University of Technology Srivijaya, Songkhla, Thailand
Jaruwat.j@rmutsv.ac.th

Thanwit Naemsai
Faculty of Engineering, Rajamangala University of Technology Srivijaya, Songkhla, Thailand
Thanwit.n@rmutsv.ac.th (corresponding author)

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ABSTRACT

Animal manure serves as a cost-effective fertilizer in Thailand, but the pelleting process is energy intensive. To reduce the reliance on unsustainable energy sources, this study developed and evaluated a Solar Biogas Electric Hybrid Dryer (SBEHD) system. Existing solar and biogas dryers use batch systems and lack the energy management required for continuous manure processing. The developed SBEHD system includes an infrared heater, a 5 mm polycarbonate greenhouse cover for heat retention, and a biogas burner. The system's drying kinetics and energy flow were optimized to within 4.00 m by 3.00 m. The drying process occurred in two stages: an initial drying of the raw manure and a subsequent drying of the pelletized product. During the daytime, the raw manure's drying performance was evaluated under three scenarios, a Solar-Biogas System (SBS), a Solar Electric System (SES), and a combined Solar Biogas Electric System (SBES). At night, a Biogas Electric System (BES) was employed to dry the pelletized manure. The SBEHD's design was informed by Computational Fluid Dynamics (CFD) modeling, and the experimental results demonstrated high drying performance with an efficiency of 37.9% and a specific energy consumption of 4.67 kWh/kg. This process reduced the manure's Moisture Content (MC) to 40% and 25% (wet basis) over a 9-h period. An economic analysis indicates strong commercial potential with an impressive Payback Period (PP) of just 1.3 years. These findings position the SBEHD as a key innovation for sustainable Thai agriculture, promoting the renewable energy and creating valuable fertilizer from waste.

Keywords-solar energy; biogas; management; hybrid dryer; animal manure

I. INTRODUCTION

Widely used in Thailand, animal manure from cattle and pigs offers a cost-effective fertilizer solution, promoting the crop growth and improving the soil health. Its ready availability and lower cost compared to chemical fertilizers, along with its ability to boost the compost formation in Thailand's hot and humid environment, make it a valuable resource. However, the subsequent manure compost pelleting process is energy-intensive and time-consuming, presenting a significant challenge [1]. To address this issue and to further enhance the utility concerns associated with raw manure, a compelling approach involves drying the fertilizer by harnessing thermal energy from solar power [2].

Authors in [3] investigated enhancing the solar dryer performance using Photovoltaic/Thermal (PVT) units and a heat exchanger. Their results showed that the heat exchanger captured waste heat (30-275 J/s) from the drying process, increasing the drying temperatures. Through COMSOL simulations, they also analyzed the impact of the drying room design on the thermal balance, identifying a design with dual air inlets (top and bottom) on one side and a fan-assisted, centralized outlet on the other (Design-4) as optimal for air distribution and thermal uniformity. This research highlights the potential of heat recovery and optimized drying chamber design for improving the solar drying system efficiency. Authors in [4] found that an Inflatable Solar Dryer (ISD) is a more efficient alternative to Open Sun Drying (OSD) for drying coffee and corn. The ISD, which uses a solar-powered fan and recycled steel-can air heater, reduced the drying time for coffee by 42.5% (27 h versus 47 h) and for corn by 42.8% (8 h versus 14 h). Based on the investigation, solar dryers are limited by their inability to function at night and their lack of energy stability. Therefore, supplementary energy sources are necessary to enable the system to operate continuously for 24 h.

To improve the energy efficiency and ensure process stability, many studies have investigated solar drying in combination with other energy inputs. A Solar Assisted Heat Pump Dryer (SAHPD) with heat recovery was shown to significantly improve the energy efficiency and drying performance for chili peppers compared to traditional methods, while a two-room configuration provided even greater effectiveness [5]. A hybrid drying system that combined a heat pump with electrical resistance heating achieved the best results for whole bananas, completing the process in 35 h and proving 37% more efficient than a standalone resistance system and 24% more efficient than a standalone heat pump system [6]. In addition, the combined use of hot air and infrared radiation is increasingly applied in agricultural crop drying [7].

