Experimental Study on the Flammability and Burning Behaviour of Live and Dead *Eucalyptus Saligna* Foliage

Ramadhan M.L.*, Zarate-Orrego S.A., Carrascal J., Osorio A.F., Hidalgo J.P.

[1] *School of Civil Engineering, The University of Queensland, St Lucia, QLD, Australia*
**Corresponding author's email: m.ramadhan@uq.edu.au*

ABSTRACT

Wildland fires are frequent catastrophic events that lead to the loss of life and economic devastation. Wildfires can involve dead and live fuels; however, only limited research has studied the combustion characteristics of those fuel conditions. This paper studies the burning behaviour of live and dead *Eucalyptus saligna* leaves using the Mass Loss Calorimeter. Tests were carried out using different indicent radiant heat flux and wide range of fuel moisture content (4-120% on dry weight for live leaves and 3-14% on dry weight for dead leaves). This study includes the proximate analysis and thermogravimetric analysis to observe the impact of chemical composition. Flammability parameters (i.e. ignition delay time, time to peak mass loss rate, burnout time, peak mass loss rate, and residual mass fraction) were analysed to identify the differences between live and dead leaves. The results show that ignition delay time of dead leaves are eight times faster than live leaves, thus the regression model derived from dead leaves cannot be used well to predict the ignition delay time of live leaves, and vice versa. From all parameters, it is concluded that live and dead leaves will not behave the same in fire condition; dead leaves are shown to be more flammable than live leaves, even though the leaves are in the same oven-dried condition. This confirms that the live fuels can no longer be assumed as wet dead fuels, and should be considered explicitly in assessing wildland fire risk.

KEYWORDS: Eucalyptus saligna, flammability, ignition, wildland fires.

INTRODUCTION

Wildland fires are the largest natural disaster in Australia that lead to the loss of life and economic devastation. However, there is still a lack of knowledge regarding the key factors that affect the flammability and burning behaviour of vegetation. Due to the climatological and seasonal conditions, as well as human interaction, water cycle plays a critical role in defining the vegetation, and eventually the intrinsic wildland fire risk. Previous research in the field of fire safety engineering has demonstrated a strong influence of moisture content on the flammability of solid fuels. In wildland fires, the fuel flammability term refers to the capability of a certain fuel to ignite and sustain fire. According to Anderson [1], the flammability can be characterised into four criteria, namely ignitability, combustibility, consumability, and sustainability. Therefore, the understanding of all parameters affecting the flammability and fire behaviour is crucial to predict future fire events and quantify the potential risks [2,3].

Wildland fires do not only spread through dead fuels, but also through a combination of dead and live (with relatively higher moisture content) fuels [4]. Wildland fires are classified as ground fire (which occurs in the decomposed organic materials), surface fire (that consumes dead fuel litters), and crown fire (that spreads through the live fuel canopies of trees) [5]. The fuel condition is an important factor for any of these type of fires. To date, there is limited work on the fire behaviour differences between dead and live fuels. This is why previous research in the area has generally

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assumed that live fuels behave as wet dead fuels. Pickett et al. [4] summarized that the common models of wildland fire spread are developed from dead fuels correlations. Nonetheless, Jervis and Rein [6], through small-scale experiments using the Fire Propagation Apparatus on live, aged, and dead pine needles, demonstrated that moisture content is not the only factor governing the burning behaviour. There must be other physical and chemical properties which could influence the fire dynamics of live, aged, and dead pine needles [6]. However, further types and conditions of vegetation should also be explored in detail to get a clear observation particularly on thousand species of Australian vegetation.

Previous studies [7-10] indicate that fuel moisture content has a dominant role in determining the flammability and burning behaviour. In the preheating process, water vapour will be produced and increase the ignition delay time by diluting the flammable volatile in the reaction zone [3]. Dimitrikopoulous and Papaioannou [7] established the flammability classification of Mediterranean vegetation by correlating the ignition delay time and fuel moisture content. The ignition studies conducted by McAllister et al. [11] indicated that a linear regression between moisture content and ignition time only provides a 74-80% fit. Further observation also showed that the trend of ignition time is not captured properly with moisture content in the ignition of live fuels [11]. This finding also confirms that there is a difference between live and dead vegetation response under fire conditions.

In this paper, we examine the combustion characteristics of live and dead *Eucalyptus saligna* (Blue Gum) leaves, which is a common vegetation in Australia's south-eastern states [12]. The species Eucalypt genus was chosen as it forms three-quarters of the total native Australian forests [13] and woodlands. Flammability analyses were performed using the bench-scale Mass Loss Calorimeter device. Investigation on the influence of fuel moisture content to the burning behaviour was determined for each fuel condition (live and dead). This approach allowed us to fill the gaps from previous wildland fire studies on this area. The results provide robust data focusing on how one specific type of fuel under different conditions behave during the combustion process.

