



Does a Single-Use Leaf Bowl Enhance Well-Being and Reduce Carbon Footprint?

Soontree Khuntong¹, Chettha Chamnanlor¹, Methee Juntaropakorn², Jamnong Thanyasit²,
Anucha Oiulong² and Pensuda Phanritdum^{*1}

¹Department of Industrial Engineering, Faculty of Engineering at Sriracha,
Kasetsart University Sriracha Campus, Chonburi 20230, Thailand

²Department of Resources and Environment, Faculty of Science at Sriracha,
Kasetsart University Sriracha Campus, Chonburi 20230, Thailand

*E-mail: pensuda.p@ku.th

Article History; Received: 18 November 2025, Accepted: 27 April 2026, Published: 28 April 2026

Abstract

Carbon footprint (CF) became one of the valuable tools for assessment of greenhouse gas emission, resulting in global warming followed by the climate change, particularly in the food sector. The impact originated from food, food production, and packaging. Natural packaging was utilized for items such as wrappings, bowls, and bamboo tubes. These replaced modernized packages, including plastic bags and boxes as well as single-use polystyrene bowls. The latter significantly caused harm to both human health and the environment. These impacts led to the aims of this research, which were (1) to mold the leaf bowls from three types of leaves: *Licuala spinosa*, *Dipterocarpus alatus* Roxb. ex G.Don., and *Nelumbo nucifera* Gaertn followed by physical and biological testing; and (2) to assess the CF of each bowl compared to a polystyrene bowl. Molding factors were optimized using Minitab software. The optimized conditions were heating the leaves at 160 °C for 8 min, applying to all leaf types. The three different leaves were arranged parallel, perpendicular, and parallel to the vein, respectively. The leaf bowls from *Dipterocarpus alatus* Roxb. ex G.Don. provided an elegant look, high tensile stress resistance, and leak resistance; moreover, no microbial contamination was observed until the 30th day. CF was assessed from the optimized factors and calculated by emission factors (EF) from the Thailand Greenhouse Gas Management Organization (TGO). A total of 1.8055 kgCO₂eq of carbon dioxide was emitted per one leaf bowl under the optimum molding factors. The emission was approximately 60% less than polystyrene foam (2.985 kgCO₂eq per kg, excluding the molding process). The significant advantages of leaf bowls were (1) no emission from raw material, (2) no toxicity, and (3) no requirement for waste management.

Keywords : leaf bow; carbon footprint; Minitab software; tensile stress; microbial contamination

Introduction

Due to data from the United Nations, food production covered one-third of greenhouse gas (GHGs) emissions: CO₂ from agriculture and land use; CH₄ from livestock production; and N₂O from fertilizer and chemical use and energy use for the supply chain and waste [1]. Food waste was divided into food waste itself and its packaging. Uneaten

food decomposes and emits CO₂ and CH₄ while emissions from packaging depend on the kind of materials, such as chilled packages, bottles, and cans, which require specialized waste management. In contrast, the food packaging made of leaves can naturally decompose; no waste management is required. After use, food packaging directly decomposed but more than one third did not enter collection system [2]. Plant-based bioplastics; biodegradable (such as

poly-lactic acid (PLA), polyhydroxybutyrate (PHB), or biopolymer-based plastics) and non-degradable (biobased polyolefins: e.g., bio-PE, bio-PP, and bio-PET), and agro-materials were recently marketed to minimize impact from food packages [3].

Starting in the 1800s, naturally occurring materials such as gourds, shells, and leaves were used to hold food. Primitive materials, including pottery, paper, and glass were shaped into food containers. From 7000 B.C., the raw materials used to make glass—limestone, soda, sand, and silica remained the same until today with additives developed to provide color, shine glass and appropriate properties [4]. Following the discovery of tin plating in Bohemia in A.D. 1200, tin-coated iron cans were used for foods and drinks. Metal cans were initially manufactured for snuff since they provided an excellent barrier to prevent moisture, microbial contamination while protecting the flavor of the products. The latter was discovered by Nicholas Appert to be used in canning operations when challenged by the French Emperor Napoleon Bonaparte to develop a method to preserve food for his army. Appert used glass bottles with corks secured with wire as a closure to contain food while heating. The glass bottles were fragile and were soon replaced by metal cans. The cans allowed products to be heat-processed to extend their shelf-life and prevent spoilage. Paperboard was first used to manufacture folding cartons in the early 1800s. Today, corrugated boxes are widely used as shipping containers to hold several smaller packages. Plastics, including cellulose nitrate, styrene, and vinyl chloride, were discovered in the 1800s but were not used in packaging until the 20th century.

By the 19th century, natural food containers and metal cans were replaced with plastic bags and boxes, or wraps for food packaging. The distillation of styrene from a balsam tree was first discovered in 1831, but the products were brittle and easily shattered. Styrene foam (boxes, cups, and trays) became available worldwide from refinery processes by the 1950s due to its insulation and cushioning properties. In 1977, polyethylene terephthalate (PETE) containers became available for beverages. By 1980, foods and other hot-filled

products, such as jams, could also be packaged in PETE [5].

Located in an advantageous geographical area, Thailand has a tropical climate resulting in various kinds of plants. Besides the main function in photosynthesis, the sizes, textures, shapes, and patterns of leaves in tropical areas are different from those in temperate areas. The big leaves of teak (*Tectona grandis*) and lotus (*Nelumbo nucifera* Gaertn) enhance the absorption of solar energy for synthesizing glucose from carbon dioxide and water. In Oriental culture, including Thai, Lao, Myanmar, various big leaves and special types of foliage, such as banana (*Musaparakdisiaca*), coconut (*Cocos nucifera* (L.) nypa palm (*Nypa fruticans*), and mangrove fan palm (*Licuala spinosa*) have been used as natural food packaging (food wraps and food baskets). These board leaves provide benefits including thick, waxy coated, palmately netted venation-convergence, pinnately paralleled venation, and palmately paralleled venation-divergence [6] for food containers.