Relying solely on solar and electrical energy, however, may bring only marginal environmental benefits. In contrast, integrating solar and biogas energy reduces the production costs while also lowering the greenhouse gas emissions and pollution from conventional sources [8, 9]. A Solar Greenhouse Biogas Dryer (SGBD) has been reported as a cost-effective and efficient option for drying water hyacinth, with the added benefit of reducing carbon emissions [10]. Systems incorporating Thermal Energy Storage (TES) with Phase Change Materials (PCMs) have been developed to enhance the drying performance and improve the product quality [11]. Such advancements address the weaknesses of traditional systems, as demonstrated in the low-temperature drying of chicken manure [12].

Further studies have emphasized the potential of livestock manure for biogas production. Work has ranged from national-scale assessments in China, to the design of reliable hybrid solar-biogas systems, applications in greenhouse heating in Switzerland, and support for farm-level adoption [13-16]. Together, these studies highlight the versatility, economic benefits, and role of biogas technology in sustainable development. Beyond biogas, manure can also be processed into other value-added resources, such as biochar [17] and biomass for combustion [18]. Still, most efforts remain focused on the batch-type production, which limits commercialization. Research has, therefore, explored continuous operation, combining solar and biogas energy with occasional electrical support to allow round-the-clock production. Hybrid solar dryers with electric and biogas backup have been tested for red chili drying, showing substantial reductions in the drying time compared to open sun drying. In particular, the biogas-hybrid mode achieved 6% higher efficiency and greater effective moisture diffusivity [19]

The BHMSD also offered energy savings by using biogas as an auxiliary heat source, making it a more eco-efficient and sustainable alternative to the traditional EHMSD. This principle underscores the importance of identifying optimal energy-efficiency strategies for greenhouses, considering the interplay of the energy consumption, crop yield, and economic costs [20].

While existing research highlights the potential of individual or dual-source solar-biogas drying systems for various agricultural products [10, 11, 19], and emphasizes the importance of energy efficiency and economic viability in greenhouse and drying operations [20], the role of electrical energy in real-world, 24/7 contexts remains underexplored. Moreover, the specific challenges and opportunities associated with animal manure, given its unique moisture characteristics and potential for both biogas production and value-added byproducts, have not been adequately addressed within a holistic energy management framework. This research aims to bridge this gap by developing and evaluating a novel SBEHD system, focusing on optimizing the energy flows, enhancing the drying kinetics, and assessing the economic performance for sustainable animal manure processing.

II. MATERIALS AND METHODS

A. Design of The Hybrid Dryer

The SBEHD design was informed by an initial site survey of the Tapraksa farm in Trang province, Thailand. This survey was crucial for defining the SBEHD's physical layout, specifically the positioning of the biogas pond, biogas piping network, and the dryer's overall footprint. Following this, CFD analysis was conducted to optimize the hot air ventilation efficiency within the SBEHD. The CFD methodology began with preparing input data by generating a mesh to create a simulation model. This required defining the independent variables; in this research, the number of biogas burner points (3, 4, or 5) to maintain a consistent drying temperature of 40–60 °C, and the exhaust fan size (8, 10, or 12 inches) were varied, reflecting the available products. The drying chamber domain is depicted in Figure 1.

The boundary conditions were defined to set up the simulation. This included specifying initial calculation values and boundary conditions for fluid flow and movement. A k-epsilon turbulence model was assumed to be the incompressible airflow, while the Shear Stress Transport (SST) model was selected for the compressible liquid flow in pipes. For the boundary conditions, the inlet was specified as a pressure inlet with a burner temperature of 100 °C (373.15 K). This high inlet temperature was utilized to maintain the dryer's internal temperature within the 40–60 °C operational range for this study. The outlet was set as a velocity outlet, with its value adjusted according to the exhaust fan's volumetric flow rate. All walls were set as non-slips with a heat flux wall temperature, calculated using a conductive heat transfer rate. The calculation stage employed the Finite Volume Method [21]. Quantities of interest, such as substance velocity and temperature, were approximated within each cell. A primary focus was validating the model's accuracy and precision. The obtained temperature and air velocity values were compared against experimental data from the field-testing section to validate the accuracy. The Mean Absolute Percentage Error (MAPE) for each parameter had to fall within an acceptable range, based on the uncertainty values.

