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Selection of plant materials and their maturity stages suitable for food packing and serving

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Abstract People around the world, including Sri Lankans, are frequently using plant materials as an age-old practice to pack and serve foods. This study aimed to select the best materials and their correct maturity stages with favourable properties for eco-friendly food packaging. Information relevant to locally utilized plant materials was collected from 75 people from plant-related sectors, including farmers, Ayurvedic practitioners, agriculture instructors and the undergraduates of the Botany study field, through a descriptive questionnaire. Further, from the list of plant materials corroborated by the respondents, twelve materials, namely, leaves of lotus, tropical almond, teak, palmyrah, coconut, portia, jack, banyan as well as leaves and sheaths of banana, and arecanut were selected and they were tested for load-bearing ability, surface area, thickness, storage stability and folding ability. The results revealed that the leaves and sheath of banana, leaves of palmyrah and the sheath of arecanut had significantly better qualities for developing food packaging materials. Further, the mature stage of banana and tender stage of palmyrah leaves demonstrated significantly ($p<0.05$) higher load-bearing capacity (LBC) (1.88 ± 0.08N, 30.90 ± 1.19 N), tear resistance (1.90 ± 0.09 N, 4.36 ± 0.21 N) and fibre content (30.38 ± 1.02%, 46.06 ± 1.11%) against other sources in developing food packaging materials.

Keywords: Food wrapping; eco-friendly packaging; load-bearing capacity; palmyrah leaves.

1. Introduction

Since modern-day food packaging has greatly encompassed synthetic polymers, they have greatly contributed to plastic pollution, particularly single-use wrapping and serving materials. This practice has subsequently led to a negative impact on natural ecosystems, mainly due to accumulation of such materials on waterways (Manalili 2011, Geyer *et al*. 2017). Sri Lanka is not an exception as a victim of this negative impact, where many plastic materials have accumulated mainly in the coastal regions, and subsequently creating a dead zone reportedly in the Indian Ocean (Ghosh and Savio-Lobo 2017).

The development of potentially biodegradable packaging materials as alternatives to single-use plastic wrappers and service ware items is luring attention to tackle plastic pollution. Hence, an urge has been raised in the research and development sectors all around the globe to invent alternative packaging materials, at least for one-time usage. A major portion of the environmentally friendly packaging materials that were developed so far and are under development, secure plant materials as the main sources. In this context, a special concern is given to leaves and sheaths of different plants, as it is evident from the fact that it is an age-old practice of utilizing them in packing and serving foods during the period when plastic packaging materials were not available. For instance, leaves of banana, teak, tropical-almond, palmyrah, turmeric, banyan, lotus, coconut, and rubber trees are among the most common plant-based packaging materials (Osman *et* al. 2018, Kora 2019, Kalina *et al*. 2024a).

The practice of utilizing plant materials, mainly the leaves is a part of the lifestyle of people, especially those living in South Asia (Osman *et al.* 2018, Metananda *et al*. 2023). They still practice this tradition on cultural occasions where different leaves are used for offering religious gifts ('prasadam') for different Gods. Further, other food items, including sweets, hot soups, cooked rice, steam-cooked dishes, and liquid foods, are either packed, cooked with, or served on various occasions using plant leaves (Kora 2019, Ross 2023).

The scientific society has proved that the leaves that were utilized for food packaging by ancient people have many benefits, including good medicinal values, anti-microbial properties, and plenty of pharmacological and phytochemical properties, which helped them stay healthy. As a result, they have provided protection against food pathogens and food-borne illnesses (Prasad *et al*. 2006, Bhardwaj *et al*. 2011, Muhammad and Mudi 2011, Mensah *et al*. 2012, Sachan *et al*. 2014, Jamkhande *et al*. 2016, Terças *et al*. 2017). In addition, there are shreds of evidence that the plant leaves contain a large number of organic compounds, mainly polyphenols, which will probably be added to the food items when they are packed, cooked or served with those leaves. These poly-phenolic compounds have anti-oxidant properties, preventing the oxidation of food components and the formation of carcinogens (Sahu and Padhy 2013, Ng 2015, Somayaji and Hegde 2016).

The long-term practice of packing and serving food using plant leaves had paved the way for modern manufacturing technology of leaf plates, sheets, and cups alike. A thrust has been shifted to utilize disposable plates made from plant leaves, which are biodegradable and enriched with antioxidants and medicinal values (Kalina *et al*. 2024a, Kora 2019). However, only certain types of plant materials that have a sufficient surface area, storage stability, and bending and folding abilities are suitable for this technology. When compared to synthetic materials, they will offer several benefits such as their availability and abundance, biodegradability, ease of disposal and nature friendliness (Aoudji *et al*. 2013, Sarin 2017, Singh 2018, Kora 2019).

However, there is a necessity for alternative packaging material to have characteristics comparable to that of synthetic plastic for its wide application in the food industry. In this context, the bioplastics produced from plant and animal biomass have exhibited good thermal and mechanical properties and higher biodegradability. These properties make them better alternatives to reduce synthetic plastic and create an eco-friendly environment (Patel *et al*. 2019). However, most of them have polylactic acid as the main component with long processing steps and these bioplastics need high temperatures for composting, and they make the soil acidic (Mihindukulasuriya and Lim 2014, Raza *et al*. 2018, Tsang *et al*. 2019, Jeevahan *et al*. 2020).

The materials under development are expected mainly to have biodegradability and sustainability, in terms of scale-up production and industrial application and, at the same time, add a functional benefit to the packed foods (Ghosh and Lobo 2017, Patel *et al*. 2019, Manzoor *et al*. 2022). Thus, manufacturing of eco-friendly and sustainable packaging materials, such as food wrappers, cups, plates, spoons, and straws from abundantly available plant parts by employing simple physical and chemical treatment/s will be helpful for mankind to overcome plastic pollution at least partly (Kalina *et al*. 2024a). Hence, the current study was conducted to identify the locally available plant materials, especially leaves with the best qualities, that support their suitability to be employed as a source in the future research work of developing nature-friendly, cheap, and durable food packaging materials, as a continuity of the effort made in recent research fields and as a preliminary step for novel bio-degradable food packaging.

2. Material and Methods

This study was done to select two best plant materials and their suitable maturity stages to be utilized as a source in the process of developing plant-based food packaging materials. The method involved surveying the plant materials used in food packing and serving, and conducting preliminary physical tests at the laboratory for the materials listed during the survey. Further, it involved testing the physicochemical properties of two selected materials to identify their suitable maturity stage for packaging material development.

2.1 Survey of plant materials used in food packing and serving

Selection of respondents

The targeted respondents in this study included residents in the Jaffna peninsula, Sri Lanka, who are aware of various plant materials and their applications. A total of 75 respondents, including 30 farmers from rural areas, 15 Agriculture Instructors, 15 final-year undergraduates from Botany study field, and 15 Ayurvedic practitioners were selected for the survey on plant materials used in food packaging. Each group of respondents was selected from different places in the Jaffna peninsula using a cluster random sampling method, where different divisional secretariat regions were considered as clusters. The information on the targeted population was collected from regional offices assigned to each sector.