MATERIAL AND METHODS

Experimental procedure

Flammability and burning behaviour studies were carried out using thermal analysis and calorimetry. Thermogravimetric Analyses (TGA) were conducted to observe the impact of fuel properties and composition on thermal decomposition. Compared to the other thermal analysis techniques, TGA has a very accurate control of the heating rate for small samples, thus allowing to investigate the thermal decomposition at a kinetic regime [14]. A Perkin Elmer Simultaneous Thermal Analyzer (STA) 6000 was used for Thermogravimetric Analyses at a heating rate of 20°C/min between 20°C and 900°C. The selected temperature range covers the complete thermal decomposition of lignocellulosic materials. In order to get a clear observation of the pyrolysis and oxidation of leaves, two different carrier gases were used: (i) nitrogen to avoid solid-phase oxidation and obtain the volatile (or organic) compounds, and (ii) air to represent the actual oxidative conditions in wildfires and obtaining the inorganic content in the material.

An FTT Mass Loss Calorimeter (MLC) was used for the combustion tests in accordance to ISO 17554:2014. The MLC was utilized to measure the mass loss of the leaf samples in severe conditions of heat exposure without any additional instruments such as chimney or thermopile to measure heat release rate as conducted by previous studies [3,15-17]. The standard MLC closed sample holder (10 x 10 x 5 cm^3) was used to minimize the convective heat transfer coefficient and focus on the influence of the fuel properties. Tests were carried out using piloted ignition with various incident radiant heat fluxes (25, 35, and 50 kW/m^2) produced by the conical heater. The conical heater provided a constant heat flux until the fuel was totally consumed. The flammability criteria used for this study corresponds to the ignition delay time (the time from the beginning of heating until the piloted ignition occurs) and burnout time (the time from ignition until flame out) were noted visually. The mass loss rate (burning rate) was recorded at 1 Hz using a load cell with a data acquisition system. Before each test, the fuel moisture content was measured using a KERN DBS 60-3 Moisture Analyser. This device uses the mass loss method to measure the moisture content of the leaves. The temperature was set to 120°C to minimize the amount of volatile matter lost in the measurement. The instrument was programmed to stop when the sample reached a constant weight within ±0.05% accuracy of moisture content. The calibration of this method has previously carried out by Madrigal et al. [16] with a set point temperature of 175 °C. All of the tests were repeated at least three times to achieve consistent data for analysis.

Sample preparation

Eucalyptus saligna foliages were used in this study. The samples were collected from five different tree locations in a park located in The University of Queensland, St Lucia Campus. In order to investigate the influence of fuel condition, live leaves (above the fibre saturation point) were collected from alive trees; dead leaves (cells contracted below the fibre saturation point) were gathered from the litterfall. Examples of the fuel condition studied are shown in Fig. 1. At the time of collection, the moisture content of the fresh leaves were measured, resulting approximately 114±6% in dry base for live leaves and 14.2±2% in dry base for dead leaves. Proximate analysis was conducted for both fresh samples to obtain the properties (e.g. volatile matter, fixed carbon, and gross calorific value), which affects the burning behaviour as can be seen in Table 1.

(a) (b)

Fig. 1. Conditions of *E. saligna* leaves used in the experiment. (a) live leaves; (b) dead leaves.

For TGA testing, both leaf samples were dried using an oven at 60°C for 48 h. The final moisture content achieved for live and dead leaves was 4.39±0.21% and 3.48±0.19% respectively. After that, the oven-dried samples were crushed and grinded into powdered form to get uniform sample size and avoid problems related to heat and mass transfer [18]. In this study, no chemical treatment was undertaken to maintain the characteristic properties of the sample. The powdered leaves were weighed into 10 mg to be used on the test as suggested by Bilbao et al. [19]. Hence, there was no influence from sample mass differences to the pyrolysis and combustion characteristics on TGA.

To get a wide range analysis result in the flammability test using MLC, the leaves were conditioned to acquire different fuel moisture content. The first condition was 'fresh sample', where the leaves were analysed and tested immediately right after the collection. In the second condition, the leaves were exposed to ambient air and humidity in the laboratory up to seven days before being tested, therefore covering an extensive range in moisture content. The moisture content degradation was measured everyday using a moisture analyser. The last condition was 'oven-dried' (OD), where the samples were dried using an oven with a similar procedure as in the TGA. From those different conditioning processes, the variation of moisture content was obtained approximately 4-120% on dry weight for live leaves and 3-14% on dry weight for dead leaves. It is not possible to obtain zero percent of moisture content on oven-dried leaves because the leaves reach the equilibrium state immediately after exposure to the ambient humidity [20].

In order to reduce the disturbance of the experimental result due to dry mass variation, the initial sample mass was fixed to 5 g on dry weight for all tests. The sample was put into the sample holder until it covered the top surface of the holder and reproduce about 0.01 g/cm^3 (~10 kg/m^3) bulk density. Even though the sample has different wet mass, it still has a similar amount and thickness of individual leaves inside the sample holder. Thus, the fuel bed thickness could be maintained visually at 5 cm. By maintaining the initial dry mass and bulk density of the leaf samples, the effect of fuel condition and fuel moisture content on the burning behaviour could be evaluated.

