Agriculture and Food

AIMS Agriculture and Food, 11(4): 929–946.
DOI: 10.3934/agrfood.2026046
Received: 28 December 2025
Revised: 26 June 2026
Accepted: 19 October 2026
Published: 03 November 2026

https://www.aimspress.com/journal/agriculture

Research article

Sustainability of teak–pandan herbal tea processing in an organic farming community enterprise: Comparative analysis of greenhouse solar and hot air-drying methods

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Abstract: This study aimed to develop a sustainable herbal tea product from teak and pandan leaves (HTP) by systematically comparing two distinct drying methods: hot air drying and greenhouse solar drying. Product quality, economic feasibility, and environmental carbon emissions were comprehensively evaluated. Specifically, the physicochemical properties, total phenolic content, and radical scavenging activity of the dried HTP powder were thoroughly assessed. The experimental results demonstrated that hot air drying preserved the highest total phenol content among the evaluated methods. An extensive economic analysis considered key financial parameters, including production costs (comprising labor, raw materials, and operational expenses), asset depreciation, initial capital investment, and projected revenue, using net present value (NPV) and payback period (PBP) as the primary indicators. While both drying systems proved to be economically efficient by yielding substantial NPV figures and relatively short PBPs, greenhouse solar drying exhibited vastly superior overall economic performance. Specifically, greenhouse solar drying reduced carbon emissions by 7.1832 kg CO_2 eq/kg and yielded between two and four times the NPV of hot air drying. Furthermore, the PBP was shortened by approximately five to fifteen months, while break-even points indicated that lower production volumes were sufficient to offset all total costs. Consequently, greenhouse solar

drying offers an eco-friendly and economically advantageous approach to herbal tea production by effectively reducing environmental impact, eliminating electricity costs, and enhancing both production capacity and overall profitability. Ultimately, this processing method represents a highly sustainable processing strategy for organic farming community enterprises.

Keywords: organic farming; herbal tea; total phenolic content; hot air drying; greenhouse solar drying; economic analysis; greenhouse gas; sustainability

1. Introduction

Recent industry estimates place the global herbal market value at more than 13 trillion Thai Baht (THB) [1,2]. By 2020, the global market for herbal supplements and remedies was projected to reach THB 4 trillion. The Asia-Pacific region was expected to be the fastest-growing market, with a compound annual growth rate (CAGR) of 7% from 2015 to 2020. Global herbal medicine exports are valued at approximately THB 1.8 trillion, and Asia-Pacific continues to show the highest growth rate in this sector. In Thailand, consumption of herbal products is increasing by about 10% annually [3]. Consumer awareness of health maintenance and personal appearance continues to drive demand for natural products and herbs.

More than 1,800 medicinal plants have been documented in Thailand, with roughly 300 species actively traded [4]. The country, as the leader in ASEAN, exports herbal products worth between THB 1.2 and 1.5 billion each year, including fresh herbs valued at about THB 500 million, herbal extracts exceeding THB 270 million, and a wide range of cosmetic products amounting to approximately a few hundred million THB [2,4]. Herbal plants are now regarded as valuable economic resources, attracting foreign investment for the extraction of active compounds to treat specific diseases [5–7]. Scientific evaluations of various Thai herbs have revealed numerous biological activities, including antioxidant, antipyretic, analgesic, hypoglycemic, wound-healing, cytotoxic, anticancer, and antimicrobial effects [5,8,9]. Thai herbs, recognized for their therapeutic properties, are used in diverse forms, such as herbal teas, topical applications, and supplements. Notably, Thai herbal tea containing lemongrass, pandan leaves, and ginger has been shown to relieve symptoms of upper respiratory tract infections in children [7].

The rising demand for herbs for both medicinal and cosmetic purposes allows many countries to profit from their sale [4,10–12]. Enhancing the value of agricultural produce and various medicinal herbs increases market prices while meeting consumer demand [7]. The herbal supply chain comprises four key groups: farmers, collectors, processors, and sellers. Sellers or traders typically apply a gross profit margin of approximately 5–10% on the price paid to farmers, while processors apply a higher margin of around 20–25% [3]. Within this supply chain, farmers play a central role in the cultivation, harvesting, and processing of organic herbs, receiving several tangible benefits. In the case of a Thai social enterprise, the organic herbal supply chain involves numerous farmers who cultivate and harvest fresh herbs and then process them through drying. These farmers have contracts to supply herbs for medicinal production to the Chaophraya Abhaibhubejhr Hospital Foundation. Consequently, they experience increased income, timely payments, reduced healthcare expenses, compliance with the Pollution Control Department's heavy metal standards, and minimized environmental impact while maintaining their economic livelihood [13,14].

Drying is one of the most essential and widely used processing techniques for medicinal herbs, as many specialized technologies require dried plant material [15,16]. Common drying methods include shade drying, sun drying, hot-air oven drying, solar drying, and freeze drying [17,18], each affecting the quality and properties of the final product differently. Successful cultivation and processing of herb crops provide both economic and environmental benefits. Solar drying of medicinal leaves, in particular, offers sustainable advantages by reducing post-harvest losses, lowering carbon emissions, and improving cost-effectiveness, making it a viable and profitable approach for herbal processing [3,11,18].

However, herb processors often face challenges with substandard processing methods that compromise product quality [4,19]. They may lack expertise in processing techniques, production methods, and cost management, and encounter difficulties with packaging and storage. Farmers may deliver products late, in insufficient quantity, of poor quality, or without laboratory inspection, creating obstacles for herbal processors to implement environmentally friendly production technologies [3].

Laohaphatanalert et al. [20] reported that teak leaves have strong potential for producing antioxidant herbal teas. However, no studies have examined how different drying methods affect the physicochemical quality and bioactive compounds in teak and pandan leaves. Therefore, this study evaluated greenhouse solar drying and hot air drying for preparing dried teak and pandan leaves, examining their impact on physicochemical quality, total phenolic content, and radical scavenging activity to identify the most practical drying method. Furthermore, no previous research has assessed the cost and greenhouse gas emissions associated with producing dried herbal tea from teak and pandan leaves.