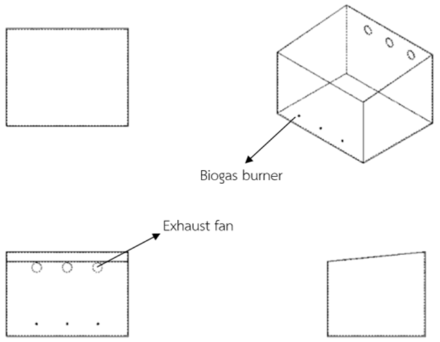


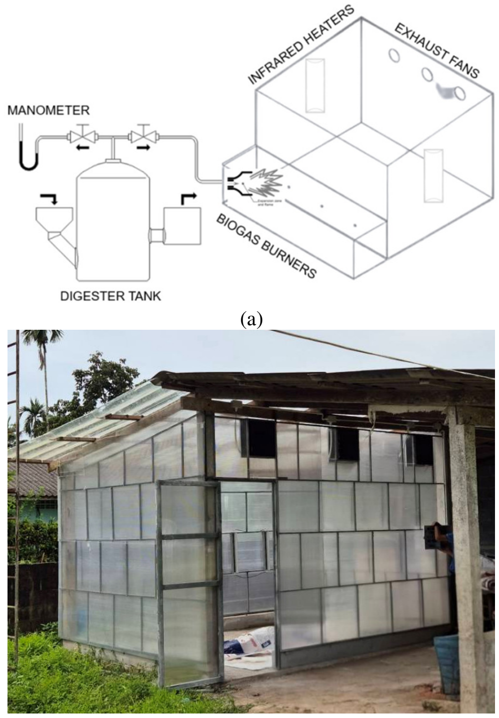
Fig. 1. The domain of the CFD model.

B. Experimental Setup and Procedure

For the experiments, the samples were divided into two categories: 5 kg of fresh animal manure and 3 kg of pelletized manure (averaging 1 cm x 0.5 cm x 0.5 cm), collected from a pig farm in Trang, Thailand. The fresh animal manure, adjusted to an MC of 100% (wet basis), was dried to 40% (wet basis). This partially dried manure was then extruded into pellets, mimicking the inherent MC of the initial pelletized manure (approximately 35%, wet basis), and dried again to a final MC of 25% (wet basis). The SBEHD was designed and installed in Trang, Thailand, with an experimental setup, as illustrated in Figure 2, comprising an infrared heater, greenhouse cover, and biogas burner. The dryer had overall dimensions of 4.00 m in length and 3.00 m in width. The greenhouse cover, constructed from 5 mm thick polycarbonate, maximized the heat accumulation while minimizing the thermal loss. The surface area of the dryer was approximately 20 m^2. The bottom of the dryer was lined with black sheet metal and insulated with 2.54 mm Aeroflex rubber sheeting.

Four 800 W infrared heaters and three 30 W exhaust fans were regulated by the temperature and relative humidity controller. The experimental drying setup featured a heating and dehumidification module; both connected to a data acquisition system. This system included a Hioki LR8431-20 temperature recorder linked to nine type K thermocouples, along with a Primus HM-005 humidity sensor, an Osman AR866A anemometer, and an SR20-D1 pyranometer utilizing Modbus. The drying room temperature was derived from the average of six thermocouple readings, while the burner inlet and outlet temperatures were each determined using three thermocouples. The humidity levels were measured at two distinct locations.

The drying system employed a hybrid approach, with different configurations for the daytime and nighttime operation. During the day, it used a solar-first strategy across three configurations (SBS, SES, SBES). Six thermocouples monitored the temperature, allowing a controller to activate supplemental biogas or electric heat only when the solar energy was insufficient. At night, the system switched to a biogas-BES configuration. The biogas burner served as the primary heat source and the electric heater as a backup. An onboard humidity sensor controlled an exhaust fan to remove the moisture and maintain optimal drying conditions.



(a)

(b)

Fig. 2. SBEHD: (a) schematic diagram and (b) prototype.

For each experimental run, 10 kg of animal manure was spread on trays within the dryer. The appropriate drying temperature for animal manure generally ranges from 40 °C to 60 °C (104 °F to 140 °F), varying with specific manure type and application. Higher temperatures risk nitrogen loss and reduce the nutrient value, while lower temperatures prolong drying [22]. The mass change of the manure was monitored using a Jadever Model JIK6-CAB 4050 balance. Hourly measurements were taken to record the mass change, along with the drying temperatures, which were measured at a steady state. The drying process was stopped upon reaching a point where the mass change was no longer significant, confirming adequate dryness. Each experiment was replicated three times, and the average MC for each sample was used to generate the drying curve. As a comparative benchmark, OSD was also conducted concurrently during the daytime hours (8:00 a.m.-5:00 p.m.). Throughout the evaluation, the SBEHD's performance was assessed under continuous operation (24 h, encompassing both daytime and nighttime). The experimental procedure is shown in Figure 3. The uncertainties associated with the measured parameters during the animal manure drying process were: temperature (±0.5 °C), air velocity (±0.1 m/s), relative humidity (±3 %RH), solar radiation (±1.0 W/m²), time measurement (±0.1 min), and mass change (±0.01 g).

