Solar Energy for Reducing the Cost of Natural Food Contact Materials Formed by the Arecanut Leaf Sheath

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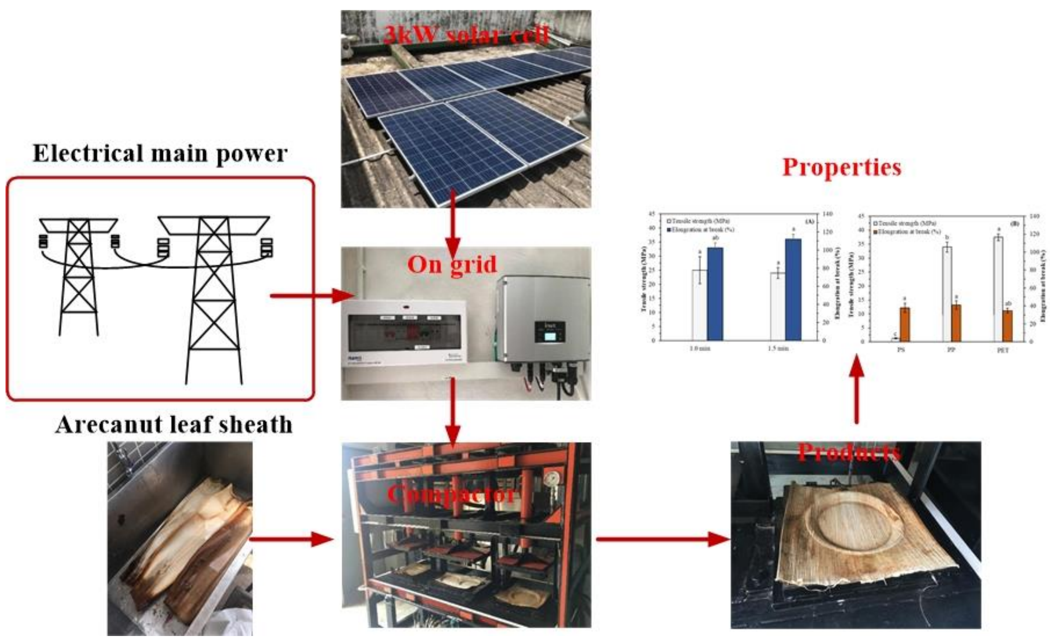
GRAPHICAL ABSTRACT



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The problem with plastic packaging is globally recognized, as plastic packages often end up in landfills without degrading. Using packages made from natural materials is the best choice to address and sustainably solve this issue. In this work, a single-use container (tray) was prepared from arecanut leaf sheath through a hot-compression molding process. The electrical energy required for the compression molding process was obtained from mainly electricity and 3 kW solar cells, reducing the cost by more than 50%, depending on the mold size and operating temperature. The pressing of arecanut leaf sheaths through a two-roll mill for 20 cycles at a high temperature (80 °C) before the compression molding process can increase the mechanical properties of the tray container. The tensile strength of the leaf sheath tray was higher than for polystyrene (PS) and polypropylene (PP) commercial trays. Reducing bacterial contamination of the plates can be achieved by using ultraviolet (UV) light. Almost all bacteria were reduced from 410 CFU/g to <10 CFU/g after UV exposure (40 μW/cm^2) for 10 min. This suggests the possibility of using arecanut leaf sheath plates as food contact material, especially in single-use container applications.

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Keywords: Solar cell; Arecanut leaf; Bio-packages

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INTRODUCTION

Waste from human activities is becoming a major issue for human health, especially when considering the use of plastic materials. The recent discovery of microplastics in most ecosystems that can spread out into the ocean has revealed the sources of toxicity, which often has its origins in the occurrence of land-based microplastics. Global plastic production has dramatically risen over the past 70 years to reach 259 million tons today. China is the world's top-ranking country, fabricating 17.5% of global plastic production, while Turkey produces the most plastic waste in the Mediterranean region at 144 tons per day. Microplastics comprise 75% of marine waste, with land-based sources responsible for 80% to 90% of this pollution, while ocean-based sources account for only 10% to 20% (Osman *et at*. 2023). While plastic plays a valuable role in human activities due to its versatility, durability, low cost, light weight, and flexibility, it has become a major pollutant and an abundant source of waste. However, the commercial production of plastic commenced with the Second World War and has since prospered all over the world within less than a century. The annual global plastic production is more than 359 million tons. It is estimated that plastic waste from 2020 to 2030 will amount to 500 million tons; from 2030 to 2040 it will be 650 million tons, and from 2040 to 2050 it will reach 800 million tons (Nayanathara Thathsarani Pilapitiya and Ratnayake 2024). The world will face a significant threat from plastic waste in the future, and therefore it will be necessary to make changes to packaging materials as one approach to reduce the amount of plastic waste.