Table 1. Proximate analysis of *E. saligna* leaves

Components	Live Leaves	Dead Leaves
Moisture Content (% adb^a)	114.21	14.22
Volatile Matter (% adb^a)	77.94	78.86
Fixed Carbon (% adb^a)	18.20	18.30
Ash Content (% adb^a)	3.86	2.84
Gross Calorific Value (MJ/kg adb^a)	20.90	22.89

^{a}As dried basis.

Data analysis

For TGA results, pyrolytic variables classified by Dimitrakopoulos [21] such as total mass loss (TML), mean volatilization rate (MVR), and peak mass loss rate (pMLR) were determined for each sample. To analyze the influence of fuel conditions on the flammability criteria, a one-way analysis of variance (ANOVA) has been widely used for previous flammability studies [2,10,15-17]. The LSD-fitted ANOVA test was used to determine if the burning characteristics measured by Mass Loss Calorimeter such as ignition delay time (t_{ig}), time to peak mass loss rate (t_{pMLR}), burnout time (t_{flame}), peak mass loss rate (pMLR), and residual mass fraction (RMF) varied significantly for the live and dead leaves under every incident radiant heat flux (25, 35, and 50 kW/m^2). A linear regression method was used to assess the correlation of time to ignition with both leaf conditions and fuel moisture content. From the linear regression results, the flammability tendency was predicted using the slope [7]. All variables related to the flammability were compared with the average values and errors (standard deviations).

RESULTS AND DISCUSSION

Thermogravimetric analysis (TGA)

The Thermogravimetric (TG) and Derivative Thermogravimetric (DTG) curves for live and dead leaves are shown in Fig. 2 and 3. There is a weight loss difference between the test conducted with air and nitrogen environment. The residual mass of samples on the nitrogen environment are higher than in the air environment due to the absence of oxidation processes. Table 2 shows that the total mass loss in air condition for live and dead leaves are 96.0 ± 0.2% and 96.5 ± 0.3%, respectively. These results provide the total ash content (inorganic matter) provided in the proximate analysis on

Table 1. The total mass loss of both live and dead *E. saligna* leaves are similar with the results of mass loss on Mediterranean plant species with the maximum TGA temperature of 700°C [21]. On the nitrogen condition, the amount of organic compounds remaining are 22.4 ± 0.04% for live leaves and 20.9 ± 1.12% for dead leaves. The higher total mass loss of dead leaves in both air and nitrogen conditions indicates that the dead leaves have more volatile matter compared to the live ones.

Table 2. Pyrolytic variables of live and dead leaves from thermogravimetric analysis

Fuel Conditions	TML (% db[a])		MVR (%/°C)		pMLR (%/°C)	
	Air	Nitrogen	Air	Nitrogen	Air	Nitrogen
Live Leaves	96.002	77.632	0.137	0.086	0.372	0.383
Dead Leaves	96.516	79.119	0.138	0.088	0.378	0.376

[a] As dried basis.

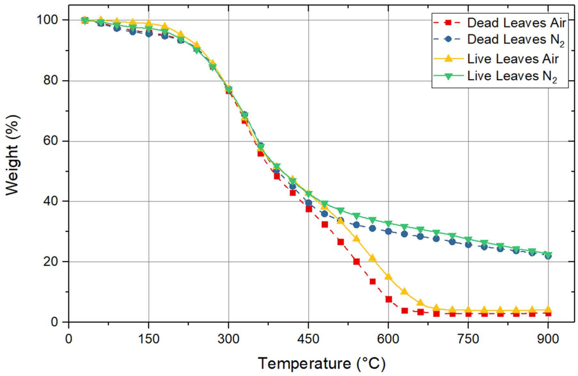
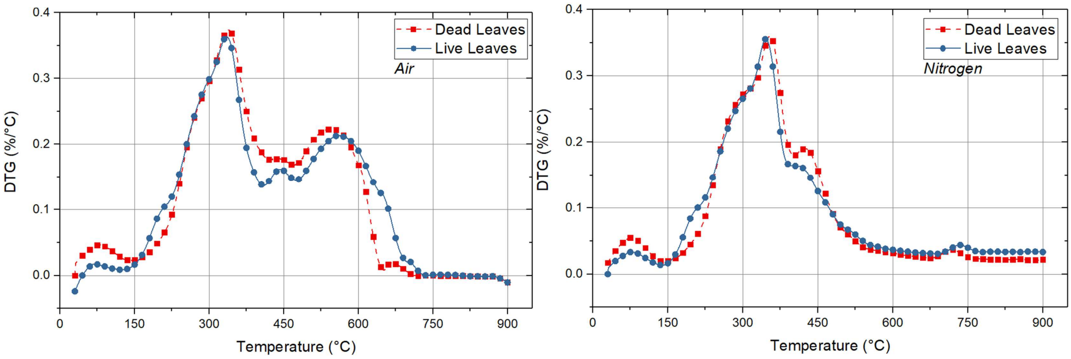


Fig. 2. TG-curves for the pyrolysis of live and dead leaves in air and nitrogen environment.