Questionnaire for data collection

Required data on the locally available plant sources used for food packaging were collected through a descriptive questionnaire. The data collection included both self-administration and interviews. The data collected mainly included the type of materials and the stage of material used, available season, treatments provided, types of food packed, the physical structure suitable for packaging, possession of antimicrobial or medicinal properties, and adding flavour to the packed food, the tendency for making packing material and acquiring stability by treatment. During data collection, the consent was assured to the participants that the data collected from the participants would be strictly confidential and any personal identity of them would not be revealed in any part of the research.

2.2 Preliminary physical testing for the selected plant materials

Plant materials

From the list of plant materials corroborated by the respondents, twelve materials (Figure 1), which are abundantly available in Northern Sri Lanka, namely leaves of lotus, tropical almond ('kottamba', in *sinhala*), teak, palmyrah, coconut, portia, jack, banyan as well as leaves and sheath of banana, and arecanut were selected for further analysis in the laboratory.

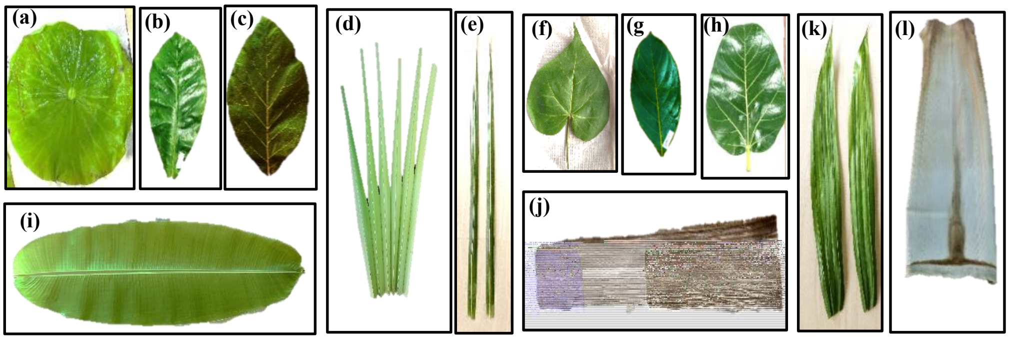

Fig. 1: Twelve plant materials collected from Jaffna Peninsula, Sri Lanka: the leaf of (a) lotus, (b) tropical almond, (c) teak, (d) palmyrah, (e) coconut, (f) portia, (g) jack, (h) banyan, leaf (i) and withered sheath (j) of banana, and leaves (k), and withered sheath (l) of arecanut.

Collection of samples

The samples of each of the twelve plant parts in the maturity stage mentioned by the respondents were harvested randomly from different parts of local terrestrial and water ecosystems in the Jaffna peninsula, Northern Province, Sri Lanka. The plant leaves, such as banana, lotus, palmyrah, coconut and arecanut were taken at the tender stage, while the leaves of tropical almond (‘kottamba’), teak, portia, jack and banyan were taken at the mature stage, and the sheaths of banana and arecanut were taken at the withered stage. The maturity stages of the plant materials were identified based on their colour difference, where the tender materials had a light green colour, mature materials had a dark green colour and withered materials or the materials at the stage of senescence had a yellow or brownish yellow colour.

Each of the twelve plant materials free from any defects was collected randomly in five numbers from five plants located at the main divisions of Jaffna peninsula (9°40'6.42"N, 80°0'26.71"E) such as Vadamaradchy, Thenmaradchy, Pachilappalli, Valligamam and Islands.

Sample preparation

The collected plant materials were cleaned with a damp and soft cloth, and used in the experiments. In the case of palmyrah, coconut and arecanut, the individual leaves were separated from the leaf axil and tested.

Experimental procedure

All the chemicals used in the experiments were obtained from Sigma Aldrich (St.Louis, MO, USA). For the twelve selected plant materials, the following physical properties load-bearing capacity (LBC), thickness, surface area, storage stability, and folding ability, were determined using five replicates.

a) **Load-bearing capacity/Tensile strength**:

The load-bearing capacities of the twelve selected fresh and withered plant parts were tested using mass hangers following a method designed (Figure 2) in line with the method recommended by Defoirdt *et al*. (2010) and Arifin *et al*. (2023) with modifications. Initially, a rectangular strip of plant material (15×0.5 cm^2) was separated in the middle part lengthwise and at the same time parallel to the midrib for plant leaves except banana leaf (where it was taken perpendicular to the mid rib). For the two sheaths, the middle portion was taken parallel to the length. Thereafter, mass hangers were allowed to hang on the strip of plant material, using paper clips and a metal stand. Then, the weights in the mass hanger were increased at a rate of 1g/s until the strip of plant material broke. The maximum weight that the plant material can bear is recorded for five replicate samples of each plant material.

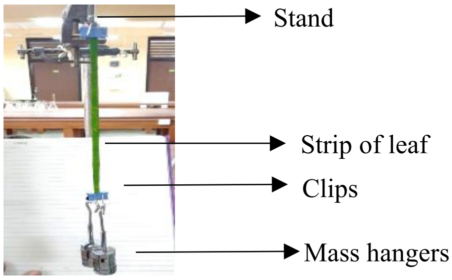

Fig 2: Method of measuring the load-bearing capacity

b) **Load-bearing capacity of treated plant materials**:

The LBC was also analyzed for the twelve plant parts after providing a simple treatment, "Blanching." The hot water blanching was done at 85°C for 5 minutes and immediately transferred to an ice water mixture. Then, the materials were dried in the shade for one day, and the load-bearing capacity was tested applying the same method used for the fresh materials.

c) **Thickness**:

The thickness of each plant part was measured using a digital micrometer screw gauge at 10 random locations in the plant material. The specimens of dimensions 15 × 0.5 cm^2 (Length × Width) were cut from samples and used for the measurements, and the mean (mm) thickness was determined with an accuracy of ± 0.001 mm.

d) **Surface area**:

The surface area of each plant part was computed using ImageJ software, by using photographs of each plant material. The photographs of the materials were taken from equal distances while keeping each material and a 30 cm ruler scale on a white background (Figure 3), and the image of the material was loaded into the application to compute the surface area at three significant decimal places.