The world is increasingly becoming a global village, yet communal human activities present a significant threat in terms of climate change. In terms of education, health, and economic development, a sustainable approach is necessary if temperatures are to be controlled. Renewable energy sources will become a crucial area to meet energy demand. Therefore, this research sought to make use of green energy, taking into consideration access to energy, along with social as well as economic evolution, and the need to limit climate change and reduce environmental issues. However, the benefits of green energy can be hindered by obstacles to climate change mitigation (Neha and Joon 2021). Solar energy involves green energy systems that rely directly on the energy from the sun. Solar energy can be activated and transformed into many other forms through regenerative technology. Other green energy sources include ocean and wind power. For solar energy, photovoltaic (PV) power generation can meet direct lighting needs, while the production of fuel derived from solar energy technologies can power transport. The total power potentially available through solar energy will significantly exceed the cumulative energy available worldwide from alternative approaches (Neha and Joon 2021).

Environmental concerns about the use of plastic packaging have resulted in an evaluation of strategies that limit plastic packaging and single-use plastics and instead promote sustainable bio-based alternatives (Macht *et al*. 2023). The arecanut leaf sheath is a component of the betel palm tree, which is commonly cultivated in the Southeast Asian region. It is derived from the outer covering of the leaves of the arecanut palm. It has been used to create environmentally friendly containers such as plates, trays, and bowls, because it is both compostable and biodegradable. Moreover, it contains fibers, lignin, and other organic components that can be influenced by heat and pressure to shape the sheaths into the desired forms. Mohanty *et al*. (2021) demonstrated that the leaf sheath can withstand forming strains up to 200%, comparable to ductile metals. The deformation response of the sheath is significantly influenced by hydration, showing a potential 400% increase in forming strain. Leaf products have an embodied energy of four to five orders of magnitude smaller than plastic or paper products. The findings establish the microstructural basis for high formability and outline a forming limit diagram, indicating shapes achievable in a single step from this plant material (Mohanty *et al*. 2021).

Additionally, arecanut leaf shows excellent strength properties in that the breaking force of the material has been reported to be about 70% that of polythene in the lengthwise direction, and 22% in the widthwise direction. Arecanut leaf exhibits excellent thermal stability, where degradation first takes place in the temperature range of 200 to 375 ºC. It has an areal density of 132.5 g/m^2 with 1 mm thickness. Arecanut leaf has shown a tearing strength of around 71% of that of polythene and reached about 5% elongation at failure. The bursting strength of the arecanut leaf was indicated to be three times stronger (0.3 kg/cm^2) than that of polythene (0.1 kg/cm^2) (Dissanayake *et al*. 2021).

This study developed a hydraulic compression machine powered by a hybrid electrical system, combining mains electricity and solar energy to produce bio-based trays for food contact. Although the power supply was not able to provide 100% support for this research when forming bio-trays, this study also used grid-tied technology, switching automatically between mains power supply and solar cells. Solar power is unreliable due to the dependence upon the weather, operating only when sunshine occurs. Additionally, this solar cell grid-tied technology can increase the power from solar panels from 3 kW to 5 kW to 10 kW, depending on the budget in the future. The primary material used was the arecanut leaf sheath, and the research investigated the effect of processing conditions on the mechanical properties of these trays. Additionally, a study was undertaken to assess the microbial quantity and sterilization effectiveness of the material using UV light to evaluate its safety. Sodium chloride, 99.5% (AR), was purchased from RCI Labscan Limited, Thailand. 3M™ Petrifilm® Aerobic Count Plates were used to determine the aerobic plate count. Baird-Parker agar and Xylose Lysine Deoxycholate agar (XLD agar) were obtained from Millipore.