(a) (b)

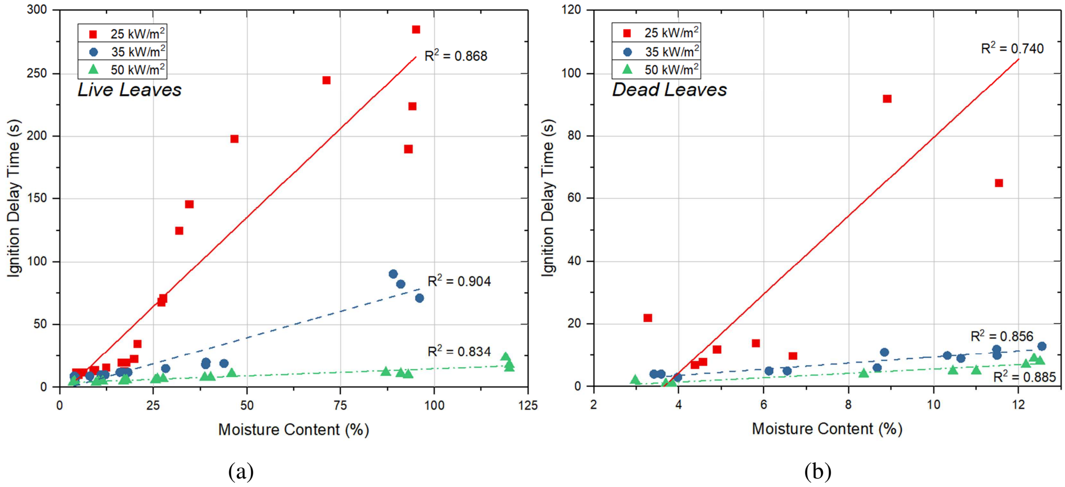
Fig. 3. DTG-curves for the pyrolysis of live and dead leaves. (a) air environment; (b) nitrogen environment.

As a lignocellulosic material, a leaf is mainly composed of hemicellulose, cellulose, and lignin [22]. Overall, the live and dead leaves produce similar shapes in all DTG-curves. Figure 3a represents the DTG-curve in air environment and it shows four main processes: (i) moisture and light volatile compounds release (<120 °C); (ii) hemicellulose degradation at 220-315 °C; (iii) cellulose and lignin decomposition at 315-400 °C; and (iv) degradation of lignin (>450 °C) [22]. The decomposition of hemicellulose and cellulose occurred almost at the same time, showed by the appearance of small “shoulder” (Grønli et al. [23]) before the first peak at 330-350 °C for cellulose decomposition. In air, there is the second peak as the result of lignin degradation and oxidation when the temperature reaches about 550-560 °C.

In air, thermal decomposition is completed at 700°C, whereas in nitrogen there is an additional decrease just before 900°C as can be seen in Fig. 2. Compared to the Mediterranean species with mean volatilization rates varying from 0.215 to 0.242%/°C, the MVR values for *E. saligna* shown in Table 2 are lower [21]. The pyrolytic variables results are quite similar for the live and dead leaves. Therefore, it may concluded that the thermal decomposition and chemical kinetics of live and dead *E. saligna* leaves essentially behave the same. Even though the TGA results did not obtain a great distinction, the variability might be very critical if it is extrapolated to the actual wildfire phenomena.

The influence of moisture content of live and dead leaves

The effect of fuel moisture content on flammability parameters has been largely investigated in previous studies [7-10]. The impact of the moisture content on the different leaf conditions (live and dead) was analysed to get a clear comparison on its role on the burning behaviour. Ranges of fuel moisture content in both sample conditions are distinct because the leaves have different initial state. Figure 4 depicts the scatter plot of the ignition delay time (t_{ig}) versus moisture content for each condition. A linear regression is found in all measurements, similar with the results observed by Dimitrakopoulos and Papaioannou [7]; Xanthopoulos and Wakimoto [24]. Overall, the trends obtained indicate that, as expected, the increase of moisture content will extend the ignition delay time. This confirms that the production of water vapor dilutes the flammable pyrolizates and the endothermic reaction may affect the thermal balance in the ignition process [25]. External radiant heat flux was also shown to affect the ignition delay time; the higher the heat flux, the lower the ignition delay time is. This could be governed by the thermal behaviour of the leaf samples (i.e. thermally thick and thin behaviour). However, McAllister et al. [11] observed that the vegetation fuel could be assumed to have a thermally-intermediate behaviour. At the low heat flux (25 kW/m^2), large internal temperature gradients were formed and delayed the water evaporation process. On the contrary, no significant evaporation occurred at 35 and 50 kW/m^2 [11].



