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Leaf Size and Shape Interact to Control Flammability: An Experiment With Artificial Leaves Cut From the Large-Leaved Species *Sapranthus palanga*

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ABSTRACT

We evaluated the flammability of leaves based on their shape and size using a single species. Rectangular and triangular shapes showed high flammability that did not vary with size, while circular shapes had minimal flammability, but this varied with size. These findings indicate that leaf shape and size impact flammability.

RESUMEN

Evaluamos la inflamabilidad de las hojas en función de su forma y tamaño. Las formas rectangulares y triangulares mostraron una alta inflamabilidad que no variaba con el tamaño, mientras que las formas circulares tuvieron una inflamabilidad mínima, pero que variaba con el tamaño. Estos hallazgos indican que la forma y el tamaño de las hojas impactan en su inflamabilidad.

1 | Introduction

Climate change is affecting disturbance regimes worldwide, including increasing the occurrence, frequency, and/or severity of fires in tropical ecosystems (Senande-Rivera et al. 2022; Cochrane 2003; Turner and Seidl 2023). This underscores the need to understand fire processes such as flammability in environments that are not typically considered fire-prone.

Flammability refers to the capacity of plant materials to ignite and sustain combustion (Anderson 1970; Pausas et al. 2017). It is typically broken down into components such as ignitability and sustainability, which are defined as the time that the flame is maintained with or without a heat source; this is closely related to the transfer of heat and flames to the plants or structures that surround the plant fuel (Behm et al. 2004), and the burn rate of the material (combustibility) which is the speed with which the fire advances on the fuel material (Anderson 1970; White and Zipperer 2010). Ignitability (ignition) is the time it takes for a material to catch fire under a heat source (Behm et al. 2004) and is strongly influenced by the thermal degradation process, which involves sequential phases such as drying (evaporation of water), pyrolysis (thermal decomposition of organic matter), ignition, and combustion (de Magalhaes and Schwilk 2012). Each phase is influenced by chemical composition (e.g., volatile compounds, lignin, moisture) and physical structure (e.g., thickness, surface area) of the leaf.

In addition to branches and wood, leaves are the most abundant potential fuel materials and generally catch fire more easily

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(Hachmi et al. 2011). Morphological traits such as leaf surface area, thickness, presence of volatile organic compounds, lignin content, moisture content, dry matter content, and shape may influence heat transfer, drying rates, and flame propagation (Cornelissen et al. 2003; Doran et al. 2004; Perez-Harguindeguy et al. 2013). For example, narrow, elongated leaves dry faster and present a larger surface-to-volume ratio, which may increase their propensity to ignite and sustain combustion (Schwilk and Caprio 2011; Jolly et al. 2012). In the study of Alzate-Guarín et al. (2022), larger leaves exhibited greater flammability, which was correlated with the area/volume ratio of the leaves. The leaves with the largest values of this ratio had lower flammability (Alzate-Guarín et al. 2022). Conversely, broad, larger, thick, or succulent leaves generally maintain a high moisture content, even in drought, and take longer to catch fire; therefore, they have low flammability (Cornelissen et al. 2003; Doran et al. 2004).

Despite these insights, the specific role of leaf size and shape in determining flammability remains poorly understood. The difficulty lies in the fact that these traits often covary with species-specific biochemical properties, such as volatile content and lignin concentration, which complicate efforts to isolate the effects of morphology alone (Van Altena et al. 2012; Perez-Harguindeguy et al. 2013).

In this study, we aimed to isolate and test the influence of leaf size and shape on flammability using standardized "experimental leaves" created from a single species with large leaves (*Sapranthus palanga* R.E.Fr.; Annonaceae). Our focus was on living leaves and not dead leaves or leaf litter, as burning leaves may directly influence other plant processes like mortality. By controlling for leaf chemistry, life stage, and venation, we were able to manipulate dimensional traits independently. We predicted that smaller or more elongated leaves with more acute apices would exhibit increased flammability, including faster ignition and faster burn rates, due to enhanced heat transfer and drying efficiency.