EXPERIMENTAL

Materials

Sodium chloride, 99.5% (AR), was purchased from RCI Labscan Limited, Thailand. The 3M^{TM} Petrifilm® Aerobic Count Plates were used to determine the aerobic plate count. Baird-Parker agar and Xylose Lysine Deoxycholate agar (XLD agar) were obtained from Millipore (Maharashtra, India).

The hydraulic compression molding machine produced was 0.76 x 1.70 m^2 in dimensions. The 100 bar hydraulic pump controlled the pressure to 3 hot plates, using a 30 hp induction motor. The 3 hot plates of (A) 0.27 x 0.27 m^2, (B) 0.48 x 0.32 m^2, and (C) 0.29 x 0.32 m^2 in dimensions were installed with heaters of both the upper and lower plates to control the temperature to a maximum of 150 °C, as shown in Fig. 1.

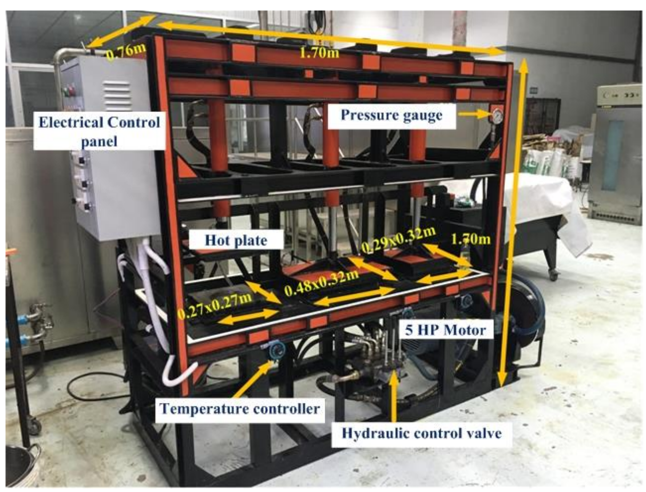

Fig. 1. The hydraulic compression molding machine

The 3 kW grid-tied inverter was installed at the Faculty of Agro-Industry, Prince of Songkla University. This 3kW grid-tied inverter can be operated through an on-grid system that combined 220 Vac, 50 Hz main electricity, and solar power as shown in Fig. 2. Meanwhile 3 kW multi crystalline solar panels were installed on the roof top of the Faculty of Agro-Industry, Prince of Songkla University.

Fig. 2. The 3-kW grid-tied inverter can connect solar power to the hydraulic compression molding machine

Fig. 3. The 3 kW multi crystalline solar panels

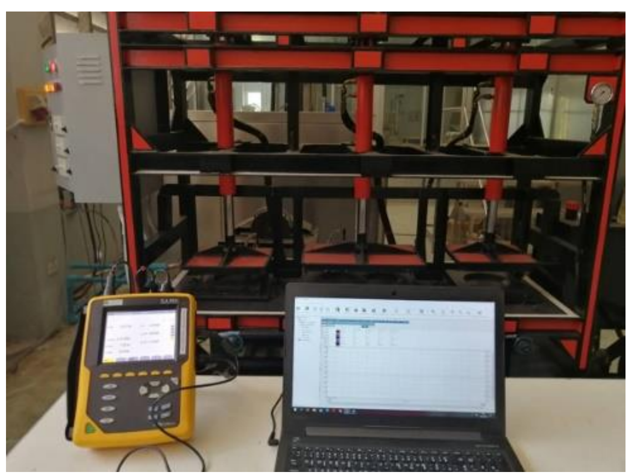

Fig. 4. The measurement of electrical consumption when operating the hydraulic compression molding machine

The arecanut leaf sheaths were collected form Phattalung and Songkhla provinces, Thailand. The arecanut leaf sheaths of 2.0 to 2.5 mm in thickness were soaked in water for