Drawing from the knowledge and experience of using several types of leaves such as for wrappings, food bowls, bamboo tube applications, modern method can create a ready-to-use containers that are pleasing, have long shelf-life, and are free from microbial contamination. As a result, the aims of this research were (1) to mold the leaf bowls from three types of leaves: *Licuala spinosa*, *Dipterocarpus alatus* Roxb. ex G.Don., and *Nelumbo nucifera* Gaertn for physical and biological testing and (2) to assess the Carbon Footprint (CF) of each bowl compared to a polystyrene bowl. The success of this research lies in the optimized factors being applicable to all kinds of leaves. Moreover, it is safe to use these single-use leaf bowls after molding and proper storage.

Materials and Methods

Pneumatic molding machines were developed in-house by the Applied Mechanics and Product Design Research Group, Faculty of Engineering at Sriracha, Kasetsart University. The electrical heating system was applied only to the upper mold, which was then pressed

down onto the leaves by the pneumatic system. A constant pressure of 6 bars was applied, replacing the downward heater. The square mold ($16 \times 15 \times 2 \text{ cm}^3$) was made of high-quality iron because its thermal conductivity (79.5 W/m K) is higher than that of steel (50.2 W/m K) [7]. Moreover, iron is soft and easily shaped with a lathe [8]. Since iron is very reactive, it must be kept under a film of cooking oil to prevent rust caused by oxidation.

Collection and preparation of leaves

Leaves were selected based on four criteria: (1) typically and locally used as food wraps or containers; (2) not toxic and (3) soft, tough, and flexible; (4) easy to find and inexpensive. The selected leaves were as follows:

1. *Licuala spinosa* (mangrove fan palm). It grows in clumps in fresh or salt water. They are 2-7 meters high with a stalk of 4-7 cm [9]. Along with palmately paralleled venation-divergence of the fan-shaped leaves with 40-60 cm-long. They are used to wrap food, particularly in the eastern area of Thailand.

2. *Dipterocarpus alatus* Roxb. ex G. Don. This is a big evergreen tree with 30-60 meters tall which grows in tropical rain forests [10]. The big leaves are thick and tough. The 3rd - 5th leaves from each treetop were collected at Kasetsart University, Sriracha, Chonburi.

3. *Nelumbo nucifera* Gaertn known as sacred lotus is the aquatic plant that grows in flood plains of slow-moving streams [11]. The large, round-shaped leaves have the ability to repel water and dirt due to their hydrophobic surface structure.

The mangrove fan palm and lotus leaves were collected from Wat Bunnak Community, Klaeng District, Rayong Province. Three consecutive steps of cleaning were applied to all types of leaves: (1) mildly scrub the leaves with a soft brush to remove muddy particulates; (2) wash them again with clean water. In steps 1 and 2, each type of leaf was dipped one by one into a water tank (0.08 m^3). The fresh leaves were shaken to remove water before being wiped dry in the final step (step 3). All leaves were left in ambient air for partial dehydration to increase softness and toughness which

prevent them from becoming brittle during the molding process.

Optimized factors for molding containers

The optimized molding factors were obtained from *Licuala spinosa* and *Dipterocarpus alatus* Roxb. ex G. Don. for appropriate conditions. The factors were then applied to *Nelumbo nucifera* Gaertn because of their morphological difference. The water content in *Nelumbo nucifera* Gaertn leaves is higher than in the other two terrestrial plants (observed from water released during molding). The factors affected by molding included leaf arrangement, temperature, and time. The tapioca paste (50 g of food grade tapioca flour in 100 ml of water followed by 200 ml of boiling water with vigorous stirring) was used as an adhesive, if necessary.

For *Licuala spinosa*, the dimensions of the leaves were 5-6 cm in width and approximately 55 cm in length, but they were tough in parallel with the vein direction. A total of 6-8 leaves were arranged in two directions: the same direction and the opposite direction of their veins. Before molding, the leaves were stuck together with adhesive. The molding temperature was varied from 100-150 °C with time intervals from 5 to 15 min.

For *Dipterocarpus alatus* Roxb. ex G. Don., the two layers of thick and tough leaves were arranged in two directions: parallel and opposite to the vein and stuck with adhesive. The heating temperatures varied from 110-180 °C and the heating time varied from 3-15 min.

The experimental design for molding *Licuala spinosa* and *Dipterocarpus alatus* Roxb. ex G. Don from all parameters was considered from the resistance to tensile stress. Three factors were examined: each parameter consisted of two levels and two replications. The number of experiments can be calculated in Eq. (1).

$$\text{No. of experiment} = \text{No. of level}^{\text{No. of}} \\ \text{parameters} \times \text{No. of replication} \quad 1$$

The parameters were calculated from 16 experiments. The controllable factors were molding size, constant pressure at 6 bars, and quantity of adhesive. The uncontrollable parameters were characteristics of the leaf and

moisture content in the leaf. The experimental design for the highest resistance to tensile stress of *Licuala spinosa* and *Dipterocarpus alatus* Roxb. ex G.Don. is presented in **Figure 1(a) and 1(b)**. The molding process was performed in a clean area, particularly the molding site of the machine. The mold was wiped with aqueous ethanolic solution (70%) to remove vegetable oil coated at the mold surface and for disinfection. The heater was warmed, and the pump was set at 6 bars. The temperature was set as a result of the experimental design while the leaf arrangement and time intervals were set as a result of the optimization factors.

The molding conditions were evaluated to produce durable leaf bowls based on their highest tensile stress. The Minitab software (License) was applied to analyze various factors, including leaf arrangement patterns, temperature, and time. Finally, the design was assigned at a significance level (α) of 0.05 and a confidence level of 95% for adequate accuracy {the probability of 5% was enough for rejecting the null hypothesis (H_0)}. Two basic hypotheses were as follows:

- H_0 = Leaf arrangement pattern, temperature, and time do not affect the tensile stress of leaf bowls.
- H_1 = Leaf arrangement pattern, temperature, and time affect the tensile stress of leaf bowls.