Leaves in nature exhibit a wide variety of shapes, including forms that approximate circles, triangles, and rectangles. These geometric characteristics may influence leaf aerodynamics, heat retention, and ventilation, which in turn could affect their resistance to ignition. As noted by Niklas (1992), leaf shape plays a significant role in thermal interactions with the environment, and more recent work suggests that shape can influence heat accumulation and airflow around leaf surfaces (Leigh et al. 2017). Although direct studies linking these simplified shapes to flammability are limited, we hypothesized that their distinct physical properties may result in differences in ignition behavior. By selecting idealized geometries (circular, rectangular, and triangular) we aimed to isolate the effect of leaf shape on flammability while controlling for other confounding factors such as venation patterns or chemical composition. This approach provides useful standardized conditions to guide future work.

2 | Methods

2.1 | Study Site

The study was carried out at the Palo Verde Biological Station (10.358 N, 85.358 W), located in Parque Nacional Palo Verde, Costa Rica, during February 2024. Vegetation consists of tropical dry forest in various stages of succession, and the area receives ~1700 mm of rainfall a year, with a strong dry season typically lasting from December to April or May (Powers et al. 2009).

2.2 | Biological Material and Experimental Design

We collected a total of 22 leaves in a similar state of development from *S. palanga*. The decision to conduct the experiment with a single species was driven by the specific aim of assessing the influence of leaf shape and size on flammability. By focusing on a species with consistent chemical composition and indumentum, we aimed to control these variables. This approach ensures that any observed differences in flammability can be confidently attributed to variations in leaf morphology. We selected this particular species due to its large leaf size (> 20 cm length), which facilitated the acquisition of diverse leaf shapes and sizes necessary for our study. *S. palanga* has simple, broadly obovate to elliptic leaves with entire margins and an obtuse to acuminate apex (World Flora Online 2024). Once the leaves were removed from the tree, they were placed inside plastic zip-top bags with a moist paper towel prior to the experiments to reduce water loss. In the laboratory, leaves were stored in the refrigerator until their use, which was on the same day of collection.

We established two treatments: one to measure the possible influence of leaf shape on flammability and another to measure the influence of size. For the first treatment, we cut experimental leaves from the larger *S. palanga* leaves with circular, rectangular, and triangular shapes. Each set of circles, rectangles, or triangular experimental leaves was cut to three standard areas for the second treatment: small (10.5 cm^2), medium (22.5 cm^2), and large (38.48 cm^2). The triangular shape had an acute apex; thus, while we standardized for area among shapes, each shape had a different edge-to-area ratio (Figure S1). Each combination of size and shape was replicated 10 times, for a total of 90 experimental leaves.

It is possible that cutting experimental leaves out of larger leaves affects their flammability because of differences in the chemical or physical properties of cut versus intact leaf edges. To rule out this possibility, prior to the flammability experiments, we performed a pilot study with 10 intact *S. palanga* leaves to compare their flammability with that of 10 leaves with trimmed margins (Table S1).

We acknowledge that natural leaves can exhibit a wide range of shapes beyond circles, rectangles, or triangles. Moreover, we did not control for differences in leaf thickness that may exist, even among leaves from the same individual. Nonetheless, using these simplified shapes can provide insights into how leaf geometric aspects may influence their flammability.

2.3 | Flammability Measurements

The device used for this experiment consisted of three candles that functioned as the heat source and a metal mesh, placed 10 cm above the tip of the candle, on which the leaf samples were placed (Figure S2). The leaf samples were placed on the mesh, right at the edge of where the flames emerged but not directly on

top of the flames, and we recorded the following response variables: time it took for the first flame to start (seconds), the time for the flame to be extinguished (seconds), and the distance that the fire reached in the sample. If the sample did not ignite after 1.5 min, it was removed from the device and recorded as time 0.

The test was conducted in a laboratory completely isolated from air currents, at a constant temperature of 27°C. The candles reached a temperature of 1053°C ± 1°C. The controlled temperature within the device space was maintained at 100.3°C, which was the maximum temperature recorded during the preliminary experiments. These temperatures were measured using an AIOMEST AI-1600 infrared thermometer.

2.4 | Data Analysis

Based on the number of positive ignitions and the ignition time, a flammability value (FV) was obtained for each of the shapes and sizes, according to the method proposed by Valette (1990; Table S2). This approach is simple, reproducible, and allows for the categorization of samples into discrete flammability classes.

