World Conference on
Timber Engineering
Oslo 2023

EXPERIMENTAL INVESTIGATION OF THE RELATIONSHIP BETWEEN TIMBER SPECIES AND SMOULDERING

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ABSTRACT: Smouldering, the exothermic solid-phase oxidation process of porous char, can damage or destroy timber structures long after a fire has burnt out or its flame front has passed. Reaction kinetic parameters (i.e. activation energy E_a and frequency factor A) of timber oxidation can be determined from thermogravimetric analysis (TGA). These parameters along with timber density could potentially be used to predict the self-sustaining smouldering of timber species. To verify this hypothesis, the relationship between the occurrence of self-sustained smouldering and the properties of different timber species, namely density and activation energies of pyrolysis and oxidation, was determined through bench-scale smouldering tests using Cone Calorimeter and TGA for nine Australian timber species. Less dense timbers with lower activation energies were more prone to initiate and sustain smouldering under extreme laboratory conditions.

KEYWORDS: Timber, Timber Species, Smouldering, Oxidation, Thermogravimetric Analysis, Fire Safety, Combustion, Bushfires

1 INTRODUCTION

As an organic material, timber is combustible and therefore its use in construction poses multiple fire safety challenges. Flaming ignition is usually considered an indicator of the start of a fire, while the extinction of the flame marks the end of the event. Because of the large amounts of energy released by visible flames, and their associated spread and damage, the focus of research and standardised guidance documents often focuses on the flaming combustion process.

Subsequent smouldering combustion is sometimes overlooked for structural fires due to its occurrence at relatively low temperatures, lack of visible indicators (i.e. flames) and slow spread rate [1, 2]. Consequently, smouldering in timber infrastructure often appears only as a footnote to recent primary research outcomes concerned with flaming. Nevertheless, the consequences of timber infrastructure under smouldering combustion can also be catastrophic. For example, a mass timber slab collapsed 29 hours after flame self-extinction, due to the subsequent smouldering combustion in a structure fire [3]. Smouldering spread along bridges via the deck planks and across the bridge via the crossbeams has been reported after bushfires [4].

Smouldering combustion can be observed in timber after it has been pyrolysed [5, 6] and is a leading combustion phenomenon in wildland fires [7, 8], constituting a hazard to assets and a health issue from the smoke (Figure 1). Moreover, the transition from smouldering to flaming can occur under the appropriate conditions [4] and introduces hazards to fire intervention in timber buildings and post-bushfire areas.

Figure 1: *Examples of wood smouldering after a bushfire exposure (photos from cn.depositphotos.com)*

Smouldering combustion of timber involves multiple chemical reactions that can be approximated by a lumped 3-step chemical pathway as described in [2, 9]:

Pyrolysis: **Wood (s)** $\rightarrow$ Pyrolyzate (g) $+$ **Char (s)** $+$ Ash (s) , $\Delta H > 0$ (endothermic) (1)

Gas-phase oxidation: Pyrolyzate $(g) + O_2 \rightarrow CO_2 + H_2O + other\ gases$, $\Delta H < 0$ (exothermic) (2)

Heterogeneous oxidation: **Char (s)** $+ O_2 \rightarrow CO_2 + H_2O + other\ gases +$ **Ash (s)** , $\Delta H < 0$ (exothermic) (3)

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 https://doi.org/10.52202/069179-0225

When solid timber is exposed to fire, its surface heats up and decomposes (pyrolysis), creating a char layer. This process occurs at around 300 °C [10]. The char comprises a porous reactive matrix with a high surface-to-volume ratio that allows oxygen diffusion [2]. The external heat supply initiates pyrolysis and other endothermic processes, such as evaporation, before oxidation occurs. Self-sustained smouldering will occur after the external heat is removed and progress if the exothermic oxidation reaction (Equations 2 and 3) generates sufficient heat to propagate pyrolysis (Equation 1) and compensate other endothermic processes such as water evaporation, sensible enthalpy increase and heat losses. Smouldering is not sustainable without these attributes and will quench [11, 12].