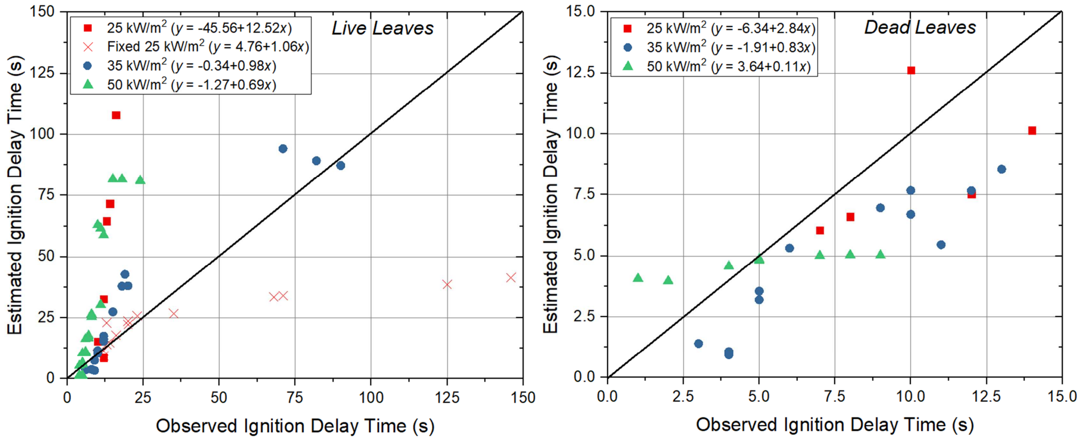
(a) (b)

Fig. 4. Effect of dry-weight moisture content on the ignition delay time (t_{ig}). (a) live leaves; (b) dead leaves.

Table 3 shows the linear regression models between moisture content and ignition delay time obtained from Fig. 4. In order to observe the correlation between live and dead leaves, the ignition delay time was calculated using linear fit models of the opposite fuel condition (models created from dead leaves were used to predict the ignition delay time of live leaves, and vice versa). Similar method was previously conducted by McAllister et al. [11] and Jolly et al. [26] to compare the observed ignition time on their experiment with the predicted value using different models. Figure 5 represents the comparison between the measured and estimated ignition delay time for both leaf conditions in all heat fluxes. From the plots, poor correlations are observed for each leaf condition. As seen in Fig. 5b, the prediction of the ignition delay times of dead leaves using the live leaves models denote adequate results since the live leaves models cover a wide range of moisture content. However, the predicted ignition delay time for dead leaves tends to underestimate the measured values. On the other hand, the dead leaves models can only predict the t_{ig} of live leaves on the relatively low moisture content (≤ 25% on dry weight). The linear fit model of dead leaves at 25 kW/m^2 was fixed by eliminating the peculiar values shown in Fig. 4b to produce a better estimation. The extended prediction for higher moisture content of live leaves would be difficult since the dead leaves only have limited range of moisture content. Different properties and water storage systems between live and dead leaves could be one of the possible influences on the ignition delay time [11].

Table 3. Linear regression models between fuel moisture content and ignition delay time

Heat Flux (kW/m^2)	Live Leaves		Dead Leaves	
	Regression Model	R^2	Regression Model	R^2
25	$y = -6.34+2.84x$	0.868	$y = -45.56+12.52x$	0.740
35	$y = -1.91+0.83x$	0.904	$y = -0.34+0.98x$	0.856
50	$y = 3.64+0.11x$	0.834	$y = -1.27+0.69x$	0.885

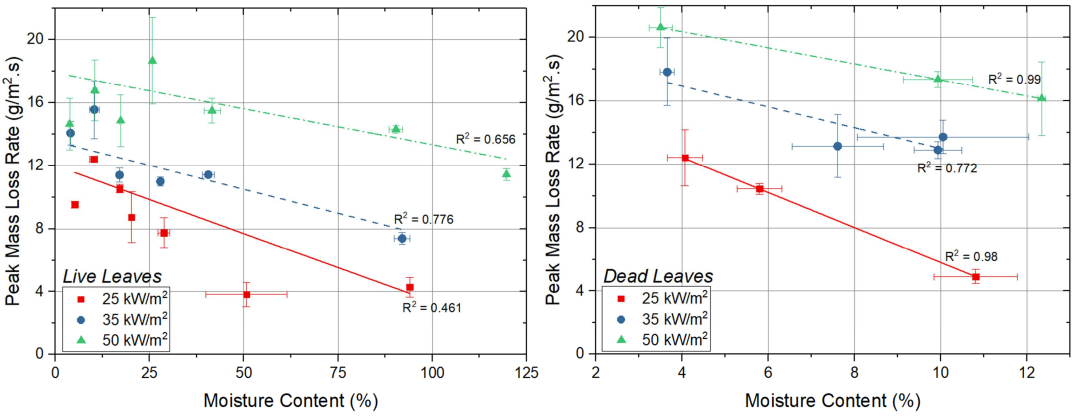


(a) (b)

Fig. 5. Comparison of observed and estimated ignition delay time (t_{ig}). (a) observed t_{ig} of live leaves and estimated t_{ig} by dead leaves models; (b) observed t_{ig} of dead leaves and estimated t_{ig} by live leaves models.