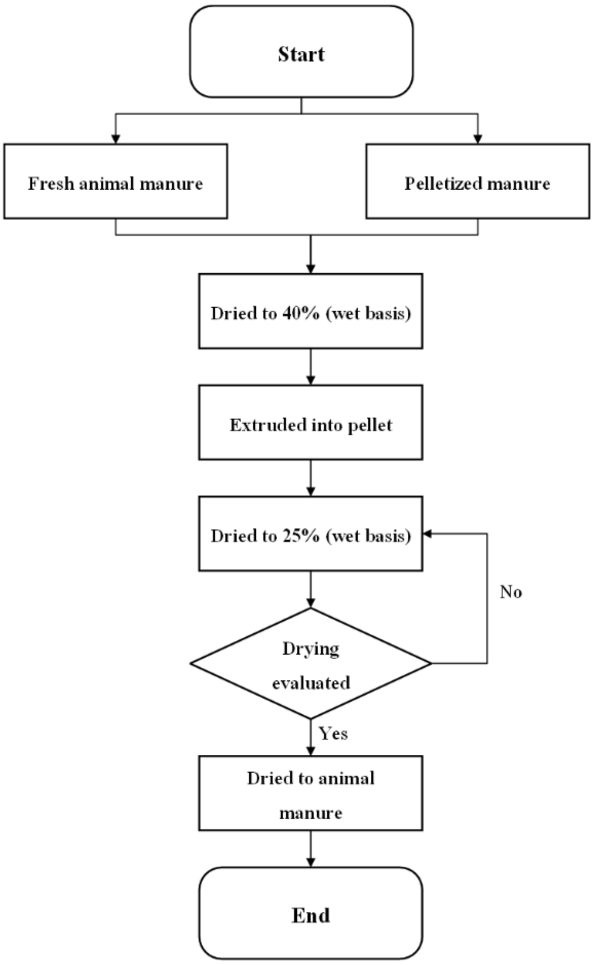


Fig. 3. Flowchart of the experimental procedure.

C. Performance and Economic Analysis

The drying performance of the SBEHD was evaluated using both drying kinetics and thermal performance metrics. Drying kinetics were determined through the MC and the Moisture Ratio (MR), calculated using (1) and (2) [5]. Thermal performance was assessed by calculating drying efficiency and specific energy consumption, as expressed in (3) and (4) [5].

$$\mathrm{MC}_{wb} = \frac{m_{wp}-m_{dp}}{m_{wp}} \times 100 \tag{1}$$

$$\mathrm{MR} = \frac{MC_t-MC_{eq}}{MC_i-MC_{eq}} \tag{2}$$

$$\eta_d = \frac{m_{evap}L}{GA_c+E_h+E_b} \tag{3}$$

$$\mathrm{SEC} = \frac{P_t}{m_{wat}} \tag{4}$$

where: m_{wp} is the wet mass, m_{dp} is the dry mass, m_{evap} is the evaporation mass, A_c is the solar collected area, E_h is the electric power, E_b is the biogas energy, G is the solar radiation, L is the latent heat, and P_t is the total energy.

The economic considerations are crucial in the design of any drying system. The PP, a key indicator of the economic viability, is determined by the Capital (or investment) Cost (CC) and the Profit (PR) generated by the system, according to [5]:

$$\mathrm{PP} = \frac{\mathrm{CC}}{\mathrm{PR}} \tag{5}$$

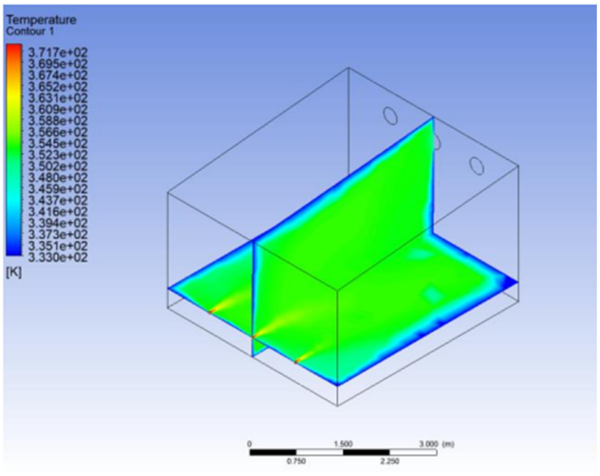
III. RESULTS AND DISCUSSION

A. SBEHD Designed by CFD

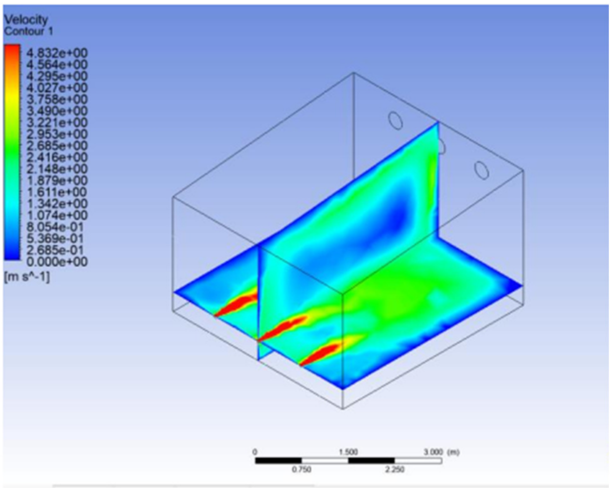
The shape of the SBEH and the number of burners and exhaust were designed using CFD. To ensure accuracy, the mathematical models simulating the airflow within the greenhouse need validation. The validated CFD models aid in the design process by accurately simulating the mass transfer and heat flow within the drying chamber, as verified against chamber data from previous work, using cricket housings [22]. The model validation results are presented in Table I, which compares experimental data with CFD-predicted values. The MAPE is used as a measure of model agreement. For the temperature parameters, the MAPE ranged from 3.89% to 3.95%, indicating a high level of agreement between the CFD model and the experimental results. Similarly, for the air velocity parameters, the MAPE ranged from 4.35% to 5.01%, also demonstrating reasonable agreement. These results suggest that the CFD model accurately simulates the thermal and airflow behavior within the drying chamber, providing a reliable foundation for design optimization. The CFD model was used to analyze the simulation results, displaying temperature values upon the completion of the calculation. These results were then analyzed to understand the flow behavior and fluid movement based on the experimental design and initial variables. With three burners and a 10-inch exhaust fan, the simulated drying chamber temperature fell within the desired 40-50 °C range, suitable for drying pig manure and representing the most cost-effective oven configuration. The analysis of the airflow within the drying chamber revealed that all tested conditions achieved an acceptable temperature range. However, with an 8-inch ventilation fan, stagnant airflow areas were observed, potentially reducing the drying rate in those specific zones. In contrast, the airflow patterns were similar for both the 10-inch (0.3 kg/s mass flow rate) and 12-inch (0.36 kg/s mass flow rate) ventilation fans, likely due to the minor difference in their mass flow rates. The temperature and air velocity distribution results within the drying chamber are portrayed in Figure 4. The temperature and air velocity distribution achieved with the three-burner and three-exhaust fan design offers the best uniformity, ensuring good quality control during the animal manure drying. This configuration is, therefore, proposed for fabrication at the farm.

TABLE I. MODEL VALIDATION

Parameter	CFD vs. Exp.	MAPE (%)
Wall temperature	2.31 °C	3.89
Air top temperature	3.55 °C	3.95
Air middle temperature	3.10 °C	3.93
Air bottom temperature	3.23 °C	3.91
Inlet velocity	0.89 m/s	4.51
Air top velocity	1.02 m/s	4.35
Air middle velocity	1.01 m/s	5.01
Air bottom velocity	0.98 m/s	4.90



(a)



(b)

Fig. 4. Optimal CFD model: (a) temperature distribution and (b) velocity distribution.