2 min to be cleaned and softened. These leaves were pressed with a 6 × 12 in^2 two-roll mill (ML-D6L12, Chareon Tut Co., Ltd., Thailand) with the nip gap of 2 mm. The pressing number and temperature were varied over the ranges of 10 and 20 times and 30 °C and 80 °C, respectively. After the pressing process, the softened leaf sheaths were compressed at 100 °C with pressure of 30 bar for 5 min to remove the sample moisture. Then the leaf sheaths were compressed again for 1.0 to1.5 min to shape them into the desired shape as shown in Fig. 3. Finally, the samples were ready for packing with the machine. The hydraulic packing machine was set up with the hot plate at 100 °C, and the samples (leaves) were deposited between the hot plates. The hydraulic packing machine firstly pressed on the sample at 30 bar for 5 min and then moved the hot plate up by about 10 cm to release steam. The hydraulic packing machine then pressed on the sample at 30 bar for 1.0 to 1.5 min, with the samples as shown in Fig. 3. Electrical power analysis used the power analyzer (Chauvin Arnoux CA 8331 Power Quality Analyzer, 1, 3-Phase, 10000A ac Max, 1000 V ac, 1200V dc Max; Chauvin Arnoux, Paris, France) that connected the operational hydraulic packing machine to the fully operational solar power system. The electrical consumption was measured for all processes until completion of the 3 packages as shown in Fig. 5.

Fig. 5. The bag of arecanut leaves used the hot plate of the hydraulic packing machine

RESULTS AND DISCUSSION

Table 1 exhibits the electrical consumption of the hydraulic packing machine when operating each hot plate. The hydraulic packing machine used 3 hot plates of different diameter such as (A) 0.27 x 0.27 m^2, (B) 0.48 x 0.32 m^2, and (C) 0.29 x 0.32 m^2. The electrical loads were applied as two types, including the 100 °C heater and 30 bar hydraulic pump. Based on real processes, the hydraulic packing machine and hydraulic compression molding machine could be operated using only the heater, or in full operation with the heater and hydraulic pump together. When the 100 °C heater was in operation, the (A) hot plate consumed 230.90 V, 23.96 A, and 1,510.00 W; the (B) hot plate consumed 227.60 V, 23.73 A, and 2,218.00 W, and the (C) hot plate consumed 228.60 V, 23.36 A, and 1,352.00 W. Meanwhile the full operation (30 bar hydraulic pump + 100°C heater) consumed electrical energy whereby the (A) hot plate consumed 227.60 V, 25.24 A, and 2,838.00 W; the (B) hot plate consumed 219.80 V, 32.12 A, and 5,548.00 W, and the (C) hot plate consumed 225.90 V, 24.45 A, and 2,791.00 W. The electrical consumption increased depending on the diameter of the hot plates so that (B) 0.48 x 0.32 m^2 was the biggest, and required the higher loading of 5,548 W of electrical power. The heat transfer generated from electrical power depends on the surface area of the hot plates (Menendez-Perez *et al*. 2022; Peng *et al*. 2023).

Table 1. Electrical Consumption of the Hydraulic Compression Molding Machine When Operating Each Hot Plate

Hot Plate (m)	Electrical Consumption	*V* (V)	*I* (A)	*f* (Hz)	*P* (w)
(A) 0.27 x 0.27	100 °C (Heater)	230.90	23.96	50.03	1,510.00
	(30 bar Hydraulic Pump + 100 °C Heater)	227.60	25.24	49.94	2,838.00
(B) 0.48 x 0.32	100 °C (Heater)	227.20	23.73	50.02	2,218.00
	(30 bar Hydraulic Pump + 100 °C Heater)	219.80	32.12	49.97	5,548.00
(C) 0.29 x 0.32	100 °C (Heater)	228.60	23.36	49.97	1,352.00
	(30 bar Hydraulic Pump + 100 °C Heater)	225.90	24.45	50.01	2,791.00

Table 2 reveals the energy savings of the hydraulic compression molding machine when applying the solar cell power plant. The solar cell power plant should be operated on sunny days because this operation used an on-grid solar cell system and main electrical power. The solar cell power plant generated 2.922 kW that was almost the full production capacity of the power plant. The hydraulic compression molding machine fully fabricated the dishes from bags of betel leaves, taking 1 h to produce 30 pieces when operating each of the (A), (B), and (C) hot plates. Based on the (A) and (C) hot plates having electrical consumption lower than 2 kWh, the on-grid system can fully consume 100% electricity from the solar cell power plant, while the (B) hot plate consumed more than 2.22 kWh; so the on-grid system can co-consume from the main power using 1.07 kW, and used the electricity from the solar cell power plant of 1.15 kWh, thus saving energy at 51.80%.