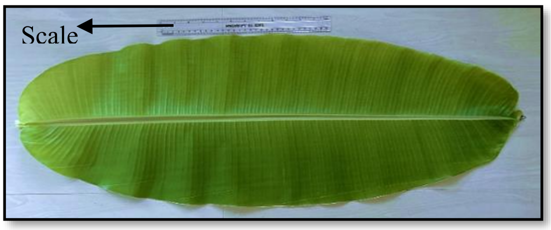

Fig 3: Image of a banana leaf taken for the computation of surface area

e) **Storage stability**:

The twelve plant parts were kept at room temperature, and the number of days it took for the material to lose its stability of color and physical structure was recorded using visual observation. When the materials changed their original colour they had at the time of sample collection, and at the same time when they lost their physical structure when folded, it was taken as the point when plant materials lost their stability.

f) **Folding ability**:

The selected plant-based materials were folded at angles of 0°, 30°, 60°, and 90° from a horizontal line drawn at the base plane where the plant parts were positioned (Figure 4), similar to the leaf folding framework mentioned by Couturier *et al*. (2011). The number of folds on each of the two halves of a selected plant material that caused no damage to the material was counted to determine the percentage of folds without any damage, which indicates the flexibility in folding.

$$Flexibility\ in\ folding = \frac{No.of\ folds\ without\ damage}{Total\ no.of\ folds} \times 100\ \%$$

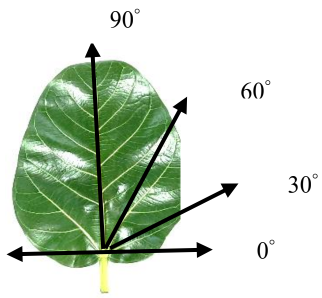

Fig 4: The angles at which the leaf was folded for testing folding ability

2.3 Screening of plant materials for further analysis

Results of the aforementioned preliminary physical tests and the responses from people for these twelve plant parts were screened to select two plant parts for further analysis in developing food packaging materials. The data collected from the respondents were analyzed using simple descriptive statistics, and the twelve plant materials were ranked based on the percentage of respondents who mentioned positively for each attribute on which the data was collected. Then, an overall ranking was obtained by calculating the total rank score for all the attributes for each plant part, where the plant part with the highest score was given the first rank.

Further, the findings of physical tests were analyzed using the Prioritization Matrix, where the values of each tested physical property were considered as a prioritization criterion, and it is multiplied by a weighted score, which was given based on the priority of that particular attribute in the process of transforming into a food packaging material. Then, the total weighted score for each plant part was calculated, and based on this total weighted score, another ranking was given to the plant materials. Finally, the two best plant materials were selected using the average of the two types of ranking, that is, based on the views of respondents and the results of the physical tests carried out.

2.4 Properties of two selected plant materials at different maturity stages

Following physicochemical tests were carried out for the two plant leaves (banana and palmyrah), which were selected based on the views of respondents and based on the physical testing performed previously. The tests were done for the leaves at three different maturity stages (tender stage, mature stage, and the stage of senescence) in five replicates, and the averages were taken.

Thickness and Load-bearing capacity

The thickness and LBC of banana and palmyrah leaves at different maturity stages were measured as done before for the twelve materials in section 2.2.

Hardness

The hardness of the selected leaves was measured using an analog type Shore durometer LXA-1 made in Eujgoov brand with 0~100HA dial scale, needle pressure of 0.55 N – 8.05 N, and a single pointer, which is a type A model that is used to measure the hardness of rubber and plastic. The test scale and method used are ASTM D2240 – Type A and ISO 868 (Ando *et al*. 2009, Shinoj *et al*. 2010, Kumar *et al*. 2021). The specimens (15 × 5 cm^2) were cut from different portions of the leaf samples and used for the hardness test by placing them on a gadget with a hole in the middle and pressing it with the shore durometer at the place where the hole is located.

Tear resistance

The tear resistance was determined using a method designed (Figure 5) in line with the process recommended by Defoirdt *et al*. (2010) and Iewkittayakorn *et al*. (2010) with modifications. For this, a rectangular strip of plant leaf (15 × 5 cm^2) was cut, and it was split longitudinally in the middle to halfway up to a depth of 2 cm. The left longitudinal edge was kept fixed without moving, and the other cut half was attached to a digital spring balance using paper clips. Then, the force required to tear off the leaf material into two pieces was recorded by dragging the other end horizontally at a uniform velocity (10 cm/s) on the right longitudinal edge using a digital balance.

Fig 5: Method designed to measure the tear resistance of plant material

Moisture content

The moisture content was determined using the oven drying method as per the AOAC (1999) standard. Accurately, 5.00g of the leaf was oven-dried at 105 ± 2^{0}C overnight, and the percentage of weight loss in the sample was calculated to determine the moisture content.

$$Moisture\ content = \frac{Weight\ lost\ in\ oven\ drying}{Weight\ of\ the\ sample} \times 100\ \%$$

Ash content

The Ash content was determined using the muffle furnace as per the method of AOAC (1984). For this purpose, 5.00g sample was incinerated in a muffle furnace at 550°C until it was free of black carbon particles and was white or grey in color. The percentage of residue remaining after the incineration was calculated to determine the ash content.

$$Ash\ content = \frac{Weight\ of\ ash\ remaining\ after\ incineration}{Weight\ of\ the\ sample} \times 100\ \%$$

Crude fibre content

The crude fibre content was determined using the muffle furnace as per the method of AOAC 978.10. For this purpose, 3.00g sample was subjected to acid hydrolysis using 1.25% H_2SO_4 followed by base hydrolysis using 1.25% NaOH. Then, the residue was washed with alcohol, followed by diethyl ether, and it was oven-dried at 105 ± 2°C until a constant weight was obtained. Finally, the dried residue was incinerated in a muffle furnace at 550°C until it was free of black carbon particles, and it was white or grey in colour. The percentage of weight loss in the sample during incineration was calculated to determine the crude fibre content.

$$Crude\ fibre\ content = \frac{W2 - W3}{W1} \times 100\ \%$$

where, W1= weight of the leaf sample, W2 = weight of the oven-dried residue, and W3 = weight of the ash after incineration.

Crude fat content

The crude fat content of the plant materials was determined using the solvent extraction gravimetric method as per the procedure described by Kirk and Sawyer (1980) and Ilodibia *et al*. (2014). For this purpose, 5.00 g sample was subjected to the Soxhlet reflux extraction process for 6 hours, where the fat from the sample was extracted using 200 mL of petroleum ether. Then, the flask containing fat extract was dried in an oven at 60°C for 30 minutes to remove any residual solvent. Finally, the weight percentage of the fat residue was calculated to determine the crude fat content.

$$Crude\ fat\ content = \frac{Weight\ of\ fat\ residue\ extracted}{Weight\ of\ the\ sample} \times 100\ \%$$

2.5 Statistical analysis

The LBC values of twelve plant materials before and after blanching treatment were compared using a paired sample t-test at P<0.05 level of significance. The findings of physical and chemical tests done for the different maturity stages of banana leaves and palmyrah leaves were analyzed using one-way ANOVA in SPSS Software, and the means comparisons of findings at different maturity stages were performed using Tukey's test at P<0.05 level of significance.

3 Results

3.1 The views of respondents on corroborated plant materials

Background information on twelve selected plant materials used in food packaging and serving

The background information on the twelve selected plant materials is important to execute the process of sample collection and preparation for further investigations and to understand the mechanism behind the processing of plant materials to obtain the final product of packaging materials. Therefore, the facts such as the maturity stages of material used, the available season, the treatments that are provided, and the types of foods packed were collected during the survey and given in Table 1.

The respondents from the agriculture related sectors believed that most of the plant materials used for food packaging are abundantly available during the rainy season except for the leaves of palmyrah and the sheaths of banana and arecanut, which are mostly available during the summer season. During the rainy season, the tender leaves are abundant, and appearance of leaf shoots is also higher. Whereas, in dry seasons, the sheaths of banana and arecanut are plentiful as a result of dry-spell and sunny days. For palmyrah, people usually cut leaves during the months of August and September before the rainy season as people are aware, it will induce the growth of new leaves and buds preceding the rainy season.