According to the Arrhenius model (Equation 4), the kinetic parameters that govern a chemical reaction are the activation energy (E_a) and the frequency factor (or pre-exponential factor A).

$$\dot{\omega}''' = Ae^{-E_a/RT} \tag{4}$$

Ea is the energy threshold and must be surpassed to transform reactant molecules into products. A represents the proportion of molecules participating in the reaction if all molecules are beyond the activation energy.

These parameters can be used to predict the reaction rate of the process and can be determined from thermogravimetric analysis (TGA) results, considering the peak temperature at the maximum decomposition rate. Wu et al. [13] found that lower activation energy in preservative-treated pine was more likely to initiate self-sustained smouldering in bench-scale (Cone Calorimeter) tests and caused faster mass loss rates during smouldering combustion. Similarly, lower-density timber also led to faster smouldering combustion. These processes may be linked to porosity of wood, which generally decreases with increased density [14-16]. In addition, high thermal diffusivity caused by low density leads to deeper heat penetration at a given time.

This study explored the influence of the timber species on self-sustained smouldering, evaluated in terms of occurrence and rate. Micro-scale TGA and bench-scale smouldering tests were performed on nine native Australian timbers with a wide range of bulk densities. Determining smouldering occurrence and rate can help assist in the selection of timber species for specific end-use applications, especially in bushfire-prone areas. Ultimately, a better understanding of the smouldering phenomenon can help to develop risk mitigation strategies and optimise trade-offs between availability, durability, design life, and fire resilience.

2 MATERIAL AND METHODS

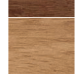
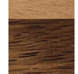
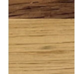
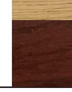
2.1 MATERIAL PREPARATION

Nine Australian hardwood timber species were used in this study: *Acacia mearnsii* (Black Wattle – BSL), *Erythrophleum chlorostachys* (Cooktown Ironwood – CTI), *Eucalyptus tetrodonta* (Darwin Stingybark – DSB), *Eucalyptus paniculata* (Grey Ironbark – GIB), *Intsia bijuga* (Merbau – MRB), *Cardwellia sublimis* (Northern Silky Oak – NSO), *Flindersia brayleyana* (Queensland Maple – QMP), *Alstonia scholaris* (Queensland Whitewood – QWW), *Elaeocarpus grandis* (Silver Quandong – SLQ).

Australian bushfire standard AS 3959 [17] defines the term bushfire attack level (BAL) as the hazard for bushfire-prone areas. The severity of BAL is measured by potential exposure to ember attack, radiant heat and direct flame contact, using radiant heat flux expressed in kW/m^2 [18, 19]. Among the species used in this work, based on their density, GIB, DSB and CTI are considered suitable timber species for BAL – 19, representing a moderate risk from ember attack and ignition of debris with a heat flux of up to 19 kW/m^2. Merbau is considered a bushfire-resistant timber species according to AS 3959 [17], enabling its use in BAL – 29 areas.

Specimens for TGA were ground to pass through a 0.25mm-mesh screen using a RETSCH Cutting Mill SM 300. The initial moisture content and dry density of all samples (measuring 100 mm by 100 mm by 19 mm) for the bench-scale smouldering tests were determined using the oven-drying method, according to ASTM D4442 [20], in duplicate. The mean density and initial moisture content of the timber species are summarised in Table 1. The oven-dry samples were used in bench-scale testing immediately after removal from the oven, to minimise the effect of different moisture contents across the timber species. This is a conservative boundary condition to assess the smouldering occurrence, where a minimum amount of additional energy is required to evaporate the free water. Ceramic paper was used as insulation around the sample edges to reduce heat losses and allow for oxygen mass transfer.

Table 1: *Dry density and initial moisture content of the nine timber species.*

Sample	Texture	Dry Density (kg/m^3)	Initial Moisture Content (%)
GIB		1048	12
NSO		504	10.3
SLQ		407	11.4
BSL		586	11.6
DSB		1047	8.5
QMP		572	11.5
MRB		769	10.5
QWW		467	10.4
CTI		1213	9.8

2.2 THERMOGRAVIMETRIC ANALYSIS

Thermogravimetric analysis of the nine timber species was conducted in an oxidative (air) environment using a NETZSCH STA449-F3 Thermogravimetric Analyzer using 10 ± 0.5 mg of undried powdered sample in an alumina crucible at 5, 10 and 20 ℃/min heating rates, from 50 to 800 ℃ and using an airflow rate of 100 mL/min. Thermal decomposition reaction rates were assessed by applying the first derivative to the mass-temperature data (DTG).