We also calculated individual aspects of flammability. The flame sustainability was calculated as the difference between the flame extinction time and its ignition time in seconds. The burning rate was calculated as the ratio of the distance traveled by the fire through the sample to the sustainability time. To measure the distance that the fire reached, we used a fixed initial ignition point and recorded the maximum extent of burned material along the central axis of the sample. To compare ignition time, sustainability time, and burning rate based on leaf shape and size, we performed nonparametric Kruskal–Wallis tests because the data did not meet the assumptions of normality and homoscedasticity, as confirmed by Shapiro–Wilk and Levene's tests. Analyses were performed in R (R Core Team 2024).

3 | Results

We found that flammability did not vary between leaves with trimmed or intact margins (Table S1); thus, we feel confident that this did not affect the results from our experimental leaves.

For the rectangular and triangular shapes, flammability was maximum (5), whereas in the circular shape flammability was minimal, with an index value of 0 (Table 1). The number of samples that ignited (ignition frequency) was greater in the triangular shape (100%), followed by the rectangular shape (80%), and lastly the circular shape (30%).

Ignition time ($X^2 = 5.46$, gl = 2, $p = 0.06$) showed marginally significant differences between the circle and triangle shapes (Figure 1a). When comparing flame sustainability time ($X^2 = 13.95$, gl = 2, $p = 0.009$) and burning rate ($X^2 = 9.74$, gl = 2, $p = 0.007$) we found that there were differences only between the circle and the triangle shapes (Figure 1b,c). The greatest values for ignition, sustainability, and burning rate were found in triangular-shape leaves.

When evaluating the flammability of shapes by size, we found that rectangular and triangular shapes maintained their flammability category (extremely flammable), but in circular shapes, these values differed by size: the flammability value was greater for the smaller samples and lower for the medium-sized samples (Table 1).

TABLE 1 | Flammability measurements for each of the evaluated sizes and shapes of experimentally manipulated *Sapranthus palanga* leaves. Ignition frequency (IF)—indicating how often samples caught fire, in percentage; ignition time (IT)—the time required to generate a flame (the mean in seconds); sustainability time (ST)—the time the flame remained after ignition (the mean in seconds); burning rate (BR)—the speed at which the flame moved along the material (the mean in mm s^{-1}); flammability values (FV)—an integrated flammability index; and the category obtained according to Valette (1990) are shown. Standard deviation values are presented in parentheses. Different letters indicate differences between shapes (Kruskal–Wallis test).

Shape	IF (%)	IT (s)	ST (s)	BR (mm s^{-1})	FV	Category
Circle						
Small	70	10.6 (±8.8)[a]	28.2 (±17.9)[b]	0.44 (±0.26)[b]	2	Moderately flammable
Medium	10	28.2[b]	16.48[a]	0.42[a]	0	Not very flammable
Large	30	15.3 (±16.4)[a]	22.3 (±5.7)[b]	0.5 (±0.33)[b]	1	Slightly flammable
Rectangular						
Small	100	5.92 (±2.4)[a]	21.4 (±9.18)[a]	1.3 (±0.88)[a]	5	Extremely flammable
Medium	100	5.47 (±4.5)[a]	28.1 (±13.4)[a]	0.83 (±0.36)[a]	5	Extremely flammable
Large	80	5.5 (±1.92)[a]	25.9 (±11.9)[a]	0.85 (±0.41)[a]	5	Extremely flammable
Triangular						
Small	100	0.5 (±0.3)[a]	17.4 (±7.9)[a]	0.98 (±0.42)[a]	5	Extremely flammable
Medium	100	3.4 (±1.7)[b]	18.5 (±10)[a]	1.15 (±0.89)[a]	5	Extremely flammable
Large	100	5.3 (±3.8)[b]	49.1 (±27.7)[b]	2.2 (±0.79)[b]	5	Extremely flammable