This study aimed to (a) examine how the proportion of teak and pandan leaves and the air-drying flow rate affect the quality of the dried leaves; (b) evaluate and compare the product quality in terms of physical and chemical properties, carbon emissions, and economic efficiency of greenhouse solar drying versus hot air drying; and (c) identify the most appropriate drying method for sustainable use in Lum Sum Organic Farming Community Enterprises.

2. Materials and methods

2.1. Study area and data collection

This research was conducted from January to December 2023 at the Lum Sum Organic Farming Community Enterprise in Sai Yok, Kanchanaburi, Thailand. Data were collected through in-depth interviews with 14 farmers. The interviews were structured into three parts: (i) general information about the farmers, including age, gender, revenue, and total cultivated area; (ii) details of the herbs grown, such as types and quantities, yield, area utilized, harvest periods, planting costs, dried herb production cost, and selling price per kilogram; and (iii) the consumption of resources and energy during the cultivation and drying processes. Figure 1 presents the system boundaries of the carbon emission calculation. The carbon emissions were estimated using a cradle-to-gate life cycle assessment (LCA) approach, covering the main processes of herb cultivation and drying. The activities considered included land preparation, planting, fertilization, harvesting, and drying. The system boundary excluded transportation between the two processes since both occurred within the same area and relied on manual labor. Input data on resource and energy consumption within these boundaries were obtained directly from farmer interviews. The outputs correspond directly to the activity data and

emission factors employed in the subsequent carbon emission calculations (see Section 2.10 Carbon Emission Analysis).

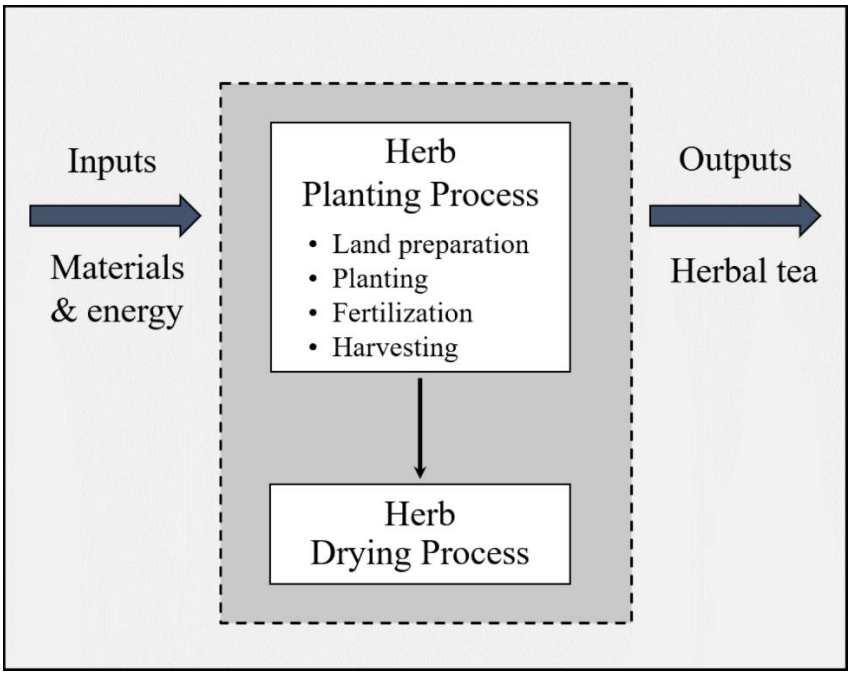


Figure 1. System boundaries of the carbon emission assessment. The outputs illustrated in this figure correspond directly to the activity data and emission factors employed in the subsequent carbon emission calculations.

2.2. Raw materials preparation

Teak leaves and pandan leaves were harvested from the Lum Sum Organic Farming Community Enterprise in Sai Yok District, Kanchanaburi Province, Thailand, between September and December 2023. Young teak leaves were selected from 3-year-old trees based on their oval shape and distinct reddish-to-purplish tint. Pandan leaves were chosen for their characteristic long, narrow, blade-like morphology, vibrant green color, and smooth, glossy surface. Only intact leaves without physical or biological damage (e.g., insect punctures or mechanical bruising) were collected. Immediately after harvesting, fresh leaves were packed in resealable bags, placed in insulated polystyrene containers, and transported to the laboratory at Silpakorn University (Nakhon Pathom, Thailand) within 2 h. Upon arrival, the leaves were thoroughly rinsed with tap water to remove surface impurities and air-dried at ambient temperature. Teak leaves were then manually cut into uniform strips of approximately 8 × 70 mm, while pandan leaves were cut into 3 × 30 mm pieces. The prepared samples were sealed in resealable bags and stored at 4 ± 2 °C prior to further processing.

2.3. Drying experiment

Two drying methods were employed: a greenhouse solar dryer (GHSD) and an electric hot-air dryer (HAD). The GHSD consisted of a parabolic roof structure made from polycarbonate sheets on a concrete floor, with dimensions of 6.0 m in width, 8.2 m in length, and 3.25 m in height. The HAD

(Kluay Namthai Trading Groups, Bangkok, Thailand) contained 24 trays. Drying in the HAD was conducted at 60 °C with an air velocity of 1 m/s in over-flow mode. The samples (300 g) were evenly spread on a 0.5 × 0.7 m² stainless-steel mesh tray at a loading density of 0.86 kg/m². Teak (initial moisture content of 53.05% wb) and pandan (initial moisture content of 73.00% wb) were dried to a constant weight, achieving final moisture contents of 6.67% wb and 6.08% wb, respectively, after approximately 5 h. For the GHSD, experiments were conducted between 10:00 a.m. and 3:00 p.m. from September to December 2023. Ambient temperature and relative humidity (%RH) near the samples were monitored and recorded using USB temperature and humidity data loggers (DL-101T, Voltcraft, Hirschau, Germany) placed directly on the drying tray. The average ambient temperature was 59 $\pm$ 3 °C and relative humidity was 28 $\pm$ 3%RH. Air velocity above the sample tray (natural convection ca. 0.01 to 0.15 m/s) was measured using a thermal anemometer (405-V1, Testo, Lenzkirch, Germany). Samples were dried until reaching the target moisture contents of 6.67% wb for teak leaves and 6.08% wb for pandan leaves. During the drying process, both samples were manually weighed every 30 min until a constant mass was achieved. The recorded sample mass was used to calculate the moisture content at each time interval using Equation (1). After drying, the samples were immediately packed and sealed in aluminum foil bags and equilibrated overnight at room temperature to ensure moisture homogeneity. The moisture content of the samples was then analyzed. The moisture ratio (MR) during drying was calculated using Equation (2). All experimental runs were performed in triplicate, with three analytical measurements taken from each drying experiment of both methods (HAD and GHSD), separately for teak and pandan leaves.