From Kissinger's model (Equation 5) [21], the activation energy (Ea) and pre-exponential factor (A) can be obtained by identifying the oxidation peak temperature (T_p) from the DTG curves of different heat rates (β).

$$\ln\left(\frac{\beta}{T_p^2}\right) = -\frac{Ea}{RT_p} + \ln\left(\frac{AR}{E}\right) \quad (5)$$

2.3 BENCH-SCALE SMOULDERING TEST

The Bench-scale smouldering method used herein was designed to simulate passing bushfire scenarios. For these experiments, the nine timber species were ignited in a Cone Calorimeter with pilot ignition to establish an initial flaming combustion period where the heat release rate was measured according to AS/NZS 3837 [22]. A heat flux of 20 kW/m^2 was chosen as the fire intensity for this study, which was considered a moderate fire risk.

Heat flux exposures were maintained at 20 kW/m^2 until flaming combustion produced a timber mass loss of 40 %. This mass loss criterion was used as an indication of the degree of physical damage associated with flaming duration. A quasi-steady flaming state before external heat removal was confirmed from stable heat release rate readings and CO_2 yield to substantiate thermal equilibrium within the sample. Once the target mass loss was reached, the external heat supply was removed, the time to ignition and flaming duration were recorded, and the samples were transferred to an Ohaus V-7000 load cell under ambient temperature conditions. From that point onwards, the mass loss over time was measured to determine the smouldering rate. Each species was tested twice to ensure repeatability.

Both optical and infrared cameras were used to record the propagation pattern of the self-sustained smouldering along the sample surface. The airflow from the exhaust hood was measured via a Hot-Wire Anemometer to vary between 0.02 to 0.1 m/s; this was the lowest achievable airflow under our laboratory conditions. Figure 2 shows a schematic representation of the equipment and procedure with the different stages of a self-sustained smouldering test.

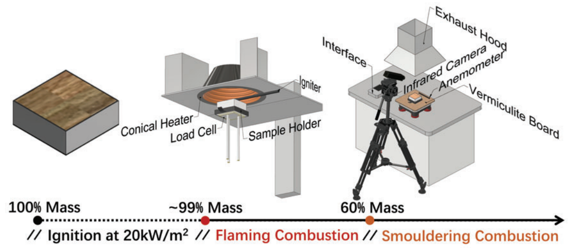


Figure 2: *Schematic representation of the equipment and procedure showing the stages of the bench-scale self-sustained smouldering tests.*

3 RESULTS AND DISCUSSION

3.1 THERMOGRAVIMETRIC ANALYSIS

Figure 3 shows representative DTG results for BSL under 5, 10 and 20 ℃/min heating rates. All timber species showed the same pattern. The first small peak from the left, around 80 ℃ was due to water evaporation. The second peak, around 320 ℃, was attributed to endothermic wood pyrolysis (Equation 1). The third peak, between approximately 450 and 485 ℃, corresponded to exothermic char oxidation (Equation 3). Both the drying and pyrolysis stages were relatively consistent among species, while more marked differences among species were observed in the onset and maximum temperature of the third peak, at all heating rates. The peak temperatures for the pyrolysis and oxidation stages of nine species are summarised in Tables 2 and 3, respectively.

Linear correlations were established by plotting $\ln(\beta/T_p^2)$ against $1/T_{(\beta,p)}$ (Equation 4**)**; the correlation fittings are shown in figures 4 and 5. The E_a for pyrolysis and oxidation stages were calculated based on the slopes from figures 4 and 5, respectively, and are summarised in Table 4.