Further, the respondents of this study mentioned that the twelve selected materials are used at different maturity stages, such as tender, mature, and after senescence, at which they have suitable and desirable properties specifically the stability and flexibility that will result in convenient packaging materials. The plant leaves at the tender stage will have greater amenability, as well as at the mature stage they will have greater forming ability and in the case of the withered stage after senescence they will have greater stability. Hence, this indicated that the maturity stage of plant materials should also be considered when selecting the plant materials to be used as food packaging and serving materials.

Table 1: Data collected on the twelve selected plant materials from the respondents during the survey regarding their utilization for food packaging and serving

Plant materials	Stage of material used	Most available season	Treatments provided	Types of food packed
Banana leaf	Tender leaves	Rainy	Flaming, boiling in hot water, soaking in water	Cooked foods, Steam cooked foods, sweets - *thothal*
Lotus leaf	Tender leaves, moderately mature	Rainy	Flaming	Cooked foods, Sweets
Tropical almond (Kottamba) leaf	Moderately mature, Mature leaves	February, March, Rainy	Flaming	Cooked foods
Teak leaf	Moderately mature, Mature leaves	February, March, Rainy	Flaming	Cooked foods, *Rotti*
Palmyrah leaf	Tender leaves	August, September	Sun drying, weaving, water soaking	Fruits, Jaggery, Porridge, Meat, as a vessel for dough making
Coconut leaf	Tender leaves	Any time	Weaving	Fruits
Portia leaf	Mature leaves	Rainy	Steaming	Used during sweets making and steam cooking, Pongal
Jack leaf	Mature leaves	Rainy	Steaming	Used as a spoon, Steam cooked foods
Banyan leaf	Mature leaves	Any time	Steaming	Cooked sweet rice – Pongal
Arecanut leaf	Tender leaves	Rainy	Boiling in hot water	Steam cooked foods
Arecanut Sheath	Withered sheath (After senescence)	Summer	Heat pressing	As serving plates, cups and spoons
Banana Sheath	Withered sheath (After senescence)	Summer	Boiling in hot water	As serving plates

Feasible properties of plant materials for food packaging

During the survey the respondents were asked whether they know any special qualities in the selected plant materials like presence of physical structure suitable for packaging, adding flavour to the packed food and possess antimicrobial property, medicinal properties, tendency for making packing material and stability by treatment. A significantly higher number of respondents believed that the leaves of banana, palmyrah, lotus, tropical almond (kottamba) and the sheath of arecanut have better qualities among the plant materials used in packing and serving food items (Figure 6). A considerable number of respondents believe the leaves of banana (52%, 33%, 44%), palmyrah (13%, 15%, 20%) and lotus (23%, 11%, 14%) have medicinal properties, anti-microbial properties and the property of adding flavor to the packed food respectively and those additions are positively perceived by the end-user.

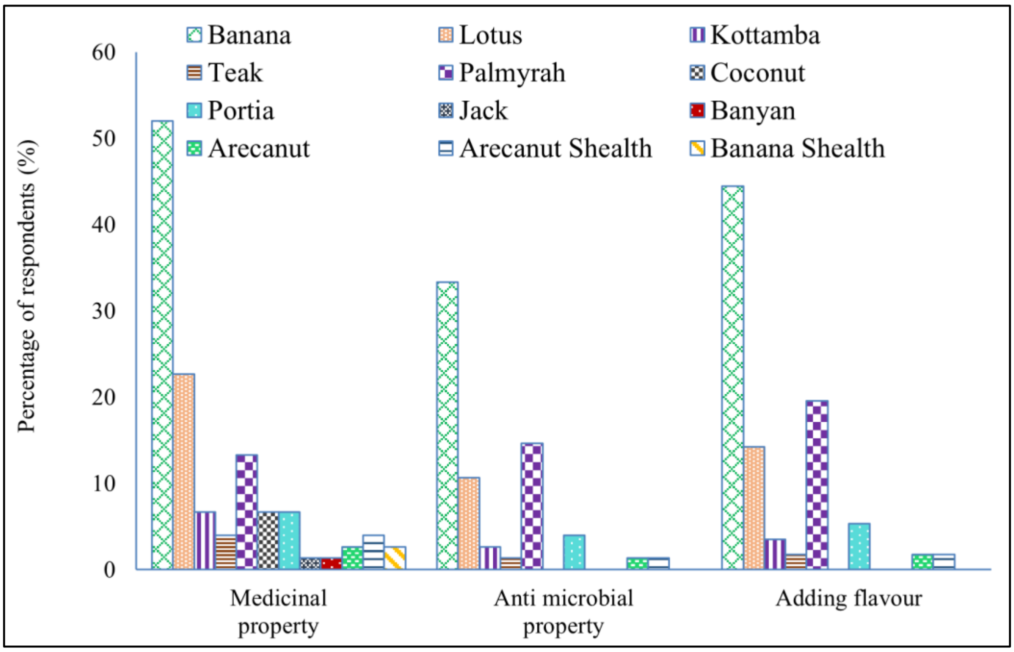

Fig 6: Survey results (%) of known properties of the selected plant materials
(medicinal, anti-microbial and flavour addition)

Similarly, a considerable number of respondents (Figure 7) believed that the leaves of banana (76%, 47%, 88%), palmyrah (44%, 31%, 44%), lotus (27%, 19%, 37%) and arecanut (10%,12%,11%) had the physical structure suitable for food packaging, tendency for developing into a packaging material and possibility to be stabilized via simple physico-chemical treatments. Further, 19% of respondents believe that leaves of tropical almond (kottamba) have the tendency to develop into a packaging material. The views of respondents are evident in the literature reviewed by Kora (2019), where wide utilization of those plant materials conventionally as well as domestically was described.

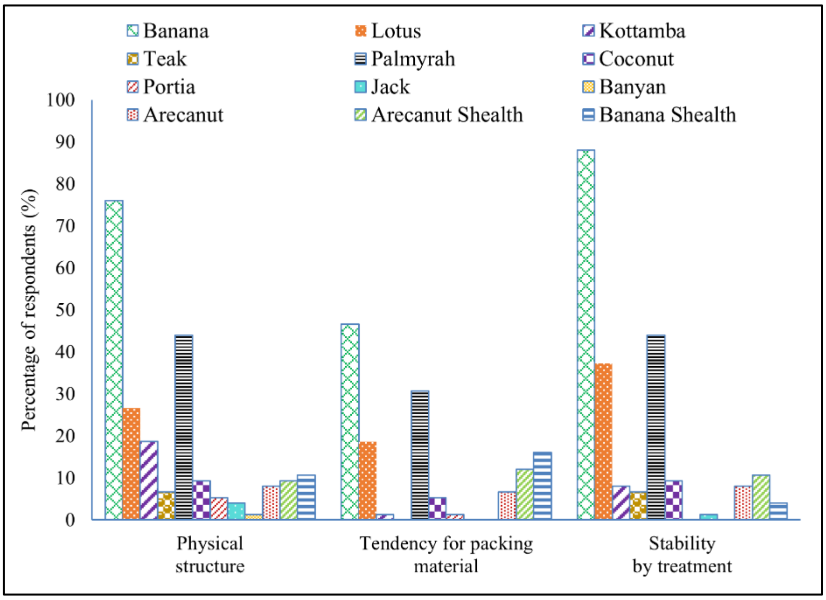

Fig 7: Survey results (%) of the selected plant materials to have physical structure, tendency for packing material and stability by treatment