The experimental design was described using constant population characteristics that were statistically evaluated from the total population. Hypothesis testing and the p -value were applied to optimize the experimental conditions on a statistical basis, resulting in the effective use of resources such as raw materials, energy, budget, and time. Two hypotheses consisted of a null hypothesis (H_0) and an alternative hypothesis (H_1). The p -value was calculated to confirm the hypothesis by fixing the α value at a significance level. The p -value is the probability that the tested values equal the observed values. If the null hypothesis is true, the p -value is defined as the lowest value at the fixed significance level, leading to the rejection of the null hypothesis (p value $< \alpha$). The statistical symbols were represented as follows: population mean (μ), standard deviation (σ), correlation coefficient of the population (ρ), and total population (τ). The steps for experimental parameters were consecutively designed starting from defined problems to be solved and objectives to setting variables, the number of experiments at a statistical level, and final output settings. The results from the Minitab software are presented in the Pareto Chart and factorial design that were investigated to evaluate the factors related to tensile stress.

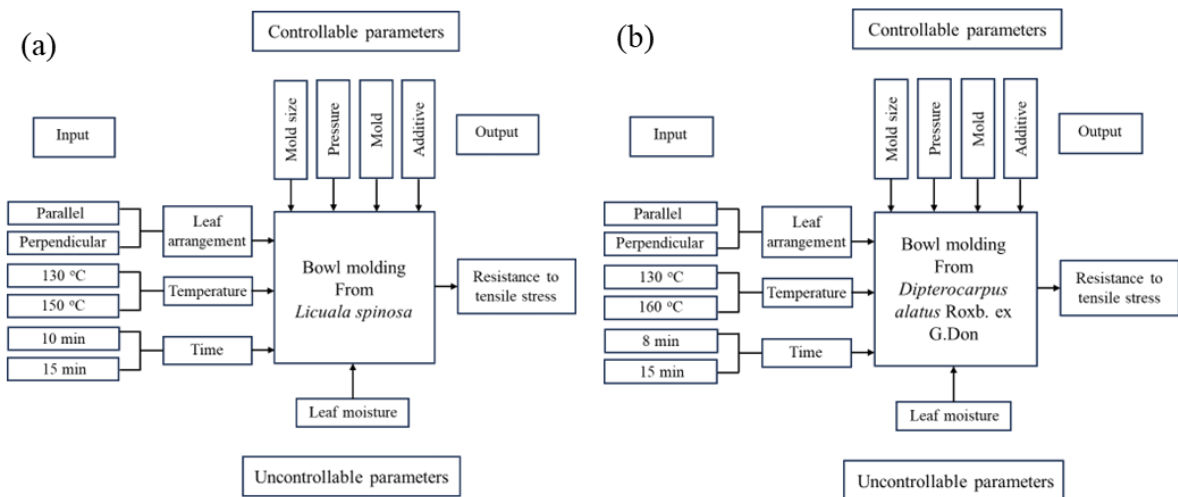


Figure 1 Experimental design for molding the leaf bowl, representing the highest resistance to tensile stress: (a) *Licuala spinosa* and (b) *Dipterocarpus alatus* Roxb. ex G.Don.

Test for physical properties of leaf bowls

There are no direct standards to qualify the physical properties of leaf bowls; they may be qualified by comparison with various paper packages seen in **Table 1**.

Microbial contaminations of leaf bowls

Tests for microbial growth were necessary for controlling pathogenic microorganism contamination and setting the shelf-life. After molding, the leaf bowl was still wet because the water inside the fresh leaves remained at the bowl surface. Before microbial testing, the leaf bowls must be dried at 40 °C for 2 h or until there is no weight change of the bowl. Swab both sides of the bowl surface with a sterile swab stick. Streak the swab stick on the nutrient agar (NA) surface in three Petri dishes. Incubate all Petri dishes at 37 °C for 24 h. Record the time interval when a colony of microorganisms is first observed.

Assessment of carbon footprint of leaf bowls

To quantify the carbon footprint, the cradle-to-gate boundary included transportation, washing, and molding. The functional unit of one leaf bowl without microbial contamination was applied. CF was accounted for from leaves to the finished leaf bowls. *Licuala spinosa* was naturally growing in community forests while *Dipterocarpus alatus* Roxb. ex G.Don. was from an almost 30-year planting at Kasetsart University, Sriracha Campus. The two types of plants can be considered as sources of green carbon sequestration. *Nelumbo nucifera* Gaertn is

an aquatic plant that is naturally grown in water resources. Each individual process and emission inventory was not shown. Each experimental step, including materials and chemicals, as well as electricity and carbon dioxide emissions was quantified. Due to the cradle-to-gate boundary, the waste disposal for used leaf bowls was not included. Furthermore, the average age of leaves in tropical areas ranged from six months to one year [13]; consequently, they naturally decay and decompose.

For the calculation of electrical consumption for heater [14], since the molding machine was assembled in-house, the electrical consumption was not directly measured. However, it was estimated using available conversion factors. A temperature increase of 1 °C was converted to 0.00052752791666667 kWh.

For the calculation of electrical consumption for pneumatic systems (Rapid Table, n.d.), the systems were used for individual machines. The consumption was calculated step by step using available conversion factors, as follows:

Step 1 Conversion of bar into pascal.

1 bar is converted to 100,000 Pa; then, 6 bars equal 600,000 Pa.

Step 2 Conversion of pressure (Pa) into energy (Joules).

$1 \text{ Pa} \times 1 \text{ m}^3 = 1 \text{ Joule of energy};$

Step 3 Conversion of thermal energy into electrical consumption.

$1 \text{ Joule} = 0.0000002778 \text{ kWh}$

Table 1 Test methods to indicate the physical properties of leaf bowls

Physical properties	Test methods
Tensile strength and elongation	Place the leaf bowl between two grips which clamp the bowl. Increase weight to the material gripped at one end while the other end is fixed. Measure the change in length of the bowl [12].
Leakage of leaf bowl	Place the dried-weighted blotting paper over each leaf bowl filled with water. Leave the bowl for periods of 0, 30, 60, 90, 120, and 150 min. Observe the leakage of the bowl from the weight increase at the first-time interval.