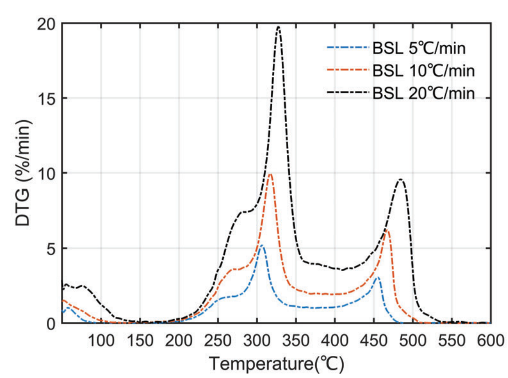


Figure 3: *Representative DTG results from TGA experiments of BSL tested in air atmosphere using heating rates of 5, 10 and 20 ℃/min.*

https://doi.org/10.52202/069179-0225

Table 2: *Peak temperatures at the pyrolysis stage (T_{P_β}) using 5, 10 and 20 °C/min heating rates.*

Sample	Heating rate (°C/min)		
	5	10	20
	T_{PP} (°C)		
GIB	307.6	319.4	331.3
NSO	302.4	314.6	325.7
SLQ	306.0	317.4	328.2
BSL	306.5	317.1	327.4
DSB	307.6	319.9	331.3
QMP	307.1	318.0	328.0
MRB	310.0	320.6	331.6
QWW	301.0	311.9	324.1
CTI	308.4	321.1	333.7

Table 3: *Peak temperatures at the oxidation stage (T_{PO_β}) using 5, 10 and 20 °C/min heating rates.*

Sample	Heating rate (°C/min)		
	5	10	20
	T_{PO} (°C)		
GIB	455.9	467.4	480.8
NSO	460.5	471.0	481.2
SLQ	456.8	464.0	471.5
BSL	455.0	467.0	484.2
DSB	473.1	488.2	510.8
QMP	436.7	442.5	448.2
MRB	449.7	460.6	473.0
QWW	435.9	446.0	455.8
CTI	470.0	483.1	498.1

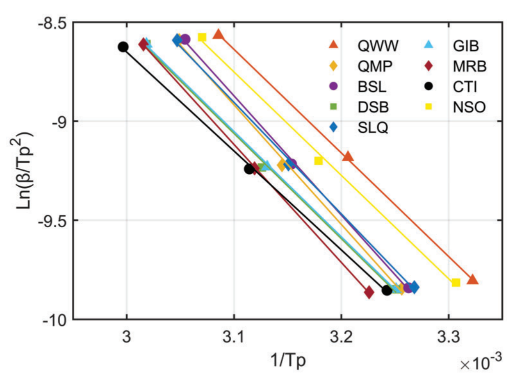


Figure 4: *Plot of ln(β/Tpp²) versus inverse peak pyrolysis temperature $1/T_{(\beta,p)}$ for all species.*

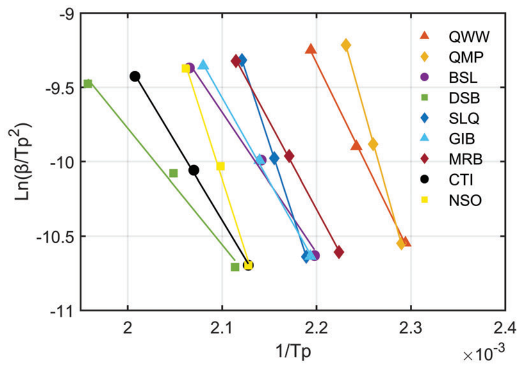


Figure 5: *Plot of ln(β/Tpp²) versus inverse peak oxidation temperature $1/T_{(\beta,p)}$ for all species.*

The Ea of the pyrolysis stage for all nine timber species was approximately 40 to 50 kJ/mole, while the Ea for the oxidation stage varied markedly across species. This indicates that wood species affected the characteristics of the char that was produced during the pyrolysis, which influenced the subsequent oxidation kinetics.