3.2 **Results of physical tests performed for the twelve plant materials**

In addition to the opinions expressed by the agriculture-related personnel, it was also intended to validate the physical properties that might be taken into consideration while transforming the selected materials into food packaging and serving materials. The results obtained for the physical parameters such as surface area, thickness and LBC and also the capabilities for stability during storage and folding, of the twelve plant materials are given in Table 2. Physical testing revealed that the leaves (5078.45 ± 1150.73 cm^2) and sheath (1059.90 ± 135.21 cm^2) of banana and the sheath of arecanut (1136.25 ± 35.99 cm^2) had a significantly ($p<0.05$) higher surface area than that of others. Similarly, the sheath of banana and arecanut and the leaves of palmyrah and coconut had significantly ($P<0.05$) higher values for thickness and load-bearing capacities before and after the blanching treatment.

Load-bearing capacities of the sheath of banana and arecanut and the leaves of palmyrah and coconut before and after the blanching treatment were significantly different ($P< 0.05$) when compared to other selected plant materials. The load-bearing capacity of palmyrah leaves and banana sheath was significantly reduced compared to that of the untreated due to blanching.

Storage life of the materials where the time period taken for the material to have a deformation in the physical configuration was also assessed. Leaves of palmyrah and coconut and the withered sheaths of banana and arecanut had relatively higher storage life. Further, the leaves of lotus, tropical almond (kottamba), teak, banyan, arecanut and leaves and sheath of banana had a higher folding ability, where they had higher flexibility in folding with minimal damage to the plant material.

Table 2: Physical properties of twelve selected plant materials (post-survey laboratory testing).

Plant material	Surface area (cm^2)	Thickness (mm)	Load-bearing capacity-Fresh (N)	Load-bearing capacity-Treated (N)	Storage Life (Days)	Folding ability (%)
Banana leaf	5078.45 ± 1150.73^{a}	$0.268 \pm 0.056^{c,d,e}$	1.48 ± 0.11^{d}	1.88 ± 0.18^{e}	2	50
Lotus leaf	$742.20 \pm 108.05^{b,c}$	$0.279 \pm 0.035^{c,d}$	0.88 ± 0.11^{d}	1.00 ± 0.14^{e}	0.5	75
Tropical almond leaf	308.39 ± 22.14^{c}	$0.229 \pm 0.023^{d,e,f}$	1.64 ± 0.09^{d}	1.76 ± 0.09^{e}	2	100
Teak leaf	$685.89 \pm 167.50^{b,c}$	$0.180 \pm 0.012^{d,e}$	1.44 ± 0.09^{d}	1.92 ± 0.11^{e}	1	75
Palmyrah leaf	$426.56 \pm 25.32^{b,c}$	0.353 ± 0.032^{c}	30.90 ± 1.19^{b}	23.00 ± 1.47^{c}	180	25
Coconut leaf	$719.56 \pm 13.94^{b,c}$	$0.328 \pm 0.031^{c,f}$	17.70 ± 3.90^{c}	35.00 ± 3.54^{d}	90	25
Portia leaf	139.13 ± 14.86^{c}	0.158 ± 0.010^{e}	1.80 ± 0.00^{d}	2.36 ± 0.22^{e}	2	25
Jack leaf	125.37 ± 16.21^{c}	0.361 ± 0.075^{c}	$2.76. \pm 0.09^{d}$	$2.44. \pm 0.09^{e}$	1	0
Banyan leaf	166.71 ± 18.11^{c}	$0.276 \pm 0.025^{c,d}$	3.08 ± 0.11^{d}	3.28 ± 0.11^{e}	3	50
Arecanut leaf	275.23 ± 38.39^{c}	$0.216 \pm 0.025^{d,e,f}$	4.00 ± 0.00^{d}	3.36 ± 0.22^{e}	2	100
Arecanut Sheath	1136.25 ± 35.99^{b}	2.622 ± 1.286^{a}	53.00 ± 2.09^{a}	75.00 ± 4.43^{a}	180	0
Banana Sheath	1059.90 ± 135.21^{b}	0.734 ± 0.121^{b}	46.00 ± 4.64^{a}	25.00 ± 5.00^{b}	180	75

*Results are presented as means of taken number of measurements ± Standard Deviation. Means in the same columns that do not share the same letters are significantly different at ($P<0.05$)

3.2 Screening of plant materials and selection of the best two plant materials

Table 3: Ranking of plant materials based on the results of survey and physical lab tests.

Plant material	Ranking based on the questionnaire survey	Ranking based on the physical tests in the laboratory	Overall ranking
Banana leaf	1	5	**1**
Lotus leaf	3	12	7
Tropical almond leaf	4	8	6
teak leaf	10	9	10
Palmyrah leaf	2	4	**1**
Coconut leaf	7	3	5
Portia leaf	8	10	9
Jack leaf	11	11	12
Banyan leaf	12	7	10
Arecanut leaf	9	6	7
Arecanut Sheath	5	1	**1**
Banana Sheath	6	2	4

Twelve selected materials corroborated by the respondents of the survey were given two types of ranking as shown in Table 3, one based on the prioritization given considering the percentage of respondents who believed that a specific material has the selected feasible qualities for making packing material. The other ranking was obtained by applying the prioritization matrix technique for the results recorded for the physical parameters tested in the laboratory.

The ranking of plant materials based on the questionnaire survey revealed banana leaf and palmyrah leaf as the two best plant materials with properties suitable for food packaging. However, the ranking of plant materials based on physical parameters indicated that the arecanut sheath and banana sheath were the first two best plant materials. Finally, based on the overall ranking, which considered both surveys rankings, the banana leaf, palmyrah leaf and arecanut sheath were the best three materials suitable for food packing and serving.

3.3 Physicochemical properties of the best selected leaves at different maturity stages

The comparison of the physical properties, such as thickness, hardness, load bearing capacity and tear resistance and the chemical properties, such as moisture content, ash content, crude fibre content and crude fat content at three different maturity stages of banana leaf and palmyrah leaf are given in Table 4 and 5, respectively.

The mature stage of the banana leaf had significantly (P<0.05) higher thickness (0.266 ± 0.056 mm) compared to the tender stage (0.218 ± 0.020 mm), however it was not significantly (p<0.05) different from the stage of senescence (Table 4). Further, the hardness at the tender stage of the banana leaf was significantly (p<0.05) lower (16 ± 2) than that of the senescence stage (20 ± 2). However, the banana leaves in the mature stage had significantly (P<0.05) higher LBC (1.88 ± 0.08 N) and TR (1.90 ± 0.09 N) compared to the other two maturity stages.