In general, peak mass loss rate (pMLR) tends to increase with the decrease of MC and increase of heat flux. For dead *E. saligna* leaves (3-14% MC), the peak mass loss rate ranged from 4.9 - 12.4 $g/m^2.s$ at 25 kW/m^2; 12.9-17.8 $g/m^2.s$ at 35 kW/m^2; and 16.1 – 20.6 $g/m^2.s$ at 50 kW/m^2 heat flux. Meanwhile, for live leaves (4-120% MC), the peak mass loss rate increased from 3.8-12.4 $g/m^2.s$ at 25 kW/m^2; 7.4 – 15.6 $g/m^2.s$ at 35 kW/m^2; and 11.4 – 18.7 $g/m^2.s$ at 50 kW/m^2 radiant heat flux. Almost all of the peak mass loss rate curves have linear fit correlation with fuel moisture content (R^2

≥ 0.6) as can be seen in Fig. 6. However, the exponential fit is only found on live leaves with 25 kW/m^2 heat flux condition generating $y = 11.268 \times \exp(-0.012x)$ ($R^2 = 0.732$; $P \leq 0.01$; data not shown). This exponential fit is in accordance with the peak heat release rate (pHRR) results conducted by Possell and Bell [3] for *Eucalyptus* species on 25 kW/m^2 heat flux; also Dahanayake and Chow [9] for ornamental plants at heat flux of 50 kW/m^2. Peak mass loss rate comparison between live and dead leaves could be observed in the relatively low moisture content (< 20%), with the pMLR values for live leaves are slightly lower than dead leaves, similar with the pHRR results obtained by Madrigal et al. [15]. These results indicate that the pMLR values are essentially controlled by fuel moisture content (changes the burning process [27]) and leaf conditions (different heat of combustion).



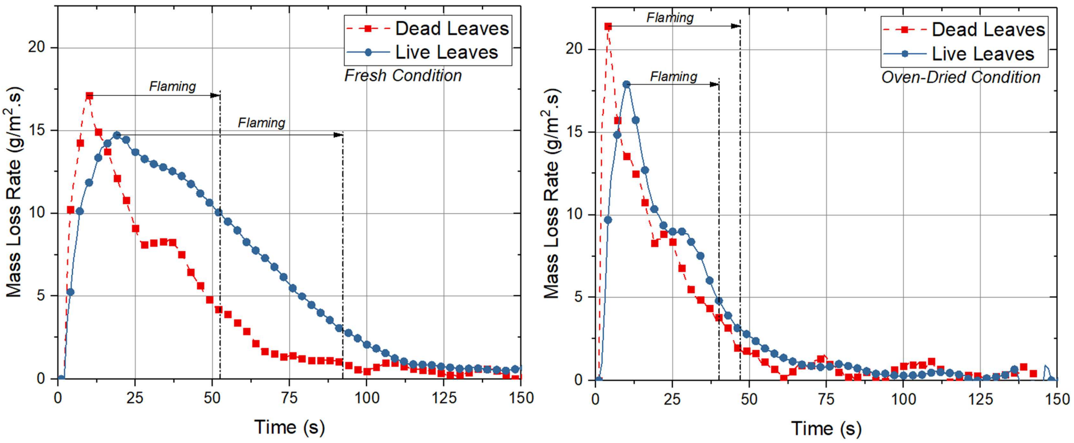
(a) (b)

Fig. 6. Effect of dry-weight moisture content on peak mass loss rate (pMLR). (a) live leaves; (b) dead leaves.

Comparison of flammability parameters between live and dead leaves

The results of the transient measurement of mass loss rate for live and dead leaves at 50 kW/m^2 heat flux condition can be found in Fig. 7. After the ignition occurs, the mass loss rate increases until it reaches the peak value and then declines along with the fuel consumption. At the time of peak mass loss rate, the flaming combustion dominates the burning process until it self-extinguishes, leading to a smouldering combustion of the char and left ash residues. As seen in Fig. 8, the differences between the ignition delay time and time to reach peak mass loss rate in every leaf condition and heat flux are very small. The linearity explains that at the time of ignition, the mass loss rate will immediately reach the peak. Thus, from the transient measurement, flaming duration for both leaves fluctuate and the quantitative results could be seen in the analysis of variance.