Table 4: *Activation energies of pyrolysis and oxidation stages for nine timber species.*

Reaction	Pyrolysis stage		Oxidation stage	
Sample	Ea_p (kJ/mole)	A (s^{-1})	Ea_o (kJ/mole)	A (s^{-1})
GIB	44.2	9.1E+06	93.6	1.5E+10
NSO	43.4	8.8E+06	115.5	4.0E+12
SLQ	46.8	2.9E+07	161.2	5.0E+08
BSL	50.0	1.1E+08	78.5	2.5E+08
DSB	44.2	8.7E+06	65.1	2.8E+06
QMP	50.2	1.1E+08	188.8	2.3E+22
MRB	49.5	6.8E+07	97.9	7.0E+10
QWW	43.5	1.0E+07	107.6	2.7E+12
CTI	41.5	2.8E+06	87.9	1.4E+09

3.2 BENCH-SCALE SMOULDERING TEST

3.2.1 Duration of heat exposure

Table 5 shows the mean ignition time and flaming duration from the bench-scale tests. Timber species with a higher density require a longer time to ignite and for the flame to consume the same mass percentage. Longer flaming increases heat production and penetration depth and generates more char as an insulator, which can affect subsequent smouldering behaviour.

Timber density was strongly positively correlated with the flaming duration with a Pearson Correlation Coefficient of 0.87 suggesting that these parameters cannot be considered independent towards smouldering performance due to their collinearity (Figure 6).

Table 5: Density, time to ignition, and flaming duration to reach 40% mass loss for the nine timber species.

Sample	Density (kg/m^3)	Ignition (minutes)	Flaming to 40 % Mass Loss (minutes)
GIB	1048	4.8	15.7
NSO	504	3	14
SLQ	407	1.5	9.7
BSL	586	2.3	8.4
DSB	1047	5.8	19.3
QMP	572	2.5	11.6
MRB	769	3.5	11.7
QWW	467	2.4	7.8
CTI	1213	22.3	20

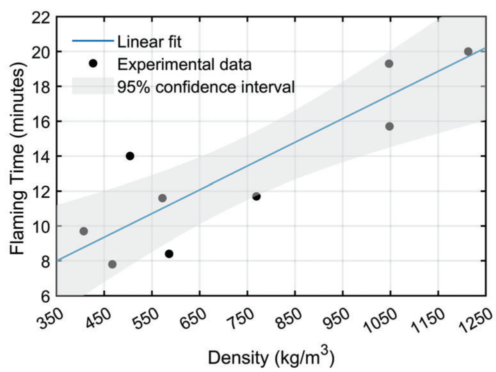


Figure 6: Linear regression between timber density and the flaming time to reach 40 % mass loss with a Pearson Correlation Coefficient 0.87.

3.2.2 Propagation pattern

A series of representative infrared and optical images of timber undergoing self-sustained smouldering at different times were used to analyse the smouldering front (Figure 7). A rapid cooling stage occurred on the surface after the external heat supply ceased (Figure 7a to 7b). The smouldering front then propagated from the edges to the centre, generating visible smoke. A transition to flaming only occurred for QWW (Figure 7b) from the insulated edge for around 10 minutes. The smouldering front then progressed deeper into the wood, coinciding with surface regression from char oxidation. At this stage, glowing could be observed (Figure 7c). Eventually, the temperature decreased until less than 1 % mass residual was left after 75 minutes (Figure 7d).

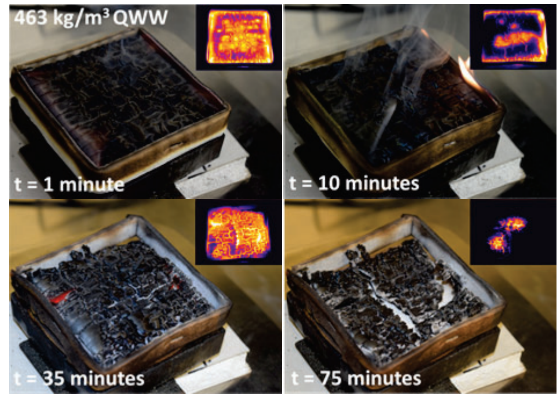


Figure 7: Photographs of QWW at different times during the smouldering combustion stage. Note the transition to flaming from one side at 10 minutes and the glowing at 35 minutes. Thermal images showing the exposed surface are inserted in the top-right corners of the figures.

3.2.3 Smouldering Performance

Figure 8 shows the mass percentage evolution during the smouldering stage for all the timber species that exhibited self-sustained smouldering (QWW, MRB, GIB, and BSL). Those samples ultimately lost more than 99 % of their initial mass. In contrast, the smouldering for other species (i.e., NSO, SLQ, DSB, QMP, CTI) either quenched during the smouldering process or never initiated smouldering. An example of QMP smouldering and quenching is shown in Figure 8, with a flat tail at around 30 % mass remaining, indicating the end of the reaction.