Table 2. Energy Saved of the Hydraulic Compression Molding Machine When Applying the Solar Cell Power Plant

Hot Plate (m)	Amount of Production in 1 h (Pieces)	Electrical Consumption (kWh)	Electricity From Solar Cells (kWh)	Electricity from Mains Power (kWh)	Energy Saved (%)
(A) 0.27 x 0.27	30	1.51	1.51	0	100
(B) 0.48 x 0.32	30	2.22	1.15	1.07	51.80
(C) 0.29 x0.32	30	1.53	1.53	0	100
Total	90	5.26	4.19	1.07	79.65

For total electrical consumption of 5.26 kWh, the transfer from the solar cell power plant was 4.19 kWh, amounting to a calculated energy saving of 79.65%. The on-grid solar cell system helped save energy for the hydraulic compression molding machine due to the automatic combination of the electricity from the solar cell power plant and mains power, with no battery required, and low maintenance. However, the limitation of this process is that it must be operated on sunny days (Han *et al*. 2016).

Table 3 shows the comparison of the cost of electricity when operating the hydraulic compression molding machine on-grid between solar cells and mains power. In terms of electrical units for calculation, the electric cost was approximately 0.13 USD/kWh. The overall electrical consumption obtained from the solar cell power plant and mains power of 5.26 kWh should cost 0.6838 USD. Meanwhile, the full operation of the solar cell power plant can transfer 4.19 kWh to the hydraulic compression molding machine, saving 0.5447 USD. Egypt has used solar cell technology for electrical power plants due to its green energy credentials with no CO_2 released into the atmosphere. They have a plan to develop to a net-zero state, meaning that all activities produce no CO_2, so their industries use solar cell technology (Kumar and Tiwari. 2002). The solar cells can transfer electricity for heating/cooling, depending on the applications (Terashima *et al*. 2023). The total cost of the 3 kW solar system was approximately 2,892 USD. The payback period when using power from the solar system is around 3 to 4 years. However, there are many factors affecting the payback period such as weather, type of solar cell, time used for operation, and electricity prices.

Table 3. Comparison of Electricity Cost When Operating the Hydraulic Compression Molding Machine Used On-Grid Between Solar Cells and Main Power

Hot Plate (m)	**Electricity from Solar Cells (kWh)**	**Electrical Units (USD)**	**Cost of Electricity (USD)**
(A) 0.27 x 0.27	1.51	0.13	0.1495
(B) 0.48 x 0.32	1.15	0.13	0.1963
(C) 0.29 x0.32	1.53	0.13	0.1989
Total	4.19	0.13	0.5447
Hot Plate (m)	**Electricity from Main Power (kWh)**	**Electrical Units (USD)**	**Cost of Electricity (USD)**
(A) 0.27 x 0.27	0	0.13	0
(B) 0.48 x 0.32	1.07	0.13	0.1391
(C) 0.29 x0.32	0	0.13	0
Total	1.07	0.13	0.1391
Overall	5.26	0.13	0.6838

Figure 6 shows the comparison between (A) production from this investigation, and (B) production from commercial packages. Normally, the hydraulic compression molding machine using arecanut leaf sheaths using only electricity from the mains power would result in the cost of packages of about 0.11 USD/piece. In contrast, the hydraulic compression molding machine connected to the 3-kW solar cell system under the on-grid system can save money, reducing the cost to 0.056 to 0.085 USD/piece. This process depends on the weather or dust situation because solar cells need sunshine to generate the electricity (Abdullah *et al*. 2022).

Fig. 6. Comparison between (A) production from this investigation, and (B) production from commercial packages

The influence of molding conditions including number of pressings (10 and 20 times), pressing temperature of the two-roll mill (25 °C and 80 °C), and molding times (1.0 and 1.5 min) on the mechanical properties of the molded arecanut leaf sheath were investigated. Moreover, the mechanical properties of the molded arecanut leaf sheath were then compared with three types of commercial plastic food trays made from different materials: polystyrene foam (PS), polypropylene (PP), and polyethylene terephthalate (PET).