Results and Discussions

Characteristics of natural leaf bowls.
The size of the leaf bowl was 16 x 16 cm². The fresh green color was different for each individual leaf (**Fig. 2**). Moreover, all types of leaf bowls offer a pleasant aroma like burnt leaves. Both color and smell can enhance food appetite. Higher temperatures and longer times increased the dark shade of the green color. The leaf bowl molded from the parallel arrangement of *Licuala spinosa* provided higher resistance to tensile stress than the perpendicular arrangement at both heating temperatures (130 °C and 150 °C). The bowl was robust and retained its shape. This arrangement can be applied to molding from parallel venation leaves, such as banana, coconut, nipa palm, and sugar palm leaves. Furthermore, the complete overlapping of zig-zag leaves resulted in higher strength than the opposite direction. For *Dipterocarpus alatus* Roxb. ex G.Don., the leaf arrangement affected the performance at both temperatures.

Experimental design for molding conditions of leaf bowls. The results from the Minitab software are presented in **Fig. 3**. The other two types were examined in the same manner.

According to the Pareto chart of standardized effects (Fig. 3a), the three factors (three-way interactions) significantly affected the resistance to tensile stress (standardized effect was greater than 2.31, as calculated by Minitab software). The resistance to tensile stress was affected by leaf arrangement (A), molding temperature (B), and molding time (C). The calculated values (Fig. 3b and 3c) indicated a *p*-value less than 0.05; thus, the integrated factors (A, B, and C) led to the rejection of the null hypothesis *H*₀. It can be concluded that factor AB (parallel arrangement of leaves and molding temperature at 150 °C) was considered as the dominant factor, followed by molding time at 10 min. The optimized conditions in Table 2 presented the highest resistance to tensile stress at 0.0003142 ± 0.0000076 N/mm²).



Figure 2 Characteristics of the three types of leaves, experimental conditions, and color of each leaf bowl

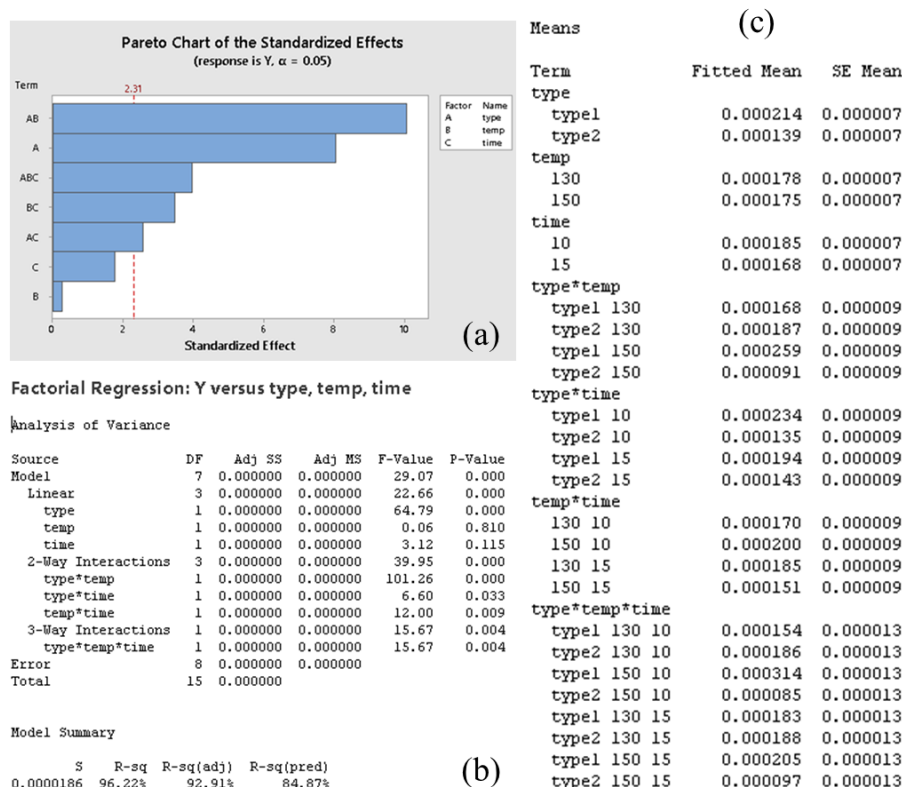


Figure 3 Optimized parameters of leaf bowl molding related to leaf arrangement patterns, temperatures, and time from *Licuala spinosa* (a) Pareto Chart, (b) Factorial regression, and (c) the average data values for resistance to tensile stress

Unlike *Licuala spinosa*, the Pareto chart of standardized effects indicated that the individual factors (A and B) significantly affected the highest resistance to tensile stress for *Dipterocarpus alatus* Roxb. ex G.Don. The *p*-values of three-way and two-way interactions were greater than α (0.05); therefore, they corresponded to the null hypothesis (H_0) (Fig. 4b). The results showed that leaf arrangement (*p*-value 0.039) and temperature (*p*-value 0.023) were significant; this indicates that only these two factors affect the resistance to tensile stress. The molding time did not significantly affect the resistance to the tensile stress, as its *p*-value (0.154) was higher than 0.05. It could be concluded that factor AB involved perpendicular leaf arrangement and a molding temperature of 160 °C. The molding time of 8 min was selected since there was no statistical effect (Fig. 4c), and avoiding the excess 7 mins reduced the CF from electrical consumption. The additional 7 min was not reasonable for three reasons: (1) the resistance to tensile stress increased only 0.000245 ± 0.000768 N/mm²;

(2) the electrical consumption and carbon dioxide emissions were almost twice as high; and (3) the highest resistance to tensile stress (at 8 min of molding) reached its maximum comparing with the other two types of leaves (Table 2).

Average resistance to tensile stress from experimental design. The variation in the data from the experimental design was evaluated to confirm the durability of the leaf bowls. The average tensile stress calculated for the optimum factors is summarized in Table 2. For *Nelumbo nucifera*, the molding conditions were evaluated based on the optimized conditions of *Licuala spinosa* and *Dipterocarpus alatus* Roxb. ex G.Don. *Nelumbo nucifera* is an aquatic succulent plant; its leaf is much different from the first two. It is round-shaped with a diameter of approximately 50 to 80 cm, possessing a hydrophobic and waxy surface. Higher resistance to tensile stress was observed when the leaves were molded at the area of the leaf petiole. Only two leaves were molded at 150 °C for 10 min to produce one bowl. The bowl possessed a resistance to tensile stress of

$0.002252 \pm 0.001343 \text{ N/mm}^2$ which was higher than *Licuala spinosa* but lower than *Dipterocarpus alatus* Roxb. ex G.Don. Due to its zig-zag morphology, the leaves could not

closely adhere to one another. The three types of leaf bowls molded under optimized conditions showed the best properties in terms of color, shape, and tensile stress (see Fig. 5).