Table 6 summarises the density, smouldering occurrence and the time to reach a remaining mass of 1 %. This time can be considered to approximately correspond to the time required to fully complete smouldering, since the asymptotic behaviour in Figure 8 indicates that 0 % mass may never have been reached.

The porosity (which can be deduced from density) of timber and char is crucial as it determines the oxygen availability in the smouldering front through oxygen diffusion.

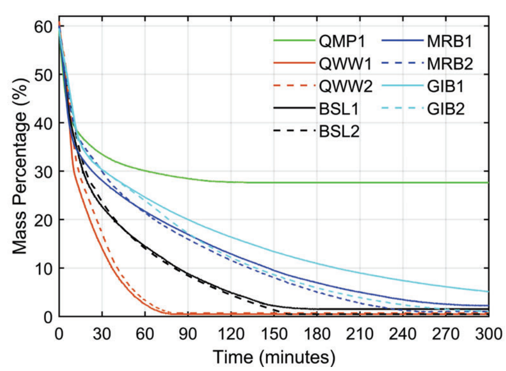


Figure 8: Mass evolution during the smouldering stage of QWW, QMP, BSL, MRB and GIB

https://doi.org/10.52202/069179-0225

Table 6: *Density, smouldering occurrence and time to reach less than 1 % mass during smouldering in nine timber species.*

Sample	Density (kg/m^3)	Self-sustained Smouldering? (Y/N)*	Time to <1% of initial mass (minutes)
GIB	1048	Y	299
NSO	504	N	-
SLQ	407	N	-
BSL	586	Y	159
DSB	1047	N	-
QMP	572	N	-
MRB	769	Y	252
QWW	467	Y	77
CTI	1213	N	-

* Y = yes, N = no smouldering initially propagated or quenched.

Table 7 combines the micro-scale measured Ea for oxidation, with the wood density and smouldering occurrence of the nine timber species tested at bench scale. These results show that:

- NSO, SLQ and QMP had the highest Ea_o, which meant they required higher residual heat from flaming combustion to initiate oxidation. This resulted in insufficient energy to initiate the reaction or caused quenching after some time, despite the relatively low densities of these species.
- CTI had the highest density (usually related to lower porosity) among nine species, which may have limited oxygen mass transfer. This would have negatively affected the reaction rate (Equation 5). Thus, despite CTI's relatively low Ea_o , smouldering did not initiate.
- In contrast, GIB with a similar density as CTI has a higher exponential factor A. However, it had the lowest smouldering rate compared to QWW, MRB or BSL, which had low Ea_o and low densities.
- DSB had the lowest Ea_o and similar density to GIB; however, the smouldering did not self-sustain. It suggests the presence of yet unknown underlying factors affecting smouldering. Further tests are required to reduce uncertainties arising in the kinetic parameters in the model.

Figure 9 graphs wood density against activation energy and demarcates the occurrence of self-sustained smouldering. High Ea_o, above a threshold between 120 and 160 kJ/mole, appeared to prevent self-sustained smouldering for species with a relatively low density. Oxidation in this range for those timber species required higher energy to initiate, which was seemingly not compensated by the increased oxygen supply that occurs in lower density (and thus higher porosity) species.

DSB and GIB have a similar density around 1050 kg/m^3; the former did not smoulder while the latter smouldered. At the same time CTI did not self-sustained smoulder, which could be attributed to its high density. Similarly, an activation energy threshold may exist around 110 kJ/mole – where two low density species (i.e., NSO and QWW) exhibited different smouldering performances. A distinction in Ea_o between these species cannot be confirmed with confidence according to the errors arising from the imperfect linear fit. These results suggest that the boundary defining the occurrence of self-sustained smouldering is sensitive to experimental variability at the bench and micro-scale (e.g., limited repetitions, measurement error, imperfect fitting, and apparatus heating non-uniformity). Furthermore, underlying parameters could affect the smouldering behaviour and merit further study. For example, the pre-exponential factor A of oxidation was the lowest for DSB (2.8E+06 s^{-1}, Table 4), which could help to explain why the smouldering quenched midway, as effective collisions for those molecules beyond the Ea_o failed to generate sufficient heat to overcome the heat losses and energy required for further pyrolysis.