$$MC_t = 100\times\left(1-\left(\frac{W_{eq}}{W_t}\times\frac{100-MC_{eq}}{100}\right)\right) \quad (1)$$

$$MR = \frac{MC_t-MC_{eq}}{MC_0-MC_{eq}} \quad (2)$$

where t is drying time (min), MC_0 is initial moisture content, MC_t is moisture content at time t min, MC_{eq} is equilibrium moisture content, W_t is sample mass at time t min (g), and W_{eq} is sample mass at equilibrium (g).

2.4. Moisture content and water activity determination

Moisture content was determined according to AOAC (2000) methods. The water activity *(a_w)* of the dried leaves was measured at 25 °C using a water activity instrument (AQUALAB 4TE, METER Group, USA). After equilibration, the water activity value was recorded. All experiments were performed in triplicate.

2.5. Tea processing

Dried, sliced samples of both leaves were coarsely ground into small pieces using a blender (HR2223/00, Philips, Thailand). To produce the mixed dried-leaf tea, the ratio of dried teak leaves to dried pandan leaves was varied according to mixture design. Teak leaves were intended to be the major ingredient of the tea, while pandan leaves were incorporated to improve color. Therefore, the dried teak leaves were set in the range of 50–100%, whereas pandan leaves were set at 0–50%. To represent three levels of each variable at low (–1), midpoint (0), and high (+1), the ratios of dried teak leaves to

dried pandan leaves at 100:0 (+1, –1), 75:25 (0, 0), and 50:50 (–1, +1) were systematically selected for this study. After mixing, 1 g of each blend was packed into a tea bag. Each tea bag was infused in 100 mL of boiling water (100 °C) for 3 minutes, with the infusion stirred four times per minute. The brewed tea was then filtered through Whatmann No. 1 filter paper (UK) and stored in amber glass vials at 3 ± 2 °C for further analysis.

2.6. Physical and chemical analysis

2.6.1. Physical analysis

The pH of each tea extract was measured using a digital pH meter (METTLER TOLEDO, Greifensee, Switzerland). Color was determined with a Colorflex EZ spectrophotometer (Hunter Lab, Reston, VA, USA). Before the measurements, the instrument was calibrated (standardized) using the manufacturer's standard black and white calibration tiles. The system set to illuminant D65 and a 10° standard observer angle. Color attributes were expressed according to the CIELAB color scale as lightness (L*), redness/greenness (a*), and yellowness/blueness (b*). All measurements were performed in triplicate.

2.6.2. Chemical determination

2.6.2.1. Total polyphenolic contents (Folin–Ciocalteu method)

Total phenolic content was analyzed following the method of Ruiz-Torralba et al. [21], with slight modifications. Tea extract (0.5 mL) was mixed with 0.5 mL of 10-fold diluted Folin–Ciocalteu reagent. After 1 minute, 2 mL of 10% sodium carbonate solution was added, and the mixture was incubated in a light-tight glass vial at room temperature for 30 minutes. Absorbance was measured at 725 nm using a spectrophotometer (Genesys 10 series, Thermo Electron, USA). Gallic acid solutions (10-200 mg/L) were used for calibration, and the results were expressed as milligrams of gallic acid equivalent per gram of sample (mg of GAE/g sample (wet basis)). All analyses were performed in triplicate.

2.6.2.2. DPPH radical scavenging activity

Antioxidant activity was determined using the DPPH assay, adapted from Ruiz-Torralba et al. [21]. One milliliter of tea extract was mixed with 2 mL of 0.1 mM DPPH solution, placed in an amber vial, and kept in the dark for 30 minutes. Absorbance was recorded at 517 nm, with distilled water as the blank. Standard Trolox solutions (1, 5, 10, 20, and 30 mg/L) were used for calibration. Results were expressed as Trolox equivalent (mg of Trolox/g sample (wet basis)). All analyses were performed in triplicate.

2.7. Statistical analysis

All experiments were performed in triplicate and mean values with standard deviation were shown. The data were analyzed using analysis of variance (ANOVA) followed by Duncan's new multiple-range test, with a confidence level of 95% ($p<0.05$), performed through SPSS statistical software (Version 18; SPSS Inc., Chicago, IL, USA). Because the sample size was limited ($n = 3$), the

assessment of normality was carried out visually through Q-Q plots and boxplots instead of formal statistical tests, which are underpowered with such a small dataset [22].

2.8. Economic analysis

The net present value (NPV) measures the expected profitability of an investment by calculating the difference between the present value of cash inflows and outflows over a set period. An NPV greater than zero indicates profitability and was calculated as follows [23]:

$$\mathrm{NPV} = \sum_{n=0}^{N} \frac{R_n - C_n}{(1+i)^n} \tag{3}$$

where C_n denotes operating cost; R_n denotes revenue; i denotes the interest rate (6.125% per year [24]); n denotes the specific year of investment; and N is the total number of years, which was 5 and 10 in this study.

The payback period (PBP) is the time required to recoup the initial investment. An investment with a shorter PBP recovers its costs more quickly. PBP was calculated as follows [23]:

$$\mathrm{PBP} = \frac{\text{Initial Investment Costs}}{\text{Net Annual Cash Flow}} \tag{4}$$

2.9. Production break-even point (BEP) analysis

The production BEP is the lowest level of production at which the revenue equals costs. It was calculated using:

$$Q = \frac{FC}{r - v} \tag{5}$$

where Q denotes total sales quantity, FC denotes fixed cost, r denotes unit selling price, and v denotes unit variable cost.