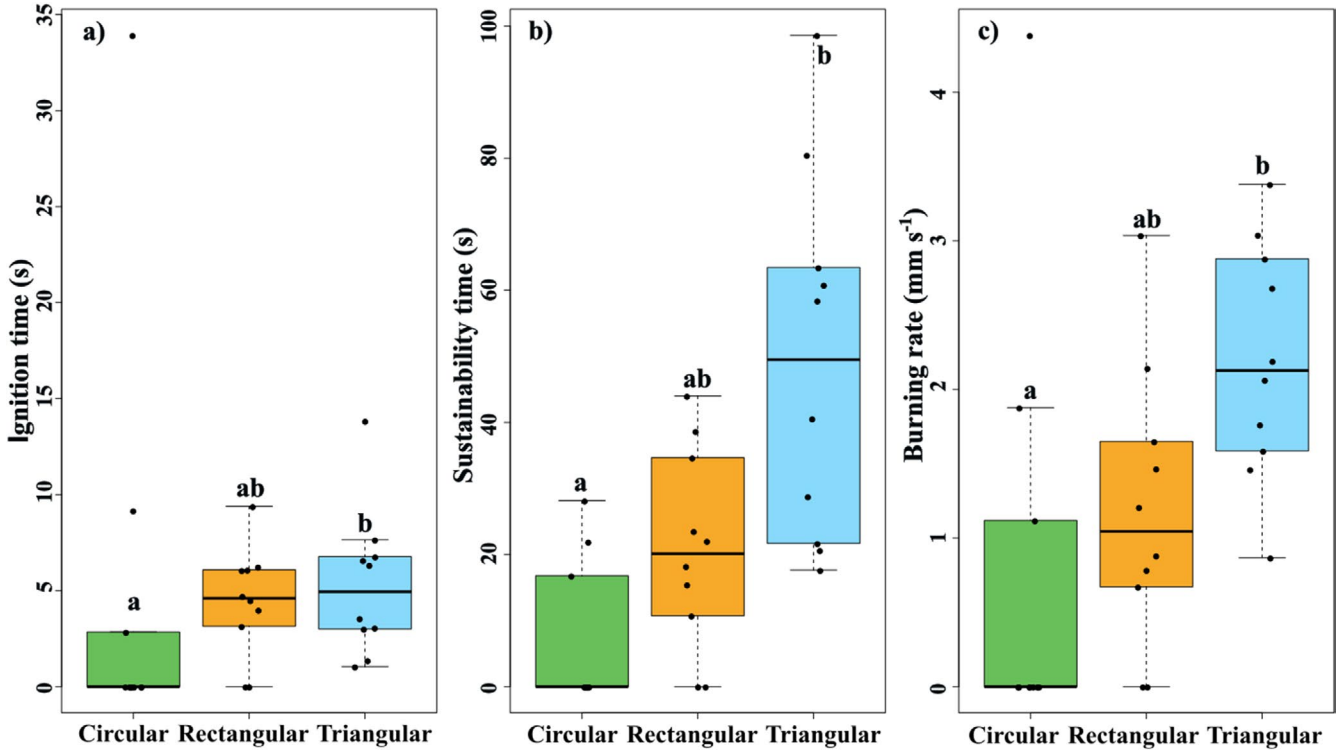


FIGURE 1 | Flammability variables estimated by shape of experimentally manipulated *Sapranthus palanga* leaves. (a) Ignition time in seconds, (b) flame sustainability time in seconds, and (c) burning rate ($mm\,s^{-1}$). Different letters above the boxes indicate differences between shapes (Kruskal–Wallis tests). Boxes represent the interquartile range (25th to 75th percentiles), and whiskers indicate the minimum and maximum values within 1.5 times the interquartile range, The bold lines within the boxes represent the median of the data. The black dots along the boxes represent each data point for each shape ($N = 30$).

Flammability metrics differed among size classes for the three shapes. When comparing ignition times ($X^2 = 6.35$, gl = 2, $p = 0.04$), flame sustainability time ($X^2 = 7.68$, gl = 2, $p = 0.02$), and burning rate ($X^2 = 6.97$, gl = 2, $p = 0.03$) for the circular shape, we found that there were no differences between the small and the large samples, but there were differences between these for the medium-sized samples. Surprisingly, the medium-sized circles had the lowest values for flammability compared to large or small circles (Table 1). Ignition times ($X^2 = 1.89$, gl = 2, $p = 0.38$), flame sustainability time ($X^2 = 1.74$, gl = 2, $p = 0.41$), and burning rate ($X^2 = 3.16$, gl = 2, $p = 0.2$) for the rectangular shape showed no differences related to size (Table 1). For the triangular shapes, ignition times were less for the smallest samples than for the medium and large samples, where values were similar ($X^2 = 19.79$, gl = 2, $p < 0.001$). For flame sustainability times ($X^2 = 11.18$, gl = 2, $p = 0.003$) and burning rate ($X^2 = 10.39$, gl = 2, $p = 0.005$), the small- and medium-sized samples showed similarity between them but different from the large samples (Table 1).