Table 7: *Ea_o and A of oxidation, densities and smouldering occurrence for nine timber species.*

Sample	Ea_o (kJ/mole)	A (s^{-1})	Density (kg/m^3)	Smouldering (Y/N)
GIB	93.6	1.5E+10	1048	Y
NSO	115.5	4.0E+12	504	N
SLQ	161.2	5.0E+08	407	N
BSL	78.5	2.5E+08	586	Y
DSB	65.1	2.8E+06	1047	N
QMP	188.8	2.3E+22	572	N
MRB	97.9	7.0E+10	769	Y
QWW	107.6	2.7E+12	467	Y
CTI	87.9	1.4E+09	1213	N

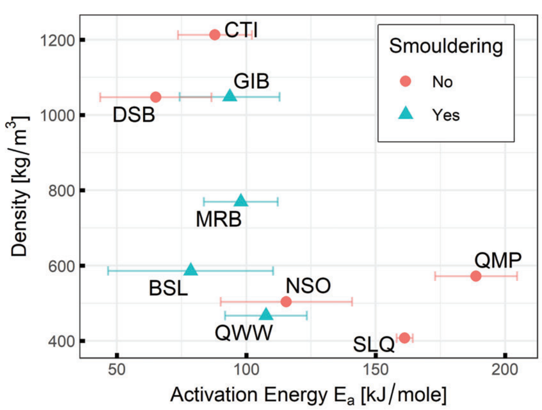


Figure 9: *Scatter plot of occurrence of self-sustained smouldering for nine timber species after 40% mass loss during flaming combustion under 20 kW/m² versus activation energy of oxidation stage. Error bar refers to standard error arising from linear fit.*

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3.3 Limitations

Some experimental conditions in this study were deliberately conservative in detecting distinct behaviour between species in smouldering. This allowed comparisons between smouldering and activation energy or density, providing fundamental knowledge about the link between self-sustained smouldering and micro-scale parameters or material properties. However, it should be acknowledged that completely dry timber is unlikely to exist in the field, even in wildfire conditions, where mean moisture contents have been reported as ranging between 3 to 6 % [23]. Thus, the results of smouldering for individual species tested herein should not be interpreted to completely account for the smouldering propensity of these species under field conditions.

While the moisture contents were chosen conservatively to be as low as possible to limit variability between species, the ventilation conditions were also chosen as low as possible to reduce their influence on the results and focus on the timber's intrinsic kinetic and physical properties instead of external conditions. The ventilation conditions were non-conservative, and increased airflow may increase the occurrence and rate of smouldering.

Further studies on external effects may help improve our understanding of smouldering factors and develop better selection criteria for bushfire performance that consider performance beyond the flaming period.

4 CONCLUSION

This paper investigated multiple factors that may affect the rate and occurrence of smouldering. Some qualitative conclusions are:

- Grey Ironbark (GIB) is considered a suitable timber species for BAL-19, and MRB is on the list of bushfire-resistant timbers. However, both show propensities to self-sustained smoulder under extreme conditions, indicating the need for more appropriate methods for assessing bushfire performance.
- Activation energy and density combined to affect the rate and occurrence of smouldering. Overall, low density and Ea_o should facilitate self-sustained smouldering.

Future work should be done to reinforce the conclusion:

- More timber species, covering a wider range of densities (i.e. complementary data points).
- More heating rates to increase confidence in linear fitting of the activation energy for each species.
- Other parameters to assess the influence of further factors (e.g., primary elemental composition difference).

ACKNOWLEDGEMENT

This research was supported by the National Centre for Wood Durability and Design Life, a collaborative program between the University of the Sunshine Coast, The University of Queensland, and the Queensland Department of Agriculture and Fisheries and funded by Forest and Wood Products Australia. The authors greatly appreciate technical support from the UQ Fire Laboratory manager, Mr Jeronimo Carrascal, during this work.

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