2.10. Carbon emission analysis

Greenhouse gas emissions (GHG) from all cultivation and drying processes were calculated by multiplying the quantities of resources or energy consumed by their respective emission factors obtained from the national database, as shown below. Results are expressed in carbon dioxide equivalent (CO_2eq).

$$CO_2\mathrm{eq} = \text{Activity Data (AD)} \times \text{Emission Factor(EF)} \tag{6}$$

To ensure the robustness and reliability of the carbon emission calculations, sensitivity analysis was employed to examine how variations in emission factors (EF) and activity data (AD) influence the overall results. Specifically, emission factors were derived from a national database, subject to quality verification via peer review, with an assumed relative uncertainty of ±10%, reflecting variability in country-specific datasets. Meanwhile, activity data obtained from direct measurement and operational records through interviews were assigned a relative uncertainty of ±5%, consistent with standard practice for primary data collection. By systematically adjusting these parameters within

defined uncertainty ranges, the analysis identified the relative contribution of each variable to the total uncertainty.

3. Results and discussion

3.1. Herbal supply chain in the Lum Sum Organic Farming Community Enterprise

The Lum Sum Organic Farming Community Enterprise comprises 14 herb farmers cultivating 35 different herb species across a total area of 32,000 m^2. The group produces about 16,500 kg of dried herbs annually, generating sales of approximately THB 1.8 million. Six key herbs account for roughly 80% of total sales value: *Andrographis paniculata* (Fa thalai chon)*, Hibiscus sabdariffa* L. (Roselle), *Thunbergia laurifolia* (Freshwater track), *Phyllanthus emblica* Linn., *Zingiber montanum* (Phlai), and *Clitoria ternatea* L. (Butterfly pea). All farmers maintain supply agreements with Chaophraya Abhaiphubejhr Hospital and Siriraj Hospital, which purchase these herbs for pharmaceutical formulation. Production and sales are coordinated collectively: for example, if an order requires 1,000 kg of butterfly pea, the 14 members share the responsibility of meeting that quantity. Farmers collect seeds from the community forest and use only organic fertilizers and compost, intentionally avoiding chemical fertilizers and pesticides. All members (women aged 55–65 years) have 20–30 years of herb-growing experience and own all their plantations. Each earns an average monthly income of THB 5000–6000.

Every three months, the hospital pharmacy department meets with the farmers to plan the types and quantities of herbs needed. After harvesting, the herbs are washed, cut, and dried using either a GHSD or a HAD. The dried herbs are then bagged and weighed. Farmers consolidate their harvests according to incoming orders. Chaophraya Abhaiphubejhr Hospital dispatches a pickup truck to collect the dried herbs, which are then processed into finished products for hospitals, pharmacies, department stores, and online sales through the hospital's website, as well as for export. The community enterprise also delivers dried herbs to Siriraj Hospital using a pickup truck, where they are further processed into various products for distribution within the hospital. The overall herb supply chain is illustrated in Figure 2.

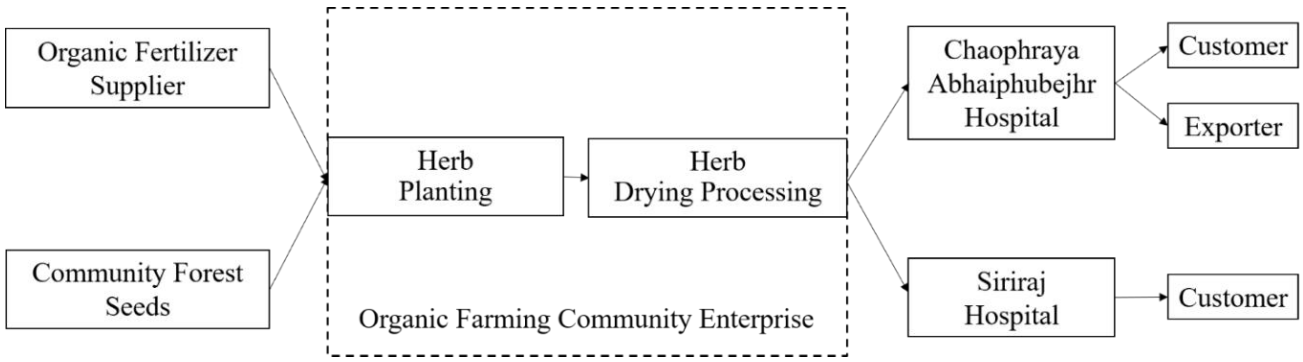


Figure 2. Herb supply chain of the Lum Sum Organic Farming Community Enterprise, Sai Yok, Kanchanaburi, Thailand.

3.2. Drying curves, water activity (a_w) and physical characteristic of teak and pandan Tea

The drying curves of teak and pandan leaves subjected to HAD and GHSD are illustrated in Figure 3. For all treatments, the MR continuously decreased with increasing drying time, indicating progressive moisture removal throughout the drying process. Regarding the drying method, HAD resulted in a faster reduction in MR of both teak and pandan leaves during the initial stage of drying. This behavior may be attributed to the higher air velocity within the HAD system, which enhanced the convective mass transfer and increased the vapor pressure gradient between the leaf surface and the surrounding air, thereby promoting moisture removal. However, after 120 min of drying, the drying rate decreased markedly for both drying methods and leaf types. This slower drying behavior may be associated with the decreasing availability of free moisture and the increasing resistance to internal diffusion as drying progressed.

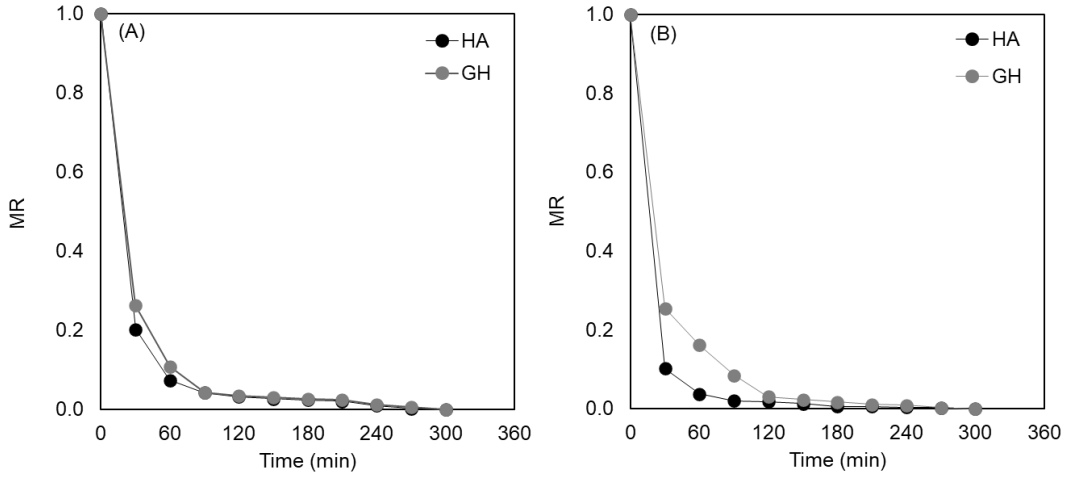


Figure 3. Drying curves of teak leaves (A) and pandan leaves (B) under different drying methods.