Table 4: Physicochemical properties of banana leaves at different maturity stages.

Physico-chemical Properties	Banana leaf - Tender stage	Banana leaf - Mature stage	Banana leaf - Stage of senescence
Thickness(mm)	0.218 ± 0.020^{a}	0.266 ± 0.056^{b}	0.281 ± 0.032^{b}
Hardness	16 ± 2^{a}	$18 \pm 4^{a, b}$	20 ± 2^{b}
Load bearing capacity (N)	1.48 ± 0.11^{a}	1.88 ± 0.08^{b}	1.46 ± 0.09^{a}
Tear resistance (N)	1.45 ± 0.12^{a}	1.90 ± 0.09^{b}	1.16 ± 0.10^{c}
Moisture Content (%)	78.95 ± 0.24^{a}	74.99 ± 0.20^{b}	82.13 ± 0.46^{c}
Ash Content (%)	4.32 ± 0.10^{a}	6.59 ± 0.10^{b}	6.63 ± 0.57^{b}
Crude fibre Content (%)	26.31 ± 1.21^{a}	30.38 ± 1.02^{b}	28.97 ± 1.69^{b}
Crude fat Content (%)	8.53 ± 0.05^{a}	8.41 ± 0.10^{a}	8.08 ± 0.17^{b}

*Results are presented as means of taken number of measurements ± Standard Deviation. Means in the same rows that do not share the same letters are significantly different at (P<0.05).

The values of chemical tests done for the banana leaf indicated that the mature stage of the banana leaf consisted of a significantly ($p < 0.05$) lower amount of moisture (74.99 ± 0.20) and a significantly higher amount of crude fiber (30.38 ± 1.02 db), compared to the other two maturity stages. Further, this amount of crude fibre obtained for mature banana leaves was also higher than the value (29.35 ± 2.5 db) obtained in a study for an unconventional feed from banana leaves (Selim *et al*. (2022). Further, the mature stage of the banana leaf consists of significantly ($p<0.05$) higher ash content (6.59 ± 0.10 db) compared to the tender stage (4.32 ± 0.10 db) and crude fat (8.41 ± 0.10 db), compared to the stage of senescence (8.08 ± 0.17 db). The value for ash is in line with the value (6.6 ± 0.61) obtained by Bari and Islam for banana leaves (Bari and Islam 2014) and the value for crude fat was similar to the value (8.43 ± 0.19) obtained for Ether Extract of unconventional feed from banana leaves (Selim *et al*. 2022).

For palmyrah leaves, the results of physical tests (Table 5) revealed that the tender stage of palmyrah leaf has a significantly lower thickness value (0.330 ± 0.031 mm) than the other two maturity stages. Further, the senescence stage has a significantly higher hardness value (61± 3) than the mature stage (58 ± 3), which is not significantly different from tender palmyrah leaf (60 ± 2). However, the palmyrah leaves in the tender stage have a significantly higher load-bearing capacity (30.9 ± 1.19 N) and tear resistance (4.36 ± 0.21 N) compared to the other two maturity stages.

Table 5: Physicochemical properties of palmyrah leaves at different maturity stages.

Physico-chemical Properties	Palmyrah leaf – Tender stage	Palmyrah leaf – Mature stage	Palmyrah leaf – Stage of Senescence
Thickness (mm)	0.330 ± 0.031^{a}	0.389 ± 0.053^{b}	0.419 ± 0.049^{b}
Hardness	$60 \pm 2^{a, b}$	58 ± 3^{a}	61 ± 3^{b}
Load bearing capacity (N)	30.90 ± 1.19^{a}	26.50 ± 1.27^{b}	20.20 ± 1.52^{c}
Tear resistance (N)	4.36 ± 0.21^{a}	3.97 ± 0.21^{b}	3.93 ± 0.15^{b}
Moisture Content (%)	62.15 ± 0.89^{a}	46.25 ± 0.07^{b}	35.88 ± 2.24^{c}
Ash Content (%)	5.96 ± 0.52^{a}	9.31 ± 0.41^{b}	9.40 ± 0.21^{b}
Crude fibre Content (%)	46.06 ± 1.11^{a}	42.39 ± 0.26^{b}	46.22 ± 1.48^{a}
Crude fat Content (%)	4.48 ± 0.12^{a}	$4.36 \pm 0.04^{a,b}$	4.26 ± 0.06^{b}

*Results are presented as means of number of measurements ± Standard Deviation. Means in the same rows that do not share the same letters are significantly different at ($P<0.05$)

The values of chemical tests done for the palmyrah leaf (Table 5), indicate a significant difference in the moisture content of three selected maturity stages, where the moisture content of palmyrah leaf decreases with the increase of maturity. This is in line with the pattern of the dry matter content of palmyrah leaves at different growth stages as reported by Sarmini and Premaratne (2018), where the dry matter content of leaves increases with maturity. Further, the tender stage of palmyrah leaf consists of a significantly higher amount of crude fibre on dry basis (46.06 ± 1.11) than the mature stage (42.39 ± 0.26) which is not significantly different from the stage of senescence (46.22 ± 1.48) and it consisted a significantly lower amount of ash (5.96 ± 0.52) on dry basis, compared to the other two maturity stages. Similarly, the tender stage of palmyrah leaf consists of a significantly higher amount of crude fat on dry basis (4.48 ± 0.12) than the other two maturity stages.

4. Discussion

Food packaging materials fulfill the aim of protecting food products during storage by retarding the migration of moisture and gases, prohibiting the migration of odors and colorants, and improving the shelf life of packed food (Bahrami *et al*. 2020). The utilization of various plant parts for packing and serving food was an age-old practice observed among various communities. Previous research reports that not all leaves are suitable for wrapping food, but the species that are being used have been tested and proven by long usage that those leaves do not contain any toxins, dyes, or irritants (Ng 2015, Osman *et al*. 2018, Kora 2019, Kalina *et al*. 2024a).

In the present study, the plant materials, such as lotus, tropical almond (kottamba), teak, palmyrah, coconut, portia, jack, banyan as well as leaves and sheath of banana, and arecanut were said to be used in food packaging and they were transformed to the applicable forms with the provision of simple treatments such as flaming, hot water boiling, water-soaking, heat pressing and weaving. Studies conducted on Asian culture have revealed the potential for creating sustainable packaging materials from plants, utilizing the processing techniques such as boiling, grilling, or steaming. In certain instances, leaves are prepared for use by being pre-softened through steaming, boiling, or grilling. The boiling also effectively removes any fine bristles present on their surfaces to ensure their cleanliness (Ng 2015).