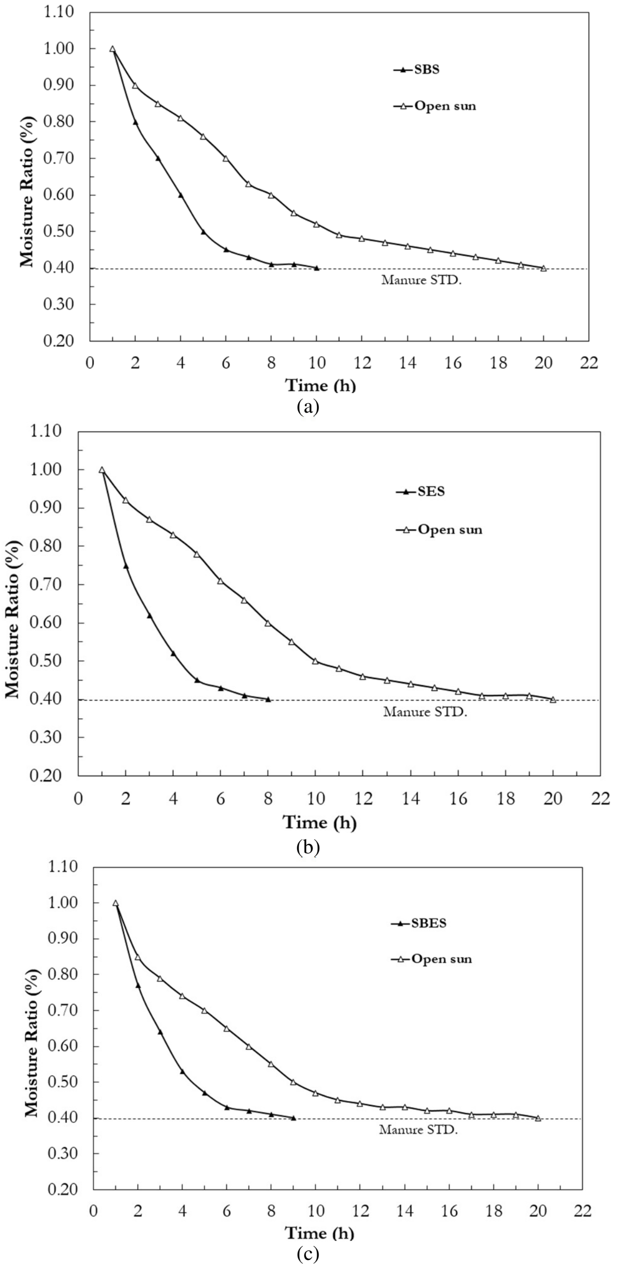
B. *Comparison of Different SBEHD Systems with Open Sun Method*

To assess the drying performance and economic viability of the SBEHD compared to open sun drying, experimental data were selected from daytime hours (8:00 am-4:00 pm). Solar radiation, ambient temperature, and average wind velocity data from Songkhla Meteorology between May 8th and 12th, 2025, were chosen due to the consistent solar intensity and clear sky conditions. The drying temperature was maintained at 45±2 °C for all cases, except for the SBS, which exhibited a wider temperature range of 45±5 °C due to the inherent variability of the solar radiation and biogas energy sources. The MC profiles were converted to MR to account for the variations in the initial MC of the animal manure and to facilitate a more direct comparison between the cases. These moisture ratios are presented in Figure 5. The drying curves for both SBEHD and open sun methods demonstrate a "falling rate period," where the drying rate slows as the manure's MC decreases. While the initial moisture is easily removed, subsequent moisture is more tightly bound. The SBEHD methods (SBS, SES, SBES) consistently exhibit faster drying rates than open sun drying, indicating superior efficiency in the moisture removal due to the controlled temperature, airflow, and potentially lower humidity. As all curves flatten towards a standard MC, indicating equilibrium with the environment, the hybrid SBEHD methods demonstrate a clear advantage by employing multiple energy sources for faster and more efficient drying, resulting in direct energy savings.

The drying behavior of the manure observed with SBES aligns with the findings from [11-14], demonstrating that SBES achieves the target MR in the shortest amount of time while minimizing the overall energy input. This efficiency is reflected in the rate of the drying curve, which plots the drying rate against the MC of the material. With SBES, the curve shows a faster approach to the target MC compared to alternative drying methods. Graphically, this translates to a leftward shift of the entire drying curve on a plot of the drying rate versus time (or MC versus time). Furthermore, the initial slope of the curve, particularly during the constant rate period (where the drying rate is independent of MC as long as the surface remains saturated), is steeper, indicating a higher initial drying rate. This steeper slope implies the SBES can more rapidly deliver heat to evaporate the surface moisture. As the manure enters the falling rate period, where the drying rate decreases as the MC falls due to the limitations in internal moisture transport, the SBES likely maintains a higher drying rate than other methods. This possibly occurs through an enhanced constant rate period, potentially achieved by providing a higher heat transfer coefficient (h) than other methods, which accelerates drying during this stage. It is also supported by the improved moisture transfer from the interior of the manure to its surface, allowing higher drying rates at lower MCs compared to other methods. The analysis of the drying rates reveals that the SBES is the most promising approach, drying faster than the SBS and SES systems, and significantly outpacing open sun drying.