The water activity (a_w) of the dried leaves ranged from 0.44 to 0.47. No significant difference was observed between hot-air-dried teak leaves (0.47 ± 0.08) and greenhouse-dried teak leaves (0.46 ± 0.09) ($p \geq 0.05$). A similar result was found for pandan leaves: the a_w of hot-air-dried pandan (0.44 ± 0.09) did not differ significantly from that of greenhouse-dried pandan (0.45 ± 0.80) ($p \geq 0.05$).

Blends of dried teak and dried pandan leaves tea in ratios of 100:0, 75:25, and 50:50 were analyzed for pH and color. Across drying methods, there was no significant difference in pH between teas prepared from hot air (HA) and greenhouse (GH) drying at ratios of 75:25 and 50:50 ($p \geq 0.05$). The highest pH (6.50 ± 0.54) was observed in tea made from HA-dried leaves at the 100:0 ratio, which was significantly higher than that of GH-dried leaf tea ($p < 0.05$) (Figure 4).

The color of tea prepared from HA- and GH-dried leaves indicated that the drying method did not affect tea color (Table 1). With increasing proportions of dried pandan leaves, the L* value increased while the a* and b* values decreased, reflecting the dominant green hue of dried pandan leaves, whereas dried teak leaves contributed more red tones. In the GH system, tea prepared at the 100:0 ratio exhibited the lowest L* value and the highest a* and b* value ($p < 0.05$).

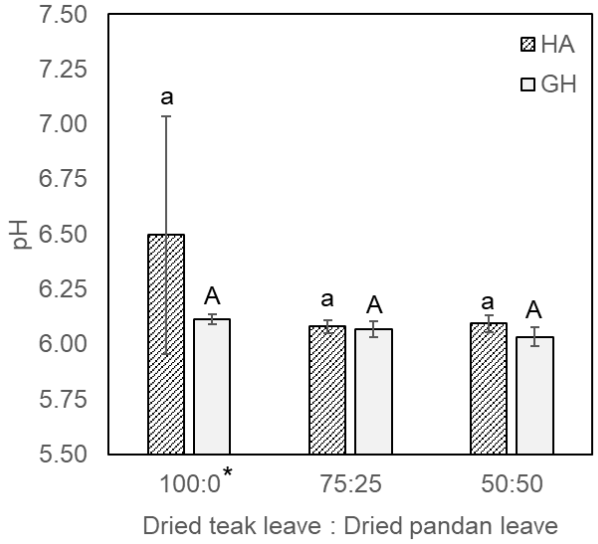


Figure 4. The pH of mixed dried teak leaf and dried pandan leaf tea prepared from HA and GH drying methods at ratios of 100:0, 75:25, and 50:50. Hot air drying = HA; Greenhouse solar drying = GH. Values followed by different letters within the same drying method indicate significant differences ($p < 0.05$). An asterisk (*) indicates a significant difference between drying methods.

Table 1. Color of mixed dried teak leaf and dried pandan leaf tea prepared from HA-dried and GH-dried leaves at different ratios of dried teak to dried pandan leaves.

Drying method	Ratios of dried teak leaves to dried pandan leaves	L*	a*	b*
HA	100:0	73.77 ± 5.25^{a}	25.16 ± 4.82^{a}	38.34 ± 9.23^{a}
	75:25	83.61 ± 1.36^{a}	13.72 ± 1.72^{a}	22.37 ± 0.81^{a}
	50:50	81.71 ± 3.61^{a}	15.93 ± 5.42^{a}	24.07 ± 4.80^{a}
GH	100:0	69.77 ± 3.86^{B}	29.92 ± 3.00^{A}	37.30 ± 5.89^{A}
	75:25	78.91 ± 5.06^{AB}	19.63 ± 5.74^{AB}	26.70 ± 3.59^{AB}
	50:50	85.21 ± 3.37^{A}	12.06 ± 3.55^{B}	19.58 ± 3.23^{B}

Hot air drying (HA); Greenhouse solar drying (GH); Values followed by different letters in the same column indicate significant differences ($p < 0.05$)

3.3. Total phenolic content and antioxidant activity of teak and pandan tea

The total phenolic content (TPC) of mixed dried teak leaf and dried pandan leaf tea obtained from HA and GH drying methods is illustrated in Figure 5A. The highest TPC was observed in tea made from single dried teak leaves (ratio of 100:0), but it was not significantly different from that of the 75:25 ratio for both drying methods. Drying leaves using HA yielded higher TPC than GH; however, at the 50:50 ratio, tea prepared from GH-dried leaves showed significantly higher TPC than HA ($p < 0.05$). A similar trend was observed for the total antioxidant capacity (TAC) of mixed dried teak leaf and dried pandan leaf tea (Figure 5B). The greatest TAC was obtained from HA-dried leaves at the 100:0 ratio; however, it was not significantly different from the 75:25 ratio ($p \geq 0.05$). Interestingly,