Figure 9 shows the normalised mass loss for oven-dried leaves on pre-ignition, also during flaming and smouldering combustion. According to Jervis and Rein [6], the mass loss occurred before ignition is mostly caused by water evaporation process. This process would be dependent on how much water is contained (moisture content) in the leaves, which tends to be higher in live leaves. Even though the oven-dried samples have similar moisture content (4.39±0.21% for live leaves and 3.48±0.19% for dead leaves), the measured pre-ignition mass loss in 50 kW/m^2 heat flux is approximately 0.14±0.04 (~14%) for live leaves and 0.02±0.01 (~2.3%) for dead leaves. This finding indicates that in the same level of moisture content, dead leaves could be ignited before all of the moisture is evaporated, while live leaves need more time to achieve enough volatile compound to be ignited. The amount of mass loss during flaming combustion indicates the quantity of volatile and carbon content, which results in dead leaves have higher amount than live leaves. On the contrary, live leaves have more char residue from flaming combustion that used for smouldering combustion, shown by the total mass consumed on smouldering combustion as seen in Fig. 9c.



(a) (b)

Fig. 7. Mass loss rate per unit area in 50 kW/m^2 heat flux. (a) fresh samples; (b) oven-dried samples.

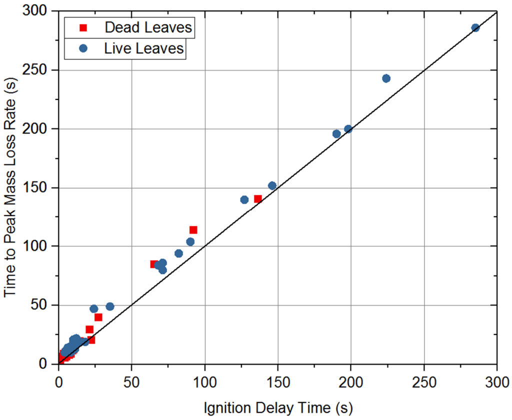
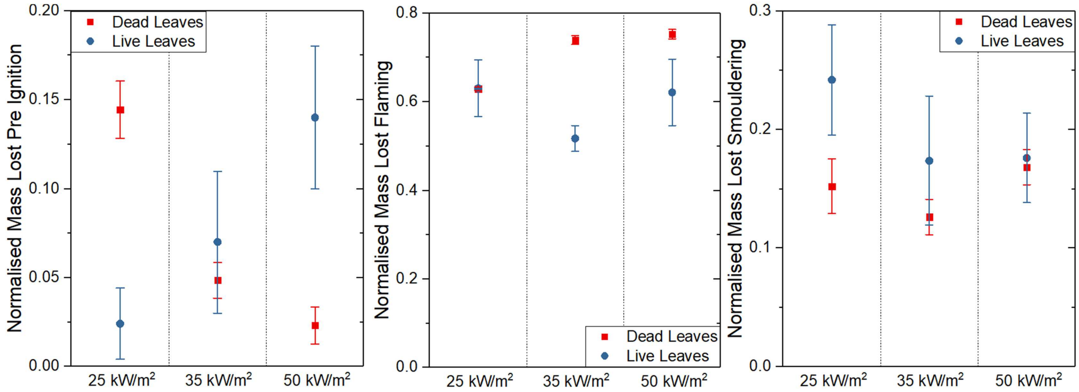


Fig. 8. Ignition delay time (t_{ig}) compared to the time to reaches peak mass loss rate (t_{pMLR}).

Analysis of variance (ANOVA) of live and dead leaves in all heat flux can be observed for some flammability parameters in Table 4. Overall, the analysis indicates that the leaf conditions that are strongly affected are t_{ig}, t_{pMLR}, and residual mass fraction (RMF); t_{flame} and pMLR are also affected under certain conditions. The ignition delay time (t_{ig}) and time to peak mass loss rate (t_{pMLR}) generate high significance level ($P \leq 0.01$) between live and dead leaves on 35 kW/m^2 and 50 kW/m^2 heat fluxes. As explained before, the ignition delay time for live leaves will always be longer than dead leaves, even in the oven-dried condition. Dead leaves could ignite up to eight times faster in fresh condition, and three times faster in oven-dried condition compared to the live leaves, consistent with the results of *Pinus contorta* (lodgepole pine) [26]. This understanding is also applied to t_{pMLR} because the peak mass loss rate would be reached no long after the fuel is ignited.

Burnout time or duration of flame occurrence (t_{flame}) for live and dead leaves have the least significance value. Four out of six analyses indicate that there is no influence of leaf conditions to burnout time. However, the average and standard deviation of oven-dried samples show that the dead leaves burnt longer than live leaves. Incident radiant heat flux of 35 kW/m^2 and 50 kW/m^2 conditions can significantly affect peak mass loss rate values, with the pMLR of live leaves being always lower than dead leaves in fresh and oven-dried situations. This is because the live leaves are less lignified which is affecting the amount of gross calorific value (commonly known as gross heat of combustion) from the proximate analysis in Table 1 [15]. The residual mass fraction (RMF) shown in Table 4 is strongly influenced by the organic content (volatile matter and carbon content), which can be seen in Table 1 and TGA results in Fig. 3. Dead leaves have a larger amount of organic content compared to the live ones, resulting in the smaller residual mass fraction.