Figure 7 illustrates the tensile strength and elongation at break of the arecanut leaf sheath sheets fabricated using the two-roll mill with different temperatures and numbers of pressing cycles.

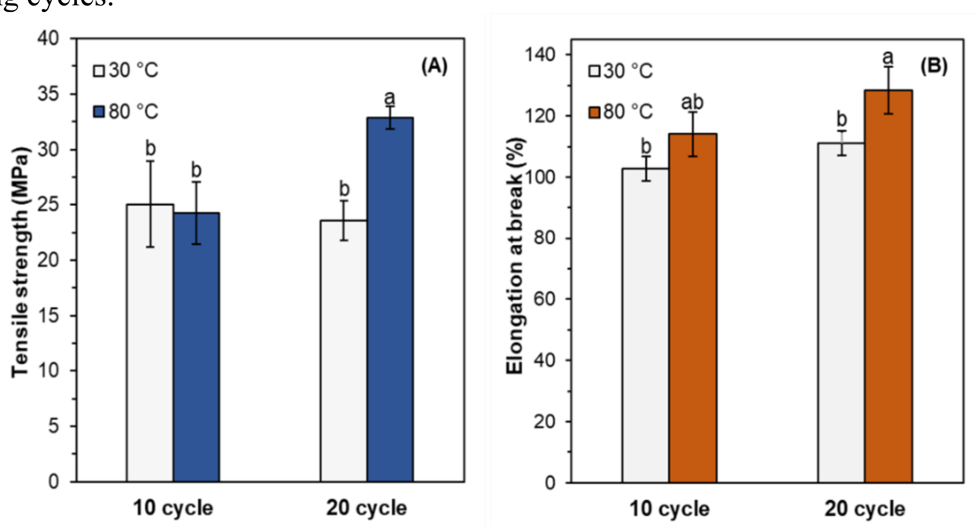

Fig. 7. The tensile strength and elongation at break of arecanut leaf sheath sheets fabricated by the two-roll mill with different temperature and numbers of pressing cycles
Note: Different letters displayed in the columns indicate statistically significant differences at a confidence level of $p < 0.05$.

It was observed that the number of pressing cycles did not affect the tensile strength and elongation at break of the material when tested along the fibre direction at room temperature (approximately 30 °C). However, when the temperature was increased to 80 °C, and the number of pressing cycles was increased from 10 to 20, the tensile strength and elongation at break of the arecanut leaf sheaths increased from ~25 to ~34 MPa. This could be attributed to the pressing under high temperature (80 °C), which might induce chemical changes in the material, leading to chemical bonding or alterations in the chemical structure of the material components. Furthermore, increasing the number of cycles in the rolling process also resulted in an increase in tensile strength and elongation at break. This is because shear forces and temperature may affect the alignment of fibres or the polymer molecules, similar to the behaviour observed in fibre-reinforced polymer composites (Tcherdyntsev 2021).

After the rolling process, the arecanut leaf sheet was converted into plates through a compression molding machine. The effect of compression times of 1.0 and 1.5 min on the mechanical properties of the molded arecanut leaf sheath was investigated with a compression temperature of 100 °C. The findings indicated that the compression time exhibited no remarkable influence on the tensile strength and elongation at break of the plates. The recorded values for tensile strength and elongation at break were in the range of 23 to 25 MPa and 101% to 111%, respectively, as depicted in Fig. 8(A). Nevertheless, based on preliminary investigations, it is not recommended to reduce the molding time to less than 1.0 min. This precaution was due to the observed high moisture content in the arecanut leaf sheaths, resulting in low dimensional stability.