increasing the proportion of HA-dried pandan leaves in the tea mixture resulted in lower TAC, whereas no significant difference was observed when the leaves were dried using GH ($p \geq 0.05$). Overall, HA appears to better preserve the TPC and TAC of dried leaves compared with GH. This may be due to the faster deactivation of TPC-degrading enzymes when plants are dried using HA. Rababah et al. [25] reported that these enzymes are rapidly inactivated during HA drying, while air-sun drying exposes leaves to oxygen and a gradual increase in temperature over a longer drying period, allowing TPC degradation to occur before the plants are completely dried. Similar results have been reported by several researchers. Li et al. [26] found that drying sea buckthorn berries using HA drying at 50 °C retained higher TPC than sun drying, attributing this to the shorter drying time associated with HA drying. Nguyen et al. [27] reported that HA drying of guava leaves at 50 °C produced approximately 25% higher TPC and nearly three-fold higher DPPH radical scavenging activity than sun drying. This may be explained by the inactivation of endogenous enzymes, particularly polyphenol oxidase (PPO), at elevated drying temperatures, which prevents oxidative reactions and better preserves the plant's bioactive compounds. In addition, high-temperature drying can cause the collapse of intercellular spaces, facilitating the release of bound phenolics and enhancing their extractability. However, Wongwatanyoo et al. [28] and Imam et al. [29] reported that TPC and TAC in dried kratom (*Mitragyna speciosa*) and sage (*Salvia officinalis*) leaves dried using an opaque GHSD were higher than those obtained using HAD. Therefore, shorter drying times and reduced exposure to light and oxygen were identified as key factors for retaining TPC and TAC during drying.

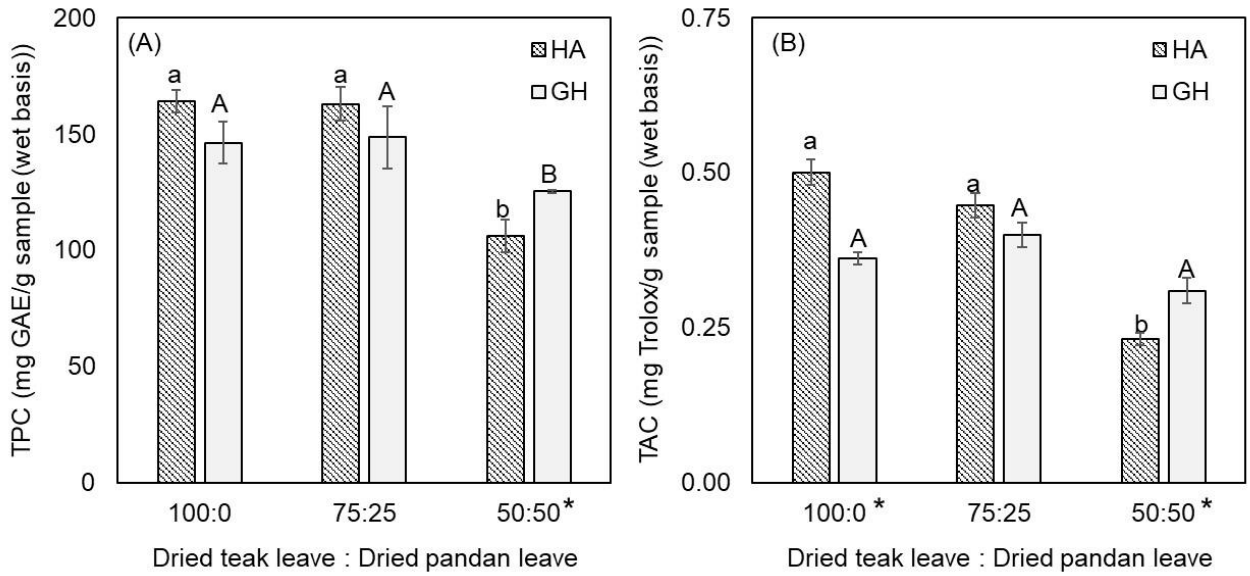


Figure 5. TPC (A) and TAC (B) of mixed dried teak leaf and dried pandan leaf tea prepared from HA and GH drying methods at ratios of 100:0, 75:25, and 50:50. Hot air drying (HA); Greenhouse solar drying (GH). Values followed by different letters within the same drying method indicate significant differences ($p < 0.05$); * indicates a significant difference between drying methods.

3.4. Economic and production break-even point analysis

The economic analysis and production break-even points for the HAD and GHSD were calculated based on actual incurred costs. Table 2 compares the values of key economic indicators and break-even points, including NPV, PBP, and BEP. The investment for dried herb production included a weighing machine (THB 7,000), a packaging label sealer (THB 20,000), and an herb grinder (THB 10,000). Land and factory rental costs were THB 240,000. Two types of dryers were used: a HAD (THB 100,000) and a GHSD (THB 170,000). All equipment, including both dryers and supplementary devices, were depreciated using the straight-line method. The weighing machine, label sealer, herb grinder, and HAD had a lifespan of 5 years, whereas the GHSD had a lifespan of 10 years. Assuming year-round production, five days per week, each dryer would process 240 batches annually. Drying capacities were 24 kg per batch for the HAD and 30 kg per batch for the GHSD. With a fresh-to-dried herb ratio of 4.4:1, this corresponds to approximately 5,760 kg of dried herbs annually for the HAD and 7,200 kg for the GHSD.

Table 2. Economic analysis and production break-even points for teak and pandan leaves using a hot air dryer and a greenhouse solar dryer.

Item	Teak leaves		Pandan leaves	
	Hot air dryer	Greenhouse solar dryer	Hot air dryer	Greenhouse solar dryer
Dryer depreciation cost (THB/year)	20,000.00	17,000.00	20,000.00	17,000.00
Supplementary equipment depreciation cost (THB/year)	7,400.00	7,400.00	7,400.00	7,400.00
Labor cost (THB/year)	84,000.00	84,000.00	84,000.00	84,000.00
Other cost (water, mask, glove, bag, etc.) (THB/year)	5,530.00	5,530.00	5,530.00	5,530.00
Material cost (THB/year)	57,600.00	72,000.00	172,800.00	216,000.00
Electricity cost (THB/year)	60,950.00	0.00	60,950.00	0.00
Total cost (THB/kg)	336.63	272.02	228.10	161.00
Price of dried herb (THB/kg)	350.00	350.00	300.00	300.00
Variable cost (THB/kg)	247.31	202.40	138.78	91.38
Production BEP (kg)	1,138.66	771.88	725.30	546.11
NPV (THB)	672,106.98	1,278,398.28	155,514.38	632,657.54
PBP (year)	1.51	1.09	2.97	1.74

The NPV of teak leaf drying using the HAD and GHSD was THB 672,107 and THB 1,278,398, respectively. It was found that the NPV of the GH drying was about twice as high as that of the HA drying. For pandan leaves, the NPV for HA and GH drying was THB 155,514 and THB 632,658, respectively. It was found that the NPV of the GH drying was approximately four times higher than that of the HA drying. The calculated PBP for teak leaves was 1.51 years (hot-air) and 1.09 years (greenhouse solar), while for pandan leaves it was 2.97 years (hot-air) and 1.74 years (greenhouse solar). It can be observed that the PBP of the GH drying for teak leaves was approximately five months shorter than that of HA drying, whereas for pandan leaves it was about fifteen months shorter. The BEP for yearly production and sales of teak and pandan leaves was higher for the HAD compared with

the GHSD. Overall, GH drying proved more cost-effective than HA drying.