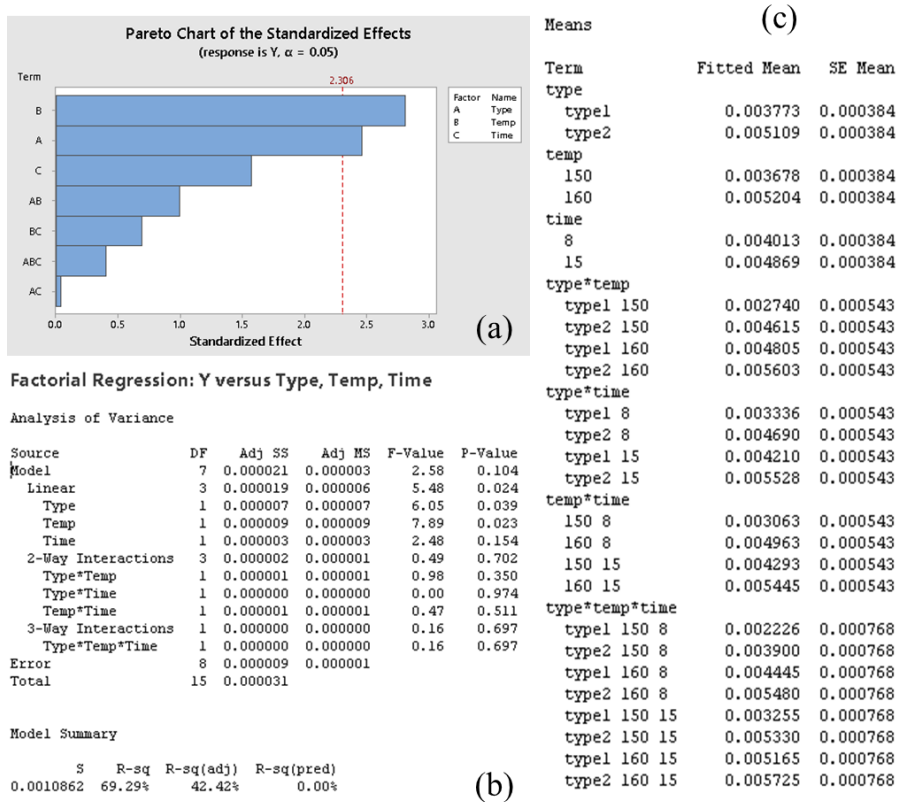


Figure 4 Optimized parameters of leaf bowl molding related to leaf arrangement patterns, temperatures, and time from *Dipterocarpus alatus* Roxb. ex G.Don (a) Pareto Chart (b) Factorial regression, and (c) average data values for resistance to tensile stress

Table 2 Summary of optimized conditions for molding the leaf bowls from three types of leaves

Leaves	Factors	Experimental conditions	Average resistance to tensile stress (N/mm ²)*
<i>Licuala spinosa</i>	Leaf arrangement	Parallel	0.0003142 ± 0.0000076
	Molding temperature (°C)	150	
	Molding time (min)	10	
<i>Dipterocarpus alatus</i> Roxb. ex G.Don	Leaf arrangement	Perpendicular	0.005480 ± 0.0005940
	Molding temperature (°C)	160	
	Molding time (min)	8	
<i>Nelumbo nucifera</i>	Leaf arrangement	Parallel (3 cm from the stalk)	0.0024173 ± 0.0006883
	Molding temperature (°C)	150	
	Molding time (min)	10	

*n = 2



Figure 5 Three leaf bowls from *Licuala spinosa*, *Dipterocarpus alatus* Roxb. ex G.Don., and *Nelumbo nucifera* at optimized conditions from Table 2

The experimental factors calculated from Minitab software were successfully applied to *Nelumbo nucifera*. The molding temperatures and time were almost in the same range except the arrangement patterns which depended on various factors such as the types of leaves, leaf vane, size, and nature of leaves. The two types of leaves were selected as samples to determine the experimental factors that could be applied to any leaf type. *Nelumbo nucifera* leaves were an example of these assumptions.

The color of the leaf bowl made from *Dipterocarpus alatus* Roxb. ex G.Don. was more uniform than *Licuala spinosa*. The leaf turned a darker color after heating because of moisture loss and tissue damage. The heat from a heater caused cell death at the leaf edges, leading to a dry, crispy brown or black color called necrosis [15]. The perpendicular arrangement resulted in higher resistance to tensile stress than the parallel arrangement because the pinnate parallel venation of the leaves in different directions made them overlap like a net. A smooth surface was observed on both sides at two different temperatures (130 °C and 150 °C), as seen in **Table 2**. At a lower temperature (less than 130 °C), the two layers of leaves could not blend into one layer, and the tapioca paste remained wet, resulting in an unstable shape. Unlike the other two types, only two large leaves of *Nelumbo nucifera* were molded in a parallel direction. They were placed close to their stalks because of their thickness. The excess water was released after molding. These bowls presented a fresher color than the other two. In addition to their naturally waxy-coated leaves, the bowls from these leaves displayed a slightly shiny surface. The aesthetic appearance of these bowls could enhance the food appetite. Since the molding process involved heat, the

smell of the leaf bowl was like roasted or baked leaves which was better than the smell of plastic.

Leakage of the leaf bowls was another important property for their application. Leakage was characterized by the time interval after putting liquid into the bowls. Leakage was observed within 30 min. Since two leaves of *Nelumbo nucifera* were used to mold the bowl, there was no leakage for up to 30 min. The parallel arrangement pattern of *Licuala spinosa* also provided less leakage than *Dipterocarpus alatus* Roxb. ex G.Don. The raw data for time intervals and volume of liquid leakage from the bowls are not shown. Due to the short time intervals before leakage, the leaf bowls are most suitable for dry foods such as fried food, grilled food, or salad. As a result, for dry food, the tapioca adhesive did not lead to leakage. During the molding process, the tapioca adhesive was dried; therefore, it did not leach or spoil the taste of the food. Using these for single-use purposes, such as a buffet or cocktail party, is more advantageous than using paper or single-use plastic bowls. They enhance food appetite and provide pleasant aroma, as well as lightening the washing load and reducing waste disposal.