4 | Discussion

The aim of this study was to determine whether morphological characteristics, specifically shape and size, influenced flammability, using the live leaves of *S. palanga* as a model. We found greater flammability in rectangular and triangular shapes, which have apices that could serve as more accessible ignition points for fire. As for the round shapes without an apex, a large percentage of these did not ignite; they only curled up on themselves due to moisture loss from their proximity to the heat of the fire. Although, to our knowledge, no prior experimental studies have directly tested the effect of live leaf shape on flammability in tropical species, several authors have suggested that morphological traits such as reduced surface area, elongation, and thinner profiles are associated with greater flammability (Cornelissen et al. 2003; Doran et al. 2004; Schwilk and Caprio 2011; Jolly et al. 2012; Zylstra 2014). Our data thus provide one of the first experimental tests of this idea, without confounding leaf chemistry with shape or size.

In our study, rectangular and triangular samples displayed maximum flammability regardless of size. However, when separately analyzing ignition times, sustainability, and burning rate, only the triangular shapes align with findings from Alzate-Guarín et al. (2022), who found that larger surface-area-to-volume ratios were associated with increased flammability. For rectangular samples, there were no differences in any of these components of flammability regulated by size. This suggests that size alone may not influence flammability in all geometric configurations. In circular samples, intermediate-sized leaves showed the lowest ignition frequencies, whereas small and large sizes displayed low to moderate flammability, albeit without a clear pattern. Although leaf thickness was not measured, we used mature, healthy leaves from a single *S. palanga* individual with uniform texture. This minimized variation and allowed us to isolate the effects of shape and size on flammability.

These findings support the hypothesis that morphological traits can significantly influence leaf flammability (Pausas et al. 2017). Specifically, leaves with apiculate shapes or smaller dimensions may facilitate ignition and fire spread. Understanding these traits is essential in the context of changing fire regimes, especially in tropical forests historically unaccustomed to frequent fires (Cochrane 2003; Bowman et al. 2009; Pausas and Keeley 2009). Assessing plant flammability through morphological, anatomical, and chemical traits allows better estimation of fire risk in vegetated landscapes (Alzate-Guarín et al. 2022).

Moreover, although our study used a limited sample size and controlled conditions, it serves as valuable proof of concept. The method is simple, low-cost, and easily replicable in the field, allowing for its application across more species and contexts. By facilitating the standardized collection of flammability data, this approach could help refine predictive fire models, particularly in tropical ecosystems, where such information is currently lacking.

In conclusion, leaf morphology (particularly shape and size) does influence flammability, at least in *S. palanga*. This study offers one of the first experimental approaches to isolate these variables in tropical live leaves, minimizing confounding effects from leaf chemistry. The simple methodology we propose can help generate comparative flammability data for broader sets of species, particularly in fire-prone or fire-expanding ecosystems.

Author Contributions

Conceptualization: E.R.-G. Data curation: E.R.-G. and J.S.P. Formal analysis: E.R.-G. Investigation: E.R.-G. and J.S.P. Methodology: E.R.-G. and J.S.P. Project administration: E.R.-G. Resources: E.R.-G. and J.S.P. Validation: E.R.-G. and J.S.P. Visualization: E.R.-G. Writing – original draft: E.R.-G. Writing – review and editing: E.R.-G. and J.S.P.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are openly available in the Dryad Digital Repository: https://doi.org/10.5061/dryad.djh9w0wch.

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Supporting Information

Additional supporting information can be found online in the Supporting Information section. **Figure S1:** Leaf shapes: (a) *Sapranthus palanga* leaves with trimmed margins and normal margins; (b) leaves with the same area but different shapes; (c) leaves of different sizes by shape. **Figure S2:** Rustic device for measuring flammability. **Table S1:** Tests for effects of cutting leaf margins on flammability. The comparison between the two conditions was performed using the Wilcoxon rank sum test ($W = 50.5$, $p = 1$), because the data did not exhibit normality and 9 out of 10 data points (per condition) had a value of 0. **Table S2:** Flammability values according to Valette (1990). 0 = not very flammable, 1 = slightly flammable, 2 = moderately flammable, 3 = flammable, 4 = highly flammable, 5 = extremely flammable, IF = ignition frequency, IT = ignition time.