For mixed teak–pandan tea (1 kg) with 750 g teak leaf powder and 250 g pandan leaf powder, the selling price was THB 600 per kilogram. The production cost using HA drying was THB 309.50 per kg, yielding a 94% profit, whereas greenhouse solar drying costs THB 244.20 per kg, yielding a 146% profit. For a 1:1 mix (500 g each of teak and pandan leaf powder), production cost was THB 282.37 per kg using HA drying (yielding 112% profit) and THB 216.51 per kg using GH drying (yielding 177% profit).

3.5. Carbon emissions

Community enterprises cultivated pandan leaves, teak trees, and various other herbs across the entire growing area. The soil was prepared by plowing with a tractor and enriched with chicken manure, relying solely on rainwater and avoiding chemical inputs. After reaching maturity, the pandan and teak leaves were harvested manually, then washed and oven-dried. The environmental impacts of these key operations, conducted by community entrepreneurs, were assessed in this study using a cradle-to-gate approach. The inventory data corresponding to 1 kilogram of the cultivated product is presented in Table 3.

Table 3. Greenhouse gas emissions from processing teak–pandan leaves (1 kg basis).

Process/activity	Unit	Quantity (per kg)	Emission factors* (kg CO_2eq/unit)	Greenhouse gas emissions (kg CO_2eq/kg teak or pandan)	
				Hot air drying	Greenhouse solar drying
Planting process					
- Diesel for land preparation using a tractor	L	0.0010	5.9162	0.0059	0.0059
- Fertilizer from chicken manure	kg	0.0050	0.1097	0.0005	0.0005
Drying process					
- Electricity	kWh	12.0000	0.5986	7.1832	0.0000
- Water for cleaning	m^3	0.0025	0.5410	0.0014	0.0014
Total				7.1910	0.0078

Note: * TGO [30].

The greenhouse gas emissions for cultivated and dried teak or pandan leaves—using both a HAD and a GHSD—were calculated and shown in Table 3. The cradle-to-gate carbon emissions from the cultivation and drying of leaves were 7.1910 kg CO_2 eq/kg when using the HAD, compared to 0.0078 kg CO_2 eq/kg with the GHSD. Thus, GH drying reduced carbon emissions by 7.1832 kg CO_2 eq/kg compared to HA drying. Carbon emissions generated by the HA drying are up to 922 times greater than those associated with the GH drying, demonstrating a significant environmental advantage of greenhouse solar drying. The substantial difference between HA and GH drying (approximately 922-fold) can be rationalized by considering the system boundary and the inherent characteristics of the drying method. HA drying involves energy-intensive processes and high carbon emission factors, resulting in a markedly higher carbon footprint. In contrast, GH production relies on relatively simple

pathways with substantially lower energy demand. This outcome is consistent with theoretical principles of life cycle assessment, which indicate that products with complex structures or resource-intensive processes typically generate disproportionately higher greenhouse gas emissions. Although directly comparable studies are limited in this area, the observed difference aligns with established theoretical expectations regarding carbon emission factors and energy intensity in product manufacturing.

In Figure 6, a sensitivity analysis was conducted to evaluate the influence of emission factors (±10%) and activity data (±5%) on the carbon emissions calculated, as presented in Table 3. The results indicated that variations in emission factors contributed more significantly to the overall uncertainty compared to activity data. When both parameters varied simultaneously in the same direction, the total emissions deviated by approximately ±15% from the baseline value, highlighting the critical importance of emission factor quality in ensuring reliable carbon emission assessment.

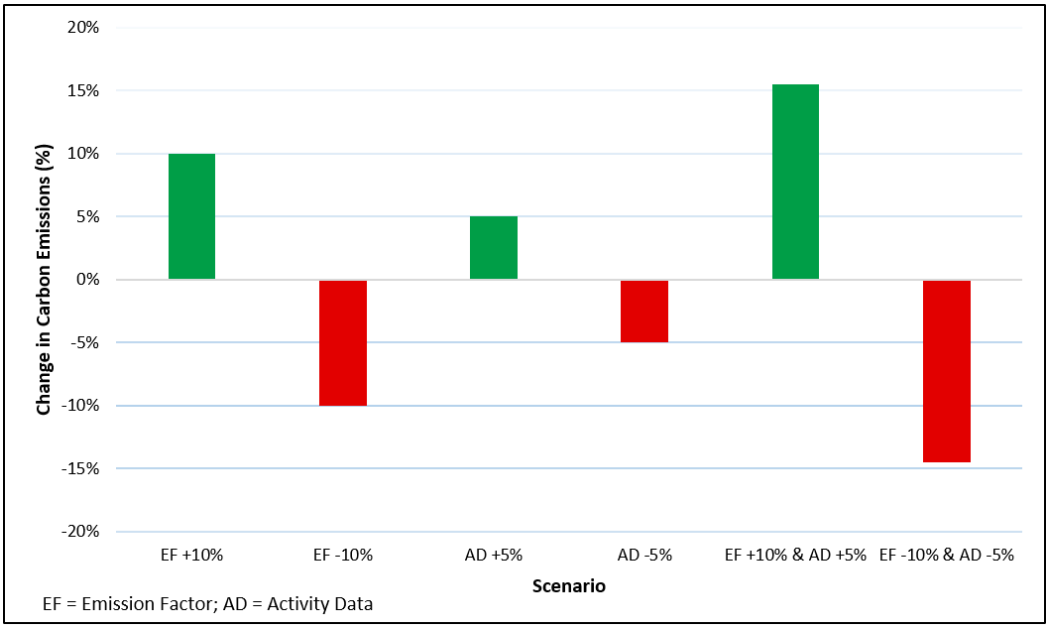


Figure 6. Sensitivity analysis of carbon emissions.