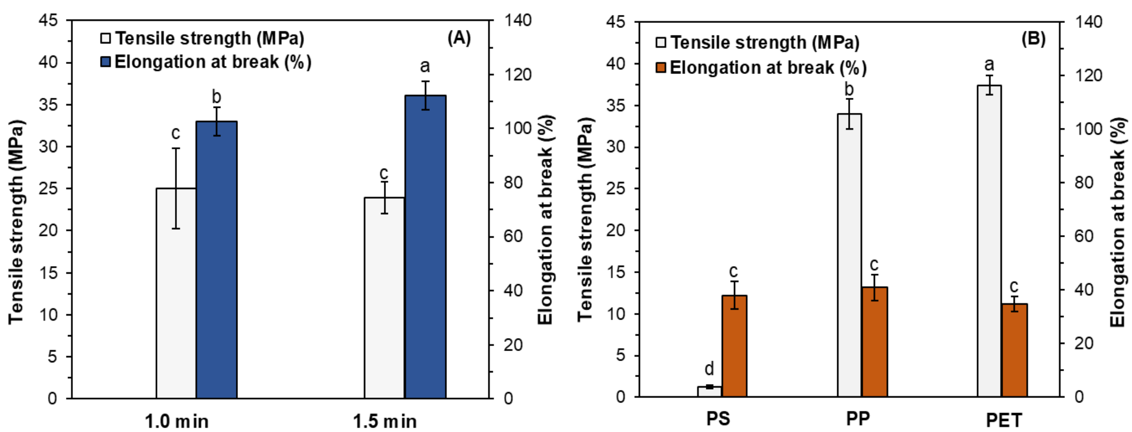

Fig. 8. The mechanical properties of arecanut leaf sheath trays produced from the compression molding process at 100 °C with different compression times (A), and the mechanical properties of commercial food trays (B). Note: Different letters displayed in the columns indicate statistically significant differences at a confidence level of $p < 0.05$. All samples in graphs (A) and (B) were analyzed and compared together.

When comparing the mechanical properties of the molded arecanut leaf sheath tray with commercially available food containers, including PS-foam trays, PP-trays, and PET-trays, it was found that the arecanut leaf sheath tray exhibited higher tensile strength than PS by more than tenfold and was within the same range as PP. However, the arecanut leaf sheath tray demonstrated slightly lower tensile strength when compared to PET. Upon assessing the elongation at break, the results showed that the arecanut leaf sheath tray, under all conditions, exhibited an elongation at break higher than other materials, around

30% to 50%, as shown in Fig. 8(B). However, the obtained values may be higher than the actual values because the arecanut leaf sheath was a natural material composed of many long fibres, resulting in a fracture pattern different from that of synthetic polymers.

From the previous experimental results, an increase in compression time did not remarkably impact the mechanical properties of the produced arecanut leaf sheath trays. Therefore, the molding condition with the lowest energy consumption for arecanut leaf sheath production was chosen as 100 °C for 1.0 min. Samples obtained under these conditions (~2.49 ± 0.45 mm in thickness, the lowest thickness of the obtained arecanut leaf sheath) were then tested for puncture resistance. It was found that the plates produced from arecanut leaf sheaths also exhibited the highest puncture resistance when compared to other types of plastic trays, as shown in Fig. 9. This ensures confidence that arecanut leaf sheath products can be effectively utilized in food packaging applications. In addition to its strength characteristics, it is noteworthy that the process of shaping the arecanut leaf sheath into trays spans a range of sizes, from small trays to larger ones, approximately 30 cm in diameter (Kiran Kumar *et al*. 2019). This variation in size is attributable to the inherently large dimensions of the raw material. Notably, the production process does not require the use of adhesives to bond the material, in contrast to the shaping of other types of leaves such as sal (*S. robusta*), addaku, and moduga, where adhesives are often necessary to maintain the structural integrity during hot compression molding processes (Kora 2019).