(a) (b) (c)

Fig. 9. Mass loss for oven-dried samples. (a) pre-ignition; (b) during flaming combustion; (c) during smouldering combustion.

Table 4. Summary of flammability parameters in every heat fluxes for fresh and oven-dried samples

Heat Flux (kW/m^2)	**Sample State**	**Sample Condition**	**t_{ig} (s)**	**t_{pMLR} (s)**	**t_{flame} (s)**	**pMLR ($g/m^2.s$)**	**RMF (%)**
25	Fresh	Live	233±48	241±45	30±8^a	4.29±1.08^a	14.81±0.03
		Dead	97±35	113±28	41±27^a	4.92±0.77^a	4.40±3
	Oven-Dried	Live	11±1^a	21±0.6^a	52±14^a	9.52±0.37^a	10.52±3.44^a
		Dead	12±8^a	12±7^a	51±5^a	12.42±3.07^a	11.26±5.46^a
35	Fresh	Live	81±9	94±9	48±23^a	7.39±0.66	8.72±1.92
		Dead	10±1	14±3	50±16^a	12.91±0.93	3.51±2.06
	Oven-Dried	Live	7±1	12±1	35±3	14.07±1.33^a	20.89±1.51
		Dead	3±0.6	8±1	48±3	17.84±3.68^a	6.02±1.54
50	Fresh	Live	11±1	18±1	79±3	14.31±0.41	13.21±0.53
		Dead	4±0.6	9±1	48±6	17.37±0.85	0.91±0.15
	Oven-Dried	Live	4±0.6	10±1	32±6^a	14.65±2.87	5.80±5.22
		Dead	1±0.6	6±1	46±7^a	20.62±2.18	7.57±0.58

^{a}Not significant ($P > 0.05$).

CONCLUSION

A series of bench-scale experiments on the burning behaviour and flammability of *Eucalyptus saligna* leaves have been conducted. Different fuel conditions (live and dead leaves) were tested in wide range of moisture content and heat fluxes. Proximate and thermogravimetric analysis were conducted to observe the micro-scale influence of fuel properties and composition on the burning behaviour. A Mass Loss Calorimeter was used to measure flammability parameters. The calorimetry results demonstrate that the combustion characteristics of live and dead *E. saligna* leaves are significantly different due to the chemical compounds.

Overall, live and dead leaves produce similar shapes in all DTG-curves. In the air, both live and dead leaves have an almost identical total mass loss of 96.0 ± 0.2% and 96.5 ± 0.3% respectively. On the nitrogen, live leaves have a slightly larger amount of remaining organic compounds compared to dead leaves, 22.368 ± 0.04% versus 20.881 ± 1.12% respectively. The higher total mass loss of dead leaves can be used to show that the dead leaves contain more flammable matter compared to the live leaves. Additional pyrolytic variables results are quite similar for both leaves, which suggests that there is only small differences on the thermal degradation process. However, these differences could lead to a critical issue if it is extrapolated to the actual wildfire phenomena.

The effect of fuel moisture content on the flammability parameters has been investigated by several authors [7-10], but only few studied the moisture content of different fuel conditions. The ignition delay time analyses of leaf conditions are separated in order to observe the correlation of the linear-regression model derived from dead leaves as a prediction on ignition delay time of live leaves, and vice versa. The results obtained for each leaf condition could not be used well to predict the ignition delay time of the opposite fuel condition. The peak mass loss rate of live and dead leaves could only be compared in the low moisture contents. Peak mass loss rate values for live leaves are slightly lower than dead leaves, similar with the peak heat release rate (pHRR) results obtained by Madrigal et al. [15]. These results indicate that the peak mass loss rate values are essentially controlled by fuel moisture content and leaf conditions.

In the transient studies of mass loss rate, the correlation between the ignition delay time and time to reach peak mass loss rate is almost linear. This proves that once the fuel ignited, the peak value of mass loss rate will be immediately reached. The measured mass loss before ignition for oven-dried samples is 14% for live leaves and 2.3% for dead leaves. This indicates that even in the same moisture content, dead leaves would ignite easier since the ignition could occur before all of the moisture evaporated. The ANOVA results determined that leaf conditions are strongly affecting all flammability parameters with the dead leaves tending to be more flammable, even though the leaves are in the same oven-dried treatment.

The results of this work justify the need to treat live and dead fuels separately, and not assume that live fuels are dead fuels with a higher moisture content. Therefore, further studies still need to be carried out for more types of vegetation. Leaf conditions are an additional fuel characteristic that needs to be considered as part of further development of wildland fire spread models and in assessing wildland fire risk.

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