3.6. Comparative analysis of production unit cost and carbon emissions

Figure 7 demonstrates that HA drying of mixed teak-pandan leaf tea results in higher unit costs and significantly greater carbon emissions compared to GH drying, primarily due to the energy consumption associated with HA drying. The environmental impact evaluation did not reveal a significant effect of different teak-pandan ratios on carbon emissions. However, the production unit cost increased with higher teak ratios. For Lum Sum Organic Farming Community Enterprise, the GH drying process appears to be a more sustainable pathway due to its advantages: increased production capacity, enhanced profitability, faster return on investment, and lower environmental impact. This method is limited by a higher initial investment and reliance on solar energy. Drying times can be unpredictable and subject to delays during periods of low sunlight or inclement weather, potentially leading to fluctuating production schedules.

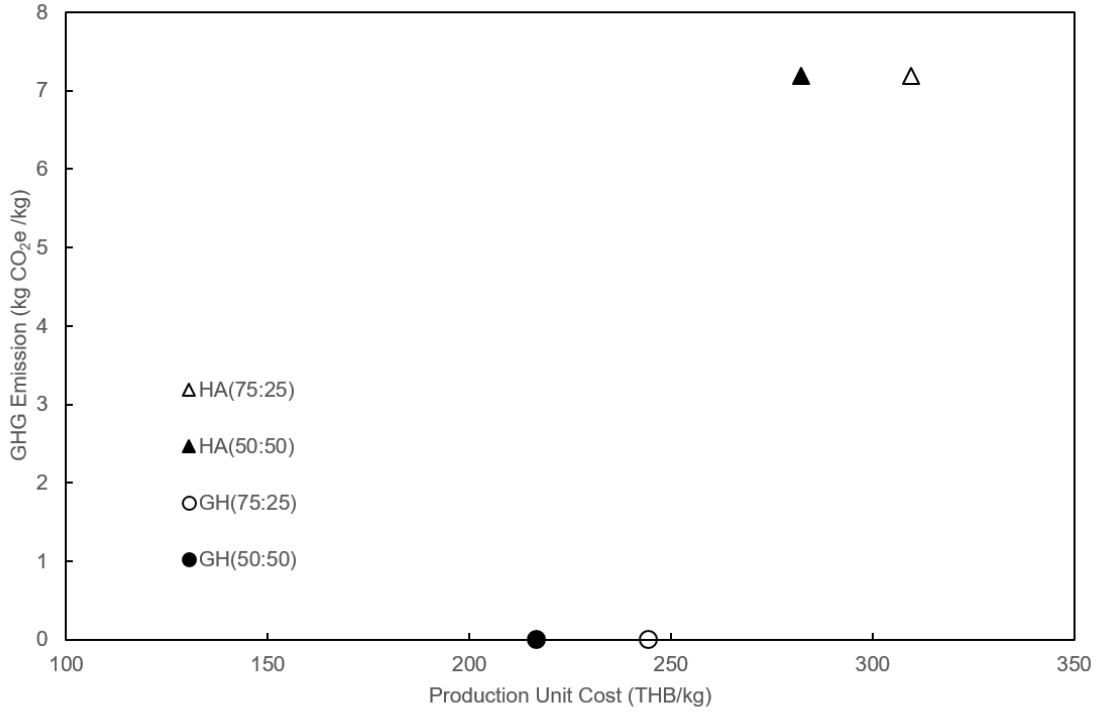


Figure 7. GHG emissions and production unit cost of teak-pandan tea dried from HA and GH drying methods at ratios of 75:25 and 50:50.

4. Conclusions

The Lum Sum Organic Farming Community Enterprise can increase the value of dried herbs and generate additional income for farmers by processing them into mixed teak-pandan leaf tea, a new product innovation. This initiative enables local women, especially housewives, to earn extra income for their families through the cultivation and processing of pesticide-free herbs using an appropriate drying method. Their farming practices maintain soil health by avoiding toxic residues, resulting in healthier products. The most suitable method for drying teak and pandan leaves into powder is the greenhouse solar dryer**,** as it emits less carbon and has lower production costs. This method harnesses natural solar energy, making greenhouse solar drying a more sustainable long-term option. It helps reduce electricity costs, increases profitability, and promotes eco-friendly production. Ultimately, this study provides a framework for fostering sustainable community enterprises through holistic integration of social, economic, and environmental aspects. Regarding the ratio of teak to pandan leaves (HTP) and product quality, although hot air-drying results in higher total phenolic content in dried teak and pandan tea compared to greenhouse solar drying, several observations were made. At ratios of 100:0 and 75:25 (teak:pandan), the high proportion of teak leaves produces a darker brown color, as also reported by Laohaphatanalert et al. [20]. As the proportion of pandan leaves increases, the color becomes lighter and greener. At the HTP ratio of 50:50, greenhouse solar drying yields higher total phenolic content than hot air drying. Overall phenolic content decreases as the proportion of teak leaves decreases, while production costs increase with a higher proportion of teak leaves. Greenhouse

solar drying is recommended for producing a 50:50 teak–pandan tea mixture, as it is cost-effective, environmentally friendly, and maintains good product quality.

Use of AI tools declaration

The authors declare that they have not used Artificial Intelligence (AI) tools in the creation of this article.

Acknowledgments

We would like to thank the Lum Sum Organic Farming Community Enterprise for providing valuable information for this research. Computational resources and data analysis for this study were funded by Thailand Science Research, and Innovation (TSRI) and the National Science, Research and Innovation Fund (NSRF): grant number 179223.

Author contributions

KK: conceptualization, investigation, data collection, writing—original draft and preparation; PR: data collection, experiments, laboratory analysis, and writing—original draft; SW: data collection and analysis; PS: validation, writing, review, and editing; SK: supervision, validation, writing, review, and editing.

Conflict of interest

All authors declare no conflicts of interest in this paper.

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