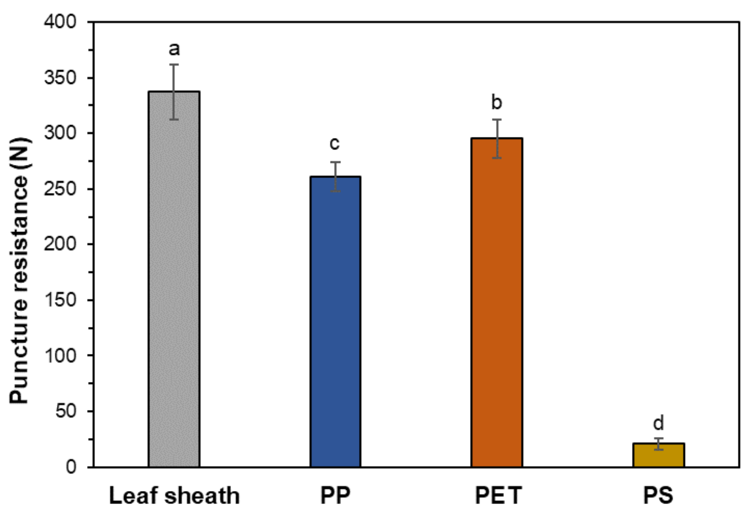

Fig. 9. The puncture resistance of arecanut leaf sheath sheets produced *via* the compression molding process at 100 °C for 1.0 min, and commercial food trays. Note: Different letters displayed in the columns indicate statistically significant differences at a confidence level of $p < 0.05$

However, the arecanut leaf sheath being a natural raw material is susceptible to microbial contamination. Hence, this study also investigated the total microbial count and specific pathogenic bacteria, including *E. coli*, *S. aureus*, and *Salmonella* spp. The results indicated that plates produced from arecanut leaf sheaths, without microbial sterilization, had a total bacterial count of 410 CFU/g. This suggests that the arecanut leaf sheath plates may not be suitable as food contact materials. According to Regulation (EC) No 852/2004, which addresses materials and articles intended to come into contact with food, it is stipulated that the packaging must not be a source of food contamination (Hladikova *et al*. 2015). Therefore, the plates should be sterilized before use for safety reasons. However, no *S. aureus* and *Salmonella* sp. were detected, while *E. coli* was found in small amounts, specifically < 3.0 CFU/g, as shown in Table 4.

Nevertheless, in order to reduce the microbial load on the product, it is advisable to subject the product to UV-C light for microbial sterilization. It was observed that the bacteria remarkably decreased, with a consistent trend stabilizing at < 10 CFU/g after exposure to UV light for more than 10 min, as depicted in Table 5. These results can be attributed to the damage inflicted on the DNA or RNA in the cells of these microorganisms. The energy from the light is absorbed by the DNA and RNA molecules within the cells, leading to the formation of thymine dimers. These dimers represent abnormal linkages between adjacent thymine bases in the DNA or RNA strands (Cutler and Zimmerman 2011). Therefore, the sterilization of microorganisms that contaminate the tray is essential (Revathi *et al*. 2021) before packaging in suitable containers that prevent the passage of moisture or gases. This will help extend the shelf life of the product, which is an interesting area for future study.

Table 4. Number of Bacteria on the Surface of the Arecanut Leaf Sheath Trays

Microorganism	Amount (CFU/g)
Total plate count	410
E. coli	< 3.0
S. aureus	ND
Salmonella spp.	ND

Table 5. Number of Bacteria on the Surface of the Arecanut Leaf Sheath Trays Before and After UV Exposure for Different Times

Time (min)	Total Plate Count (CFU/g)
0	410
1	300
5	200
10	< 10.0
15	< 10.0

CONCLUSIONS

1. The hydraulic compression molding machine applied to arecanut leaf sheaths using electricity only from the main power resulted in a cost of each package at 0.11 USD/piece. When the hydraulic compression molding machine was connected to the 3 kW solar cell system under the on-grid system resulted in a lower cost at 0.056 to 0.085 USD/piece. Solar cell energy must be applied to the machine compression.

2. The tensile strength and elongation at break of the arecanut leaf sheath trays were affected by pressing temperature and number of cycles. An increase in tensile strength and elongation at break was observed at 80 °C with 20 pressing cycles. However, compression time did not remarkably affect the mechanical properties of the trays.
3. The arecanut leaf sheath trays exhibited higher tensile strength than PS, comparable to PP, and slightly lower than PET. Regarding elongation at break, the arecanut leaf sheath trays consistently outperformed other materials, showcasing their potential as a natural and sustainable alternative.
4. Furthermore, microbial sterilization was essential to ensure compliance with safety standards for the use of these products in contact with food. The research underscores the importance of addressing microbial contamination through UV-C light exposure.
5. The arecanut leaf packaging can be applied to real situations, particularly in the case of the green market (Tainod Green's Market, Phatthalung, Thailand), since this market has strongly promoted the elimination of plastic packaging. Additionally, the product lifespan of the trays can be further studied to assess the suitability of the packaging.

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