The survey also revealed that these plant materials were used in Sri Lanka for packaging foods such as cooked foods, sweets, liquid foods, fruits and meat and also to hold, pack and cook the intermediates like dough and batters in the cooking process, after the transformation. Banana leaves are widely used in Malay foods, especially cakes, which vary in the method of packaging process. Similarly, in China, the leaves of lotus, teak, and coral trees are utilized for serving and packing foods in restaurants. They also use banana leaves to serve a food item called 'ang koo' to avoid sticking it to the serving plate. In posh Chinese restaurants, a rice dish wrapped in lotus leaves is popularly known for the characteristic flavour imparted to the dish from the lotus leaves (Osman *et al*. 2018). In Africa, the coffee beans that are offered as a traditional gift are packed in small banana leaf bags. Further, palmyrah palm leaves are woven to form baskets, buckets, and boxes in which foods are transported (Aoudji *et al*. 2013, Rao *et al*. 2021). A diversified range of food is packaged with teak leaves: maize paste, bean cake, wheat paste, smoked fish, cassava cake, flat cake of groundnut, soya bean cheese, leafy vegetable, beef meat, etc. (Aoudji *et al*. 2013).

The respondents believed that the twelve selected materials had special qualities such as medicinal properties, anti-microbial properties and adding flavor to food. The beliefs of respondents were scientifically proven in many studies. The plant materials used for packaging contain many functional compounds such as vitamins, polyphenols, tannins, alkaloids, saponins, steroids, glycosides, and many others (George *et al*. 2016, Orabi and Orabi 2016). Due to the presence of these compounds, most of the plant leaves have good pharmacological and phytochemical properties such as antioxidant, anti-diabetic, antibacterial, antifungal, anticancer, anti-obesity, anti-inflammatory, antimalarial, and many more (Prasad *et al*. 2006, Bhardwaj *et al*. 2011, Muhammad and Mudi 2011, Sachan *et al*. 2014, Terças *et al*. 2017).

Banana leaves, which are most preferred as dining plates, consist of an abundance of polyphenols, which act as antioxidants and aid in the digestion of the food by incorporating their ingredients, such as vitamin C and potassium, when hot foods are served with them. The inexhaustible leaves of bananas are water and leak-proof and provide characteristic flavor and aroma while serving hot and steamed food (Mensah *et al*. 2012, Sarin 2017, Hedge *et al*. 2018). A recent study reveals that the banana leaves used for wrapping Olèlè, a steamed cowpea paste, had a significant effect on its sensory characteristics with clearly distinct sensory profiles, and it is most appreciated when compared to teak leaves (Aïssi *et al*. 2023).

The leaves of the banana were proven to contain antioxidant, anti-diabetic, aphrodisiac, antibacterial, antifungal, and anticancer properties. It also purifies blood, boosts the immune system, stimulates appetite, aids in food digestion, chlorophyll soothes the mucus lining, prevents intestinal ulcers, and protects from skin diseases, kidney stones, bladder-related diseases and heart diseases (Imam and Akter 2011, Mensah *et al*. 2012, Sarin 2017, Hedge *et al*. 2018). The leaves of palmyrah consist of antibacterial, antifungal, anti-helminthic, and antioxidant activities (Jamkhande *et al*. 2016, Vengaiah *et al*. 2017, Rao *et al*. 2021). Therefore, it will be an additional advantage even if the plant material is leached into the food item while packaging.

The present study also analyzed the physical properties of twelve selected plant materials, which decide the versatility of those materials to be used in food packaging. There are some recent research aroused the importance of studying physical and chemical properties of arecanut sheath (Shashikmar *et al*. 2016, Kumar *et al*. 2019, Acharya *et al*. 2020, Jong *et al*. 2020, Dissanayake *et al*. 2021, Mohanty *et al*. 2021), processing of banana leaves (Nongman *et al*. 2016, Jumaidin 2021, Arumugam *et al*. 2023) and studying the properties of fibres from palmyrah leaf stalks (Kumar *et al*. 2021) and banana stem (Nongman *et al*. 2016). However, in-depth studies need to be performed in order to shift them into the phase of the application in the food packaging industry

A study done by Shashikumar *et al*. (2016) mentioned that the maximum surface area of arecanut sheath was 2,300.35 cm^2 while the minimum was 806.40 cm^2 with a mean value of 1,487.95 cm^2 at 9 -14.5% of moisture content which had a wider range than present study. It is also revealed that the thickness was 3.92 ± 1.03 mm which included range obtained in the present study. However, there was a limited amount of literature available on the physical properties of other materials subjected to this study.

Further, the current study also analyzed how load bearing capacity (LBC) changes upon blanching treatment. Blanching treatment imposes an acceptability condition in leaves with retention of constituents and fresh-like (primeval) quality and also impose the destruction of microorganisms present on the surfaces of plant materials (Kumar and Sandeep 2014, Meher *et al*. 2017). But an important factor for plant leaves to be used in food packaging is flexibility, which allows them to be folded without breaking, and strong water-proofing and leak-proofing quality (Ng 2015). A study done in Sri Lanka had developed bio wrappers from banana leaves by curing with boiled water

(Weerasinghe *et al*. 2007). It was observed during the study that when the materials are less amenable, they tend to break due to poor flexibility. The blanching treatment has resulted in water absorption by plant fibers and making them more amenable in nature. However, the LBC of palmyrah leaves and banana sheath was significantly reduced than that of the untreated due to blanching. This may be due to the texture changes and softening of fibres through hot water absorption during boiling (Meher *et al*. 2017). Further, the materials may need further processing steps like drying to reinforce the LBC.

Based on the survey and preliminary physical testing results, the best materials ranked first were the leaves of banana and palmyrah and the sheath of arecanut. The possibilities of the plant materials such as banana leaf and arecanut sheath to be used in packaging material development were proved by the studies of Jeenusha and Amritkumar (2020), and Dissanayake *et al*. (2021), respectively. However, the best two leaves that are more abundantly available in the Jaffna peninsula: banana leaf and palmyrah leaf were chosen and analyzed for physico-chemical properties at different maturity stages.

In case of banana leaves, there are very few studies done in evaluating their physical and chemical properties which were tested in the current study. Hence, the findings in the present study would bring about new criteria for characterizing plant materials for food packaging material development. It was revealed that, among the three selected maturity stages of banana leaves, the mature stage had significantly higher crude fibre content, LBC and TR than the other two stages. However, when the crude fibre content of palmyrah leaves in current study was considered, even though the percentage on a dry basis is different from that was reported (49.3%) by previous researchers (Sarmini and Premaratne 2018), the statement made by Oelberg (1956) where the amount of fibre increases with the maturity of leaves may be true. Another study indicated that, as the leaves of amaranth, basella, hibiscus, rumex, and spinach matured from tender to mature and to coarse stage, the Total Dietary fibre (TDF) and Insoluble Dietary Fibre (IDF) contents increased significantly ($P<0.05$) (Punna and Paruchuri 2004). Further, the Soluble Dietary Fiber (SDF) content significantly ($P<0.05$) increased from tender to mature stage in all selected leaves of the above study and however, there was no further increase of SDF from mature to coarse stage except in Rumex. The fact behind this may be that the amount of fiber may be increasing, and at the same time, other dry matters such as chlorophyll, polyphenols, and other chemical compounds are also increasing reciprocally with maturity (ŠEsták and Václavík 1965). Crude fiber includes insoluble fibres, mainly cellulose and lignin. During the stage of maturity, the increase of insoluble fibre may be less compared to the soluble fibre and also compared to other chemical compounds that are increasing with maturity in palmyrah leaves.

