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Review

A Review of Leaf-Level Flammability Traits in Eucalypt Trees

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Abstract: With more frequent and intense fires expected under future climate conditions, it is important to understand the mechanisms that control flammability in Australian forests. We followed a systematic review approach to determine which physical traits make eucalypts leaves more or less flammable. Specifically, we reviewed 20 studies that covered 35 eucalypt species across five countries and found that leaf water content, leaf area (LA), and specific leaf area (SLA) are the main drivers of leaf flammability. These traits are easy and straightforward to measure, while more laborious traits (e.g., volatile organic compounds and structural carbohydrates) are seldom measured and reported. Leaf flammability also varies with species, and, while the biochemistry plays a role in how leaves burn, it plays a minor role in fire behaviour at landscape scales. This review highlights the range of different protocols used to measure flammability and leaf water content, warranting caution when comparing traits and results between studies. As a result, we propose a standardised protocol to measure leaf water content and advocate for long-term measurements of leaf traits and flammability. This study not only contributes to the understanding of how and why eucalypt leaves burn but also encourages research into the relative importance of traits in influencing flammability and provides a guide for selecting traits that can be monitored using satellite images to inform fire management policies and strategies.

Keywords: fire; ignition; combustion; fuel moisture content; leaf morphology; dry matter content

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1. Introduction

Fires are common in many landscapes across the globe because they help maintain ecosystem health, promote reproduction and regrowth [1]. However, changes in the climate system are expected to make fires more intense and frequent [2,3]. For example, the catastrophic 2019–2020 fires in Australia resulted in the death of 33 people, burned more than seven million hectares of forests and woodlands, and had a major impact on biodiversity, including threatened species [4–7]. Between 2001–2018, fires burnt approximately 2% of the total eucalypt forest area in Australia each year; in stark contrast, during the 2019–2020 fire season, 18% of their area was burnt, with several fires surpassing 100,000 hectares in extent, thus highlighting the need to understand the drivers behind these events [7,8]. With communities, industries, and critical infrastructure expanding into fire-prone areas, the potential for fires to affect them is increasing. As recently demonstrated in Australia and elsewhere, current methods of suppression and containment are becoming increasingly inefficient, costly, and dangerous for firefighting crews and volunteers; therefore, new monitoring and response strategies are urgently needed [6,9].

Recent national [6,9] and international reports [10] have recommended better monitoring of forest fuels and their flammability as a way of reducing fire risk. Prescribed burns and other risk management activities rely on a thorough understanding of what makes vegetation ignite and spread a fire; that is, they rely on understanding the flammability of the vegetation, which controls the likelihood of ignition, fire intensity, rate of spread, behaviour and, as a result, the fire risk to communities and infrastructure [11,12]. Despite this, studies regularly draw on physical (e.g., slope) and meteorological variables (e.g., vapour pressure deficit) to estimate vegetation flammability and fail to assess the flammability characteristics of the vegetation itself.

Flammability is the ability of leaves and vegetation to burn (i.e., ignite and sustain a flame) [13,14]. Building on [15], and following [16] we disaggregate flammability into four components: ignitability, combustibility, sustainability, and consumability. Ignitability refers to how easily leaves catch fire or burn, measured as time to ignition [s]. Combustibility is the speed and intensity at which leaves burn, often measured as heat released [MJ], mass loss rate [$g \cdot s^{-1}$], flame front spread [$mm \cdot s^{-1}$], or maximum temperature of the burning sample [°C]. Sustainability refers to the length of time leaves continue to burn once ignited, measured as burn duration [s], and consumability is a measure of how much leaf material is burnt [g]. These four flammability components can be positively or negatively related between themselves and are influenced by different leaf traits [17]. The main leaf-level traits that influence these components of flammability can be classified into five broad categories: water content, physical traits, volatile organic compounds (VOCs), structural carbohydrates, and other compounds. Physical traits, for example, include leaf size, while volatile organic compounds refer to metabolites and molecules such as leaf oils that make eucalypt trees more flammable than other trees and shrubs. Leaf water content, or the amount of water stored in the leaves, is often measured separately from other traits and, thus, is considered as a separate characteristic of leaves. These leaf-level flammability traits are expected to vary between species, between geographical locations, as well as over time in response to different global change drivers [18,19]. Gaining insights into the dynamics of the primary flammability characteristics in vegetation communities is an important step in understanding which eucalypt species are more likely to burn.