SBES achieves the target MR more quickly, minimizing the required energy. As a hybrid solution, SBES harnesses solar energy and biogas, two renewable energy sources, which reduces the dependence on fossil fuels and reduces the environmental impact by using both sources. The performance evaluation of the manure drying was depicted in Table II. Based on the performance evaluation data, the SBES is the most energy-efficient method for drying manure. While the SES has a slightly shorter drying time at 8 h compared to SBES's 9 h and SBS's 10 h, SBES achieves a lower Specific Energy Consumption (SEC) of 4.67 kWh/kg, outperforming SES at 4.75 kWh/kg and SBS at 4.88 kWh/kg. The SBES also has a higher drying efficiency (η_d) of 37.9%, compared to

36.8% of the SES and 35.3% of the SBS, implying a greater conversion of the renewable energy into a useful drying output. This enhanced efficiency translates to reduced reliance on conventional energy sources and a smaller environmental footprint, aligning with the core principles of renewable energy and environmental assessment by minimizing the resource depletion and greenhouse gas emissions. Therefore, SBES is the most effective option for sustainable manure drying. In addition, the pelletized manure further.



(a)

(b)

(c)

Fig. 5. MRs at different scenarios: (a) SBS, (b) SES, and (c) SBES.

TABLE II. PERFORMANCE EVALUATION OF THE MANURE DRYING

Parameter	SBS	SES	SBES
Average drying temperature (°C)	41	45	43
Average solar radiation (W/m^2)	815	800	760
Drying time (h)	10	8	9
SEC (kWh/kg)	4.88	4.75	4.67
η_d(%)	35.3	36.8	37.9

C. SBEHD Drying of Pelletized Manure at Maximum Capacity

For pelletized manure production, a two-stage drying process is required. This study proposes using the SBES during daylight hours for the initial drying of the raw material, followed by a BES at night for drying the extruded pellets. The economic analysis includes a comparison with the traditional OSD method. The MCs of manure and pellets were shown in Figure 6. Analyzing Figure 6, which depicts the MC (% wet basis) versus time for both SBEHD and open sun drying, the superior performance of SBEHD is demonstrated. The SBEHD method reaches the "Manure STD" (approximately 37% MC) in roughly 8 h, while OSD requires over 20 h. Furthermore, to reach the "Pellet STD" (approximately 24% MC), SBEHD takes around 12 h, an accomplishment that OSD struggles to achieve even after 24 h. The SBEHD method significantly reduces the drying time. Furthermore, the overall SEC and drying efficiency were 5.12 kWh/kg and 32.3 %, respectively. Compared to previous research [23] on manure drying, which reported a drying efficiency range of 17.5-39.9% for cow manure due to variations in animal manure composition, this study achieves a comparable efficiency of 37.9%. While the current study demonstrates a higher drying efficiency of 37.9% compared to the 25.4% in [19] for a similar system, this is particularly noteworthy because the present research processed material with a higher initial MC (100–25% w.b.) versus the chili peppers in [19] (70.2–17.7% w.b.). Typically, a greater moisture load necessitates a higher energy expenditure, which would lead to a lower overall efficiency. Consequently, the superior efficiency achieved in this study suggests that the design and components are more effective than previous designs. However, it is also important to recognize that high-efficiency commercial dryers, despite their thermal effectiveness, are often unsuitable for implementation at the farmer level due to the requirement for a substantial product volume per operational cycle.

The system's operational performance is thermodynamically constrained by both the ambient environmental conditions and the rate of biogas generation. Incident solar irradiance, a function of atmospheric transmissivity, dictates the rate of energy input into the system via radiative heat transfer. Concurrently, the volumetric flow rate of biogas, dependent on the mass and composition of the available animal manure feedstock, determines the potential chemical energy input available for conversion into thermal energy. These variables collectively influence the internal temperature of the drying chamber, governed by the principles of the heat transfer and the thermodynamic properties of the materials involved, and thus constrain the overall energy balance of the system, influencing the rate of moisture removal.