When considering the ash content of palmyrah leaves, it is increasing with the stage of maturity as stated by Sarmini and Premaratne (2018). Further, Oelberg found that Calcium is the major element of cellular material in leaves (Oelberg 1956), and the study done by Cook and Harris (1950) revealed that Calcium content availability in all plant parts. Hence, the mineral content of leaves may be increasing due to the formation of new compounds with maturity.

When selecting the best plant materials, the physical/mechanical properties, and the factors affecting the mechanical strength of the plant materials, were prioritized. Hence, when selecting the suitable maturity stages of the two leaves, the properties such as hardness, LBC, TR and crude fibre content were taken into consideration. It was revealed that, among the three selected maturity stages of leaves, the mature stage of the banana leaf and the tender stage of the palmyrah leaf had significantly ($p<0.05$) higher crude fibre content, load-bearing capacity and tear resistance compared to the other two stages. Further, the hardness values are also significantly higher than at least one of the other two stages selected in this study. Hence, mature banana leaves and tender palmyrah leaves have more potential to be transformed into packaging materials.

As an advancement in the practice of using plant materials, scientists have developed sheets and plates from leaves. In Sri Lanka, researchers have developed plates from banana leaves which cured by dipping in boiled water and then the plates were made using simple processing steps (Weerasinghe *et al*. 2008). Further, there are some recent researches revealed the possibilities of developing food wrapping and serving materials from the leaves of banana (Mensah *et al*. 2012, Sarin 2017, Hedge *et al*. 2018, Jeenusha and Amritkumar 2020, Arumugam *et al*. 2023), Lotus (Choe *et al*. 2011) and the leaf sheath of arecanut (Kalita *et al*. 2008, Shashikmar *et al*. 2016, Kumar *et al*. 2019, Acharya *et al*. 2020, Jong *et al*. 2020, Dissanayake *et al*. 2021, Mohanty *et al*. 2021). Those studies have examined the properties of these plant materials in terms of mechanical strength after transforming them into sustainable packaging materials such as films, sheets, papers, and plates.

Biofilm made out of the starch of mature banana peels had tensile strength values in the range of 4.18 MPa (Ramadhany *et al*. 2021). Further, bioplastic films were developed using starch from jackfruit waste and sago mixed with lemon extract, water, polylactic acid and crude palm oil, which showed the best tensile strength of 5.24 MPa (Krishnamurthy and Amritkumar 2019). The composites made by laminating “banana stem particle boards” with banana leaf tapes treated with glycerin had a maximum tensile strength of 2.2 MPa (Nongman *et al*. 2015). These values were comparatively greater than the LBC value of mature banana leaves, which was 1.25 MPa and less than the LBC values of tender palmyrah leaves which were nearly 18.75 MPa. However, these values could be improved for the plant materials by applying simple chemical treatments (Kalina *et al*. 2024b).

Previous research conducted by various researchers disclosed that the tensile values of biodegradable trays made from cassava starch and corn husk had tensile strengths within the range of 0.012 to 0.024 MPa (Aguirre 2023), and an opaque film made out of starches of cassava and corn had 0.07 MPa to 0.28 MPa (Akmeemana *et al*. 2024). The tensile strengths obtained for potato and yam starch-based bioplastic were 0.6 MPa and 1.9 MPa, respectively (Ismail *et al*. 2016). This proved that the selected leaves of the present study had better tensile strength or LBC than previously developed films. On the other hand, the tensile strength of synthetic polypropylene was 3.8 MPa (Chiellini 2008), which is less compared to that of palmyrah leaves. This is due to the presence of a greater amount of fibres in the banana leaf and palmyrah leaf as proved in the present study. The Load-bearing capacity of materials is mainly depending on the strength of fibres present in the plant material (Yan *et al*. 2014, Jia *et al*. 2023).

Further, the selected stages of banana leaf and palmyrah leaf selected in the present study had a tear resistance of nearly 2 N and 4.5 N, respectively. The packaging sheets formed from cassava leaves treated with a mild concentration of NaOH (15%) solution had a tear index value of 784.7 $mN \cdot m^2/g$ (Sharif *et al*. 2015), which is less compared to the selected plant leaves of the current study. However, the tear strength of fabric tents ranges between 200N and 250N (Eltahan 2018), which was higher when compared to the selected plant materials.

Furthermore, food packaging and serving materials derived from foliage possess numerous advantageous properties, such as imperviousness to leakage and water, absence of malodorous substances, biodegradability, and safety for employment in cold storage, microwaves, and ovens. In addition, these materials are versatile, being able to accommodate both wet and dry comestibles, serving as disposable containers for the former and reusable receptacles for the latter (Shashikumar *et al*. 2016, Kora 2019). Moreover, some Indian companies (Imarc Group) and start-up industries are currently manufacturing single-use food serving materials from banana leaves, palm leaves, and sheaths. They offer a viable alternative to polystyrene items, which are widely applied in food services. These plant-based materials possess the attributes of durability, heat resistance, and safety for freezers and microwaves, as well as the ease of accommodating hot, cold, heavy, and messy foods (Kalina *et al.* 2024a).

However, there are certain constraints in developing plant-based food packaging materials. The versatility, mechanical properties and functional properties of synthetic packaging materials are still better than the plant-based packaging materials produced so far, thus limiting their industrial applications (Da-Rocha *et al*. 2018). Employing plant-based materials in packaging still presents a barrier for liquid foods, and their sealing properties have limitations. The hydrophilic nature of developed films results in greater permeability to water compared to synthetic films, and these also generally demonstrate weaker and less flexible structures (Wang *et al*. 2015, Das and Chowdury 2016, Jong *et al*. 2020, Khodaei *et al*. 2021).

The mechanical properties, barrier characterization, colour and optical properties, water solubility, biodegradability, and sealing properties are the principal aspects that constitute the main criteria for packaging polymers in industrial production. Plant-derived packaging materials must satisfy the food packaging requirements that are applicable to conventional synthetic packaging materials. These plant-derived packaging materials must remain unaltered and operate in a safe and efficient manner until the point of disposal (Krochta 2002).

Hence, the present study which was done as a preliminary investigation on the suitable plant materials and their maturity stages to be applied in food packing and serving, will pave way for the advanced future researches on developing plant-based, biodegradable and at the same time sustainable food packing and serving materials, to be used as effective and efficient alternative for synthetic single-use plastic, which immensely cause plastic pollution.

5. Conclusions

The present study has undertaken the preliminary step of identifying suitable plant materials and their maturity stages to be used in the development of more sustainable food packaging material. Based on the results, the leaves of banana and palmyrah were selected as the best two materials among the twelve selected materials to be used in food packaging material development. Further, the sheath of arecanut also has the best qualities to be used as a source for a similar purpose. Moreover, based on the mechanical properties such as load-bearing capacity and tear strength, the mature stage of the banana leaf and the tender stage of the palmyrah leaf were suitable for developing the packaging material. Further studies are underway to confirm the above findings.

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