Microbial contamination of leaf bowls was evaluated. These bowls must be free from contamination of pathogenic microorganism contamination for a specific period. This is the most important property of the bowls since they could not be cleaned after molding. It was considered that the bowls were sterilized by heat during the heating process. Unfortunately, the molding machine possessed only one front heater; thus, the excess water inside the leaves remained on the back side, enhancing microbial growth. Furthermore, the leaf bowls cannot be

washed with dishwashing liquid. The bowls molded from *Licuala spinosa* and *Dipterocarpus alatus* Roxb. ex G.Don. were slightly contaminated after molding. Contamination was observed after 15 days, and the bowl surface was heavily contaminated within 30 days. While microorganisms on the leaf surface were sanitized by heat (150 °C) during the molding process. The zig-zag morphology and deep leaf grooves of *Licuala spinosa* leaves protected microorganisms within the serrations, where the temperature was not high enough to kill them (Fig. 6).

For *Dipterocarpus alatus* Roxb. ex G.Don., the microbial contamination was slight on the 15th day and almost disappeared by the 30th day. The naturally dried leaves and waxy smooth surface of the leaves left no space between the layers of the leaves. The drying process (40 °C for one h) resulted in the removal of water accumulation between the leaf layers. Microbial growth was inhibited by reducing the amount of water; thus, no microbial contamination was observed after 30 days. In contrast to the other two types of leaves, microbial contamination did not appear in the bowls molded from *Nelumbo nucifera*. Only two

leaves were molded, so there was no overlap between the leaves. The leaves were also sterilized via the molding process (150 °C for 10 min). Moreover, the removal of water occurred during both the molding and drying processes (40 °C for one h). However, the shelf-life of the natural leaf bowl was short compared to paper or single-use plastic bowls; it became crispy and broke after almost one month. Bowls molded from dried leaves, including banana leaves, coconut leaves, or betel palm sheaths, might be selected to extend the shelf-life.

Carbon dioxide emissions from a single leaf bowl. To assess the quantities of carbon dioxide emitted from molding one leaf bowl, the study was divided into direct data collection and calculations from available reference data. The inventory data for the molding process is presented in Table 3. The carbon footprint of the product was evaluated specifically for the molding process. Regarding characterization, the carbon footprint was mostly similar for each batch of molding. The most important procedure was sampling each to ensure reproducibility. The inventory data for leakage and microbial contamination is presented in Table 4.

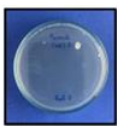
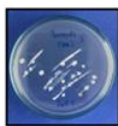
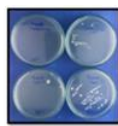
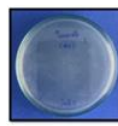
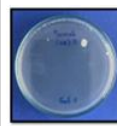
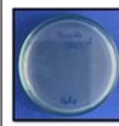
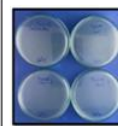
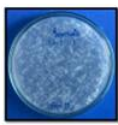
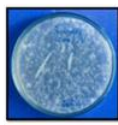
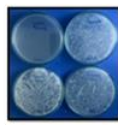
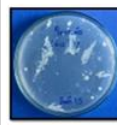
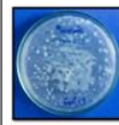
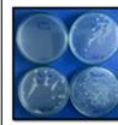
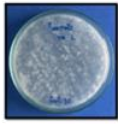
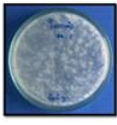
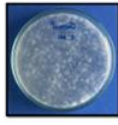
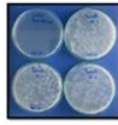
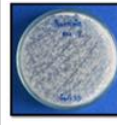
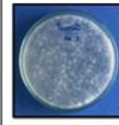
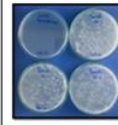
Test period (day)	Front sides of the leaf bowls				Back sides of the leaf bowls			
0								
15								
30								

Figure 6 Microbial contamination on the surface of leaf bowls molding from *Licuala spinosa*.

Note Data not shown for *Dipterocarpus alatus* Roxb. ex G.Don and *Nelumbo nucifera*

Table 3 Inventory data and emission factors (EF) of raw materials for molding leaf bowls

Inputs	Unit	Quantities	EF ² (kg CO ₂ eq)
Collection of <i>Licuala spinosa</i> and <i>Nelumbo nucifera</i>			
Diesel oil for van from KU Sriracha Campus) to Glang District, Rayong Province	km	110 *2	0.3522
Cleaning of leaves ¹			
Tap water	kg	80*2	0.5410
Molding Process			
Electricity for heating ³	kWh	0.0844	0.5986
Electricity for pneumatic ⁴			
<i>Licuala spinosa</i>	kWh	0.17	0.5986
<i>Dipterocarpus alatus</i> Roxb. ex G.Don.	kWh	0.14	0.5986
<i>Nelumbo nucifera</i>	kWh	0.17	0.5986

¹For each 50 bowls: *Licuala spinosa* 100 leaves, *Dipterocarpus alatus* Roxb. ex G.Don 150 leaves; *Nelumbo nucifera* 100 leaves.

²Emission factors from Thailand Greenhouse Gas Management Organization (Public Organization) [16].

³The optimum temperature for all three leaf types, calculated using Minitab was 160 °C, which is equivalent to 0.0844044666666672 kWh.

⁴Calculation of electrical consumption for pneumatic systems:

For *Licuala spinosa* and *Nelumbo nucifera* (molding time 10 min)

$$600,000 \text{ Pa} \times (0.012 \text{ m}^3/\text{min}) \times 10 \text{ min} = 612,000 \text{ Joules}$$

For *Dipterocarpus alatus* Roxb. ex G.Don. (molding time 8 min)

$$600,000 \text{ Pa} \times (0.012 \text{ m}^3/\text{min}) \times 8 \text{ min} = 489,600 \text{ Joule}$$

Calculated thermal energy for *Licuala spinosa*, *Dipterocarpus alatus* Roxb. ex G.Don. and *Nelumbo nucifera* were 0.17, 0.14 and 0.17 kWh, respectively.