The quality of the pellet fertilizer was evaluated according to the Department of Agriculture's 2014 Notification on Organic Fertilizer Criteria [24]. For non-liquid organic fertilizers, these criteria specify: (a) a minimum total nitrogen (N) content of 1.0% by weight, a minimum total phosphorus (P_2O_5) content of 0.5% by weight, a minimum total potassium (K_2O) content of 0.5% by weight, or a minimum total macronutrient content of 2.0% by weight and (b) a maximum MC of 30% by weight. Both dried manure and pelletized manure satisfied these requirements, as shown in Figure 7. A comparison of the elemental composition of the pelletized cow manure fertilizer with the established standards showed higher values for all components, as presented in Table III.

TABLE III. COMPARISON OF PELLETIZED MANURE WITH STANDARD MANURE

Parameter	Pelletized manure results	Department of agriculture's 2014 criteria [24]
Nitrogen	1.5% ± 0.5	≥1.0% by weight
Phosphorus	1% ± 0.5	≥0.5% by weight
Potassium	0.75% ± 0.5	≥0.5% by weight
MC (%)	24% ± 0.5	≤30% w.b. basis

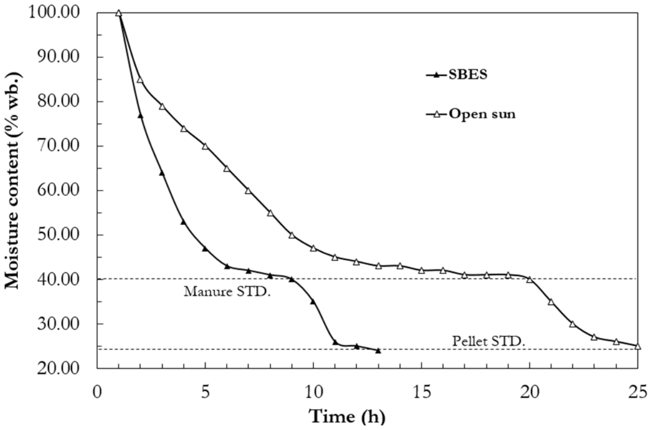
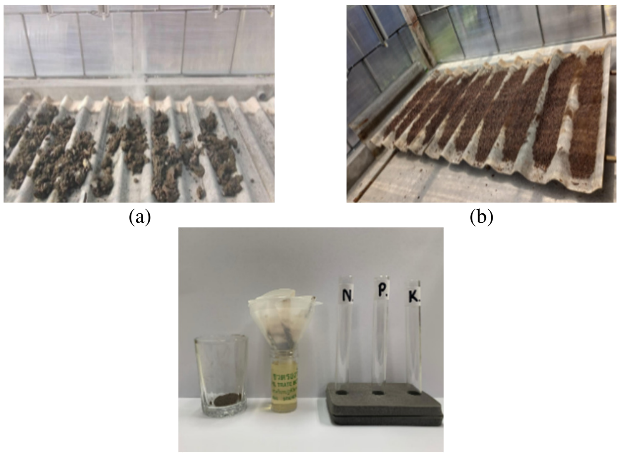


Fig. 6. MC of manure and pellets.



(a)

(b)

(c)

Fig. 7. Quality verification: (a) dried manure, (b) pelletized manure, and (c) testing procedure.

IV. CONCLUSIONS

This study successfully designed a Solar Biogas Electric Hybrid Dryer (SBEHD) using a Computational Fluid Dynamics (CFD) model. Three energy management scenarios were compared to Open Sun Drying (OSD), leading to the recommendation of an optimal configuration for producing high-quality dried and pelletized manure. The experimental results revealed that the SBEHD provides high drying performance, achieving a drying time of 9 h, a SEC of 4.67 kWh/kg, and a drying efficiency of 37.9%. This enabled a reduction in manure Moisture Content (MC) from 100% to 40% (wet basis) during the day and further drying of manure pellets from 35% to 25% (wet basis) at night. The experimental results demonstrate the clear advantage of integrating multiple energy sources, showing that the hybrid system significantly reduces both the drying time and the unit cost of the product compared to relying on a single energy source. The system's economic analysis determined a Payback Period (PP) of approximately 1.3 years. This was calculated based on the average cost of its controllable energy sources (electricity, biogas, and solar) and a fixed annual selling price, which suggests that the system is a beneficial investment for future commercialization. The SBEHD represents a vital, long-term investment for sustainable Thai agriculture, as its adoption would reduce the greenhouse gas emissions, convert manure waste into valuable fertilizer, and increase the farmer income while promoting rural renewable energy. Future research could enhance the methodology by incorporating an IoT system for automated monitoring and control, thereby yielding more accurate and consistent data.

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