The word "eucalypt" refers to a group of trees and shrubs in the Myrtaceae family, most of which are native to Australia, and can belong to the *Eucalyptus*, *Corymbia*, or *Angophora* genera [20]. There are approximately 800 species of eucalypts, and approximately 110 have been introduced to over 90 countries around the world where they grow naturally and in dedicated plantations [21]. In Australia, eucalypts grow in every state and territory (Figure 1) dominating 77% of the country's native forests [20,22]. Eucalypt forests are fire-prone environments, and are believed to have evolved to promote the occurrence of fires [13,23,24]. Reference [25] hypothesised that some plant communities evolved traits that enhanced their flammability. For example, fire-adapted plants can survive exposure to heat such as the fire tolerance of their stems [26]. They can also benefit from fire directly, such as when fire initiates cone opening and seed release, or indirectly, as fewer competing plants of fire-sensitive species remain [13]. Fossil records show that around 60 million years ago, the Myrtaceae family evolved traits that helped them not only endure fires, but to recover quickly after these events [26,27]. At the leaf level, eucalypts have specific characteristics or traits that make them highly flammable compared with other species; therefore, it is critical to understand not only which, but also how, leaf-level traits make eucalypt forests fire-prone environments.

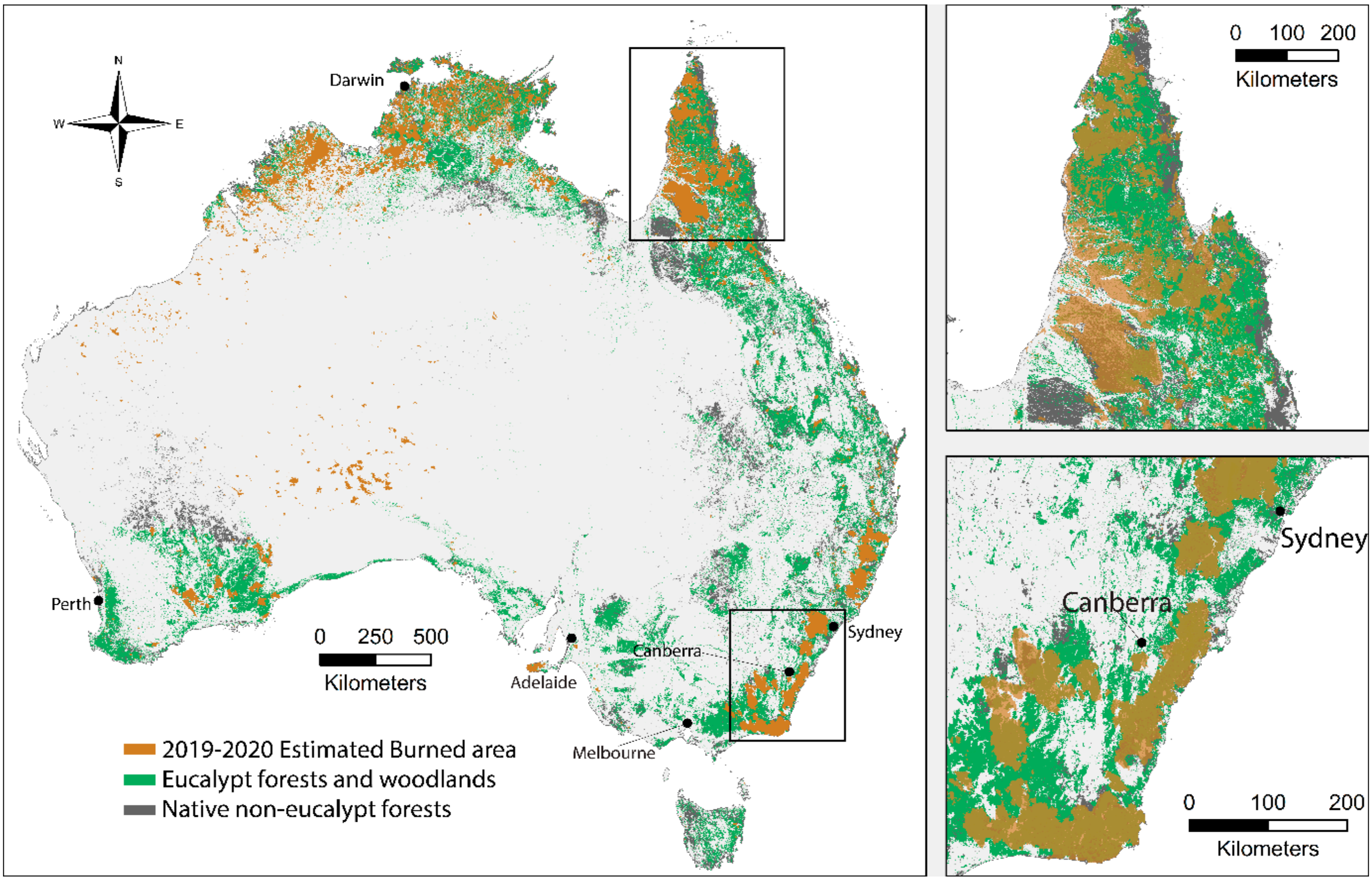

Figure 1. Distribution of native eucalypt forests and woodlands in Australia (green), and the calculated extent of different fires between September 2019 and June 2020 (brown), including prescribed and low-intensity fires. Insets show regions where large areas of native eucalypt forests and woodlands burned during the 2019–2020 fire season. Sources: distribution of eucalypts [20], burned extent [28].

A range of studies have investigated the flammability of eucalypts (e.g., [29,30]) and other tree and shrub species in Australian forests. However, these studies vary widely in which aspect of flammability they target, the species, methods, and the traits they measure. More recently, Some researchers [31,32] reviewed the literature related to the flammability of live and dead fuels, but did not focus specifically on eucalypt trees. As a result, there are fragments of information scattered around the literature that impede a comprehensive assessment of eucalypt flammability and prevents deriving practical suggestions for flammability at scale for improved fire prevention and recovery.