Table 4 Electrical consumption for microbial examination

Step	Processes	Units	Quantities	Electrical consumption (kWh)
1	Manually mixing of nutrient agar (NA) 0.115 g in .5 l of distilled water	-	-	-
2	Culture sterilization by autoclaving at 120 °C for 20 min	kWh	3.0	3.0 x 1/3 = 1.0
3	Dry the leaf bowls at 40 °C for 1 h	kWh	3.0	3.0 x 1 = 3.0
4	Swab the surface of leaf bowl followed by spread on the NA in Laminar air flow for 2 h)	kWh	3.4	3.4 x 2 = 6.8
5	Incubate at 37 °C for 24 h	kWh	1.8	1.8 x 24 = 43.2
6	Sterile the cultured NA plate by autoclaving at 120 °C for 20 min	kWh	3.0	3.0 x 1/3 = 1.0

The carbon footprint of each leaf bowl was basically calculated using carbon dioxide emission factors from TGO (2023). The quantities of carbon dioxide were 1.8055 kgCO₂eq per bowl, compared to 2.985 kgCO₂eq per kg of polystyrene [17], excluding the molding process (single-use container). Since the cleaning step was very important, the leaves must be cleaned to remove dust and other contaminants, its GHG emission reached the highest level (95.01%). In this study, tapioca paste used as an adhesive was excluded because the amount was negligible and did not critically affect to the leaf bowls [18]. Similarly, tap water also provided the highest GHG emission, followed by the electrical consumption for analytical weighing machines. In the microbial contamination test, the incubation step consumed large amounts of

electricity due to the long duration required for microbial growth. Among three individual processes, the calculated GHG emissions were 5.10%, 2.64%, and 92.15% for molding, leakage, and microbial contamination, respectively. The new model of molding machines includes heaters on both sides of the mold; thus, it can be operated on-site without a pneumatic pump and adhesive, lowering GHG emissions by removing the transportation step. The carbon footprint of microbial testing reached its highest point at 32.9322 kgCO₂eq per batch (Table 5). However, it is not necessary to test an individual batch. If the molding and storage conditions of each batch are consistent, they may remain free from microbial contamination, similar to the results of the leakage test.

Table 5 Greenhouse gas emissions for one leaf bowl

Process	Material	Quantities	EF	GHGs emission (kg CO ₂ eq)	Percentage of GHGs emission
Molding processes					
Transportation ¹	Diesel oil	18.7 kg	0.3522 kg CO ₂ eq/kg	0.0659	3.62
Cleaning ²	Tap water	160 l	0.5410 kg CO ₂ eq/l	1.7312	95.01
Molding	Heat ³		0.5986 kg CO ₂ eq/kW h	0.008421	0.46
	Pneumatic ⁴		0.5986 kg CO ₂ eq/kW h	0.01696	0.93
Total				1.822481	100
Leakage (CF for 15 tests/batch)					
	Tap water	1.2 l	0.5410 kg CO ₂ eq/l	0.6492	68.83
	Tissue paper	0.03697 kg	0.6677 kg CO ₂ eq/kg	0.024685	2.62
	Weighing	0.450 kWh	0.5986 kg CO ₂ eq/kW h	0.26937	28.59
Total				0.943255	100
Microbial examination (CF for 54 tests/batch)					
	Nutrient agar	0.115 kg	0.0800 kg CO ₂ eq/kg	0.0092	0.03
	Sterilization	1.0 kWh	0.5986 kg CO ₂ eq/kW h	0.5986	1.82
	Drying	3.0 kWh		1.7958	5.45
	Lamina flow	6.8 kWh		4.07048	12.36
	Incubation	43.2 kWh		25.85952	78.52
	Autoclaving for sterilization	1.0 kWh		0.5986	1.82
Total				32.9322	100

Calculation

¹Greenhouse gas emissions from diesel fuel

Distance from KU SRC to Klaeng District, Rayong Province = 110 x 2 = 220 km

Fuel consumption = 220 km / 10 km/l = 22 l = 22 l x 0.850 kg/l = 18.7 kg

Greenhouse gas emissions = 18.7 x 0.3522 / 100 bowls = 0.0659 kg CO₂ eq

²Greenhouse gas emission from tap water

Greenhouse gas emissions = 80 x 2 x 0.5410 / 50 bowls = 1.7312 kg CO₂ eq

³Greenhouse gas emission from heat

Greenhouse gas emissions = 0.0844 x 10/60 x 0.5986 = 0.008421 kg CO₂ eq

⁴Greenhouse gas emission from pneumatic

Greenhouse gas emissions = 0.17¹ x 10/60 x 0.5986 = 0.01696 kg CO₂ eq

¹The longest molding time was selected to calculate carbon footprint.

The most significant advantages of leaf bowls are: (1) naturally sourced the raw materials and (2) no required waste management; they decay naturally. Due to organic waste separation, leave bowls can be considered as organic waste, it can be managed similar to organic waste mostly composting. No special management, transportation or landfill may require. Although, carbon dioxide emissions of natural leaf bowls were slightly lower than polystyrene foam, the utilization of polystyrene bowls generated a variety of VOCs [19]. Polystyrene (petroleum-based plastic) was a household waste including human carcinogen and mutagen [20]. It was a persistent chemical after exposure and recovery; it enhanced reactive oxidative stress (ROS) to aquatic organisms such as diatoms [21]. Finally, biodegradation of polystyrene was over 500 years in landfills [22]. There were no real limitations from seasonal availability of leaves. It could be explained as follows: (1) *Licuala spinosa* and *Dipterocarpus alatus* Roxb. ex G.Don are the evergreen trees in the tropical regions. The latter is slightly different due to shedding leaves occasionally; (2) the rhizome of *Nelumbo nucifera* is still alive beneath the clay while the leaves and stems decay during the short period of the cold season. The types of plants could be found all around the country [23]. Although the conventional package such as plastics, papers and polystyrene is more convenient than modernized packages but they are self-sufficient and sustainable from their natural origins.

Conclusions

Natural leaf bowls via heat and pneumatic molding of *Licuala spinosa*, *Dipterocarpus alatus* Roxb. ex G.Don, and *Nelumbo nucifera* leaves can replace paper or single-use plastic bowls. The highest resistance to tensile stress was observed at 0.005480 ± 0.0005940 N/mm² of leaf bowl molded from *Dipterocarpus alatus* Roxb. ex G.Don. The optimized factors for these three leaf types were situated within the same range; therefore, they could be applied to most other leaf types. Leaf bowl molding based on these experimental factors, combined with leakage and shelf-life evaluation data, may yield microbial contamination results similar to those presented in this research. The most significant advantages

of leaf bowls are that they replace single-use paper and plastic bowls, reduce carbon dioxide emissions, and require no waste management. In alignment with Thailand's tourism policies, the leaf bowls may enhance the value added of food, particularly street foods such as Pad Thai, fried chicken, and fried or toasted meatballs. Moreover, as Thailand is located in a tropical region, a variety of leaves are available for molding or wrapping. These leaf bowls should be promoted on a commercial scale or through SMEs at a low cost, as they will serve as a distinctive identity for Thai street food.

Acknowledgements

We would like to express our sincere thanks to the Office of Sriracha Campus, Kasesart University, Sriracha Campus for their financial support. We also thank the Applied Mechanics and Product Design Research Group, Faculty of Engineering at Sriracha, for supporting the molding systems. Our gratitude is also extended to the Environmental Laboratory, Faculty of Science at Sriracha for providing the microbial testing facilities for our research. Finally, we would like to thank the members of Wat Boonnak community for their kindness and support and in collecting of the *Licuala spinosa* and *Nelumbo nucifera* leaves.

References

- [1] Hobert, R. and Negra, C. 2020. Climate change and future of food. Climate, energy and environment. <https://unfoundation.org/blog/post/climate-change-and-the-future-of-food>. March 12, 2026.
- [2] World Economic Forum. 2016. The new plastics economy rethinking the future plastics. World Economic Form.
- [3] Moura, M.R., Mattoso, L.H.C. and Zucolotto, V. 2012. Development of cellulose-based bactericidal nanocomposites containing silver nanoparticles and their use as active food packaging. J. Food Eng. 520-524.
- [4] Berger, K. and Welt, B. 2005. A Brief History of Packaging. <http://edis.ifas.ufl.edu/pdf/FILES/AE/AE20600.pdf>. April 25, 2025.

- [5] Hook, P and Heimlich, J.E. 2025. A history of packaging. Ohio State University. <https://ohioline.osu.edu/factsheet/cdfs-133>. April 25, 2025.
- [6] Il, 2025. Morphology of leave. Institute of innovative learning. Mahidol University. <https://il.mahidol.ac.th/e-media/>. April 25, 2025.
- [7] Hyperphysisc, 2024. Thermal conductivity. Department of Physics and Astronomy, Georgia State University. <http://hyperphysics.phy-str.gsu.edu/hbase/Tables/thrcn.html>. April 26, 2025.
- [8] Alliancesteel, 2025. What is the difference between iron and steel ? Alliance Steel. Chicagoland. USA. <https://www.alliancesteel.net/what-is-the-difference-between-iron-and-steel/>
- [9] Plants of the World Online, 2024. *Licuala spinosa* Roxb. Royal Botanic Gardens, Kew. UK. <https://powo.science.kew.org/taxon>. May 2, 2025.
- [10] WFO, 2025. *Dipterocarpus alatus* Roxb. ex G.Don. The World Flora Online. <https://www.worldfloraonline.org/taxon>. May 2, 2025.
- [11] Turi, C.E. and Saxena, P.K. 2020. Sacred Lotus (*Nelumbo nucifera* Gaertn.). Spiritual Botany. <https://www.spiritualbotany.com/issue-1/sacred-lotus-a-plant-profile>. May 2, 2025.
- [12] mtu, 2025. Tensile test experiment. Materials Science and Engineering. Michigan Tech. <https://www.mtu.edu>. May 26, 2025.
- [13] Himpant, W. 2025. Tree age estimation: case study of *Pterocarpus macrocarpus* Kurz. Royal Forest Department. www.forest.go.th. July, 16, 2025.
- [14] ConvertUnit, 2025. Measurement of unit converter. <https://www.convertunits.com>. July 16, 2025.
- [15] Wiersma, J. 2021. Flag leaf burning: Hot weather and leaf tip necrosis in wheat. University of Minesota Extension. <https://extension.umn.edu/growing-small-grains/flag-leaf-burning-hot-weather-and-leaf-tip-necrosis-wheat>. March 25, 2026.
- [16] TGO, 2025. Emission factor (CEP). Thailand greenhouse gas organization (Public organization). <https://thaicarbonlabel.tgo.or.th>. May 19, 2025.
- [17] Climatiq, 2026. Emission Factor PS (polystyrene). Climatic Data Coverage. <https://www.climatiq.io/data/emission-factor>. March 25, 2026.
- [18] Usubharatana, P. 2025. Life Cycle Assessment. Center of Excellent on Eco-Energy (CEEE). Department of Chemical Engineering, Faculty of Engineering. Thammasat University.
- [19] Bagley, C.J., Mclean, J.S. and Stockton, M.B., 1990. Control of emission from polystyrene manufacture. Research Triangle Park, North Carolina. USA.
- [20] Farrelly, T.A. and Shaw, I.C. 2017. Polystyrene as hazardous household waste. Household hazardous waste management. IntechOpen Books. <https://www.intechopen.com/books>. July, 16, 2025.
- [21] Meng, C., Yang, H, Du, Y. and Li, X. 2025. Persistence and Recovery of Polystyrene and Polymethyl Methacrylate Microplastic Toxicity on Diatoms. Toxics. 13, 376.
- [22] Marczewski, M., Kamińska, M.E., Marczevska, H., Godek, M., Rokicki, G. and Sokołowski, J. 2013. Catalytic decomposition of polystyrene. The role of acid and basic active centers. Appl. Cat. B: Environ. 129: 236-246.
- [23] Plant database, 2026. e-Flora of Thailand. Forest Botany Division. Department of National Parks, Wildlife and Plant Conservation. https://botany.dnp.go.th/index_eng.html. March 25, 2026.