This review aims to (1) synthesise the existing literature on leaf-level traits that influence the flammability of eucalypt species, (2) understand *how* and *why* these traits change the flammability at the leaf level, and (3) identify priorities for future research. Through compiling available information on how flammability relates to leaf-level traits, this review will guide methods for targeted monitoring of forest fuels and their flammability status, including the design of future technologies targeting forest flammability across Australia and other regions where eucalypts are abundant.

2. Systematic Review

We followed a systematic review approach to screen the published literature and find the leaf traits that influence eucalypt flammability [33] (Figure 2).

We consulted two databases (Scopus and Web of Science) on 8 September 2021 using a search strategy comprising three terms: vegetation type, fire or flammability component, and the part of the tree (i.e., leaf or shoot):

> (eucalypt*) AND
> (*fire* OR flammab* OR ignit* OR combust*) AND
> ((leaf flammab*) OR (shoot flammab*) OR (leaf trait*))
>
> (eucapyto) AND
> (fuego OR incendio OR (incendio forestal) OR *flamable OR ignici* OR combust*) AND
> (hoja OR caracteristica) AND
> (Language: Spanish)
>
> (Eucalipto) AND
> (Fogo OR incêndio OR (incêndio florestal) OR *flamável OR ignição OR combustão OR combustível) AND
> (folha OR (folha de árvore) OR característica) AND
> (Language: Portuguese)

We used the wildcard character "*" to account for variations in words such as *wildfires*, *fires*, *ignition*, and *ignitability* and searched for documents published between 1980–2021 to cover the most up-to-date literature. Importantly, we avoided studies that involved bark, stems, trunks, and wood and focused only on fresh leaves, shoots, and litter. Likewise, we found that variations in the terms "*sust**" and "*consum**", for sustainability and consumability, respectively, produced documents not related to fires; therefore, these terms were excluded from the search. To account for publications from Latin America and Western Europe (i.e., Portugal, Spain, and Brazil) where eucalypts are also common, we translated the search strategy into Spanish and Portuguese and included documents in the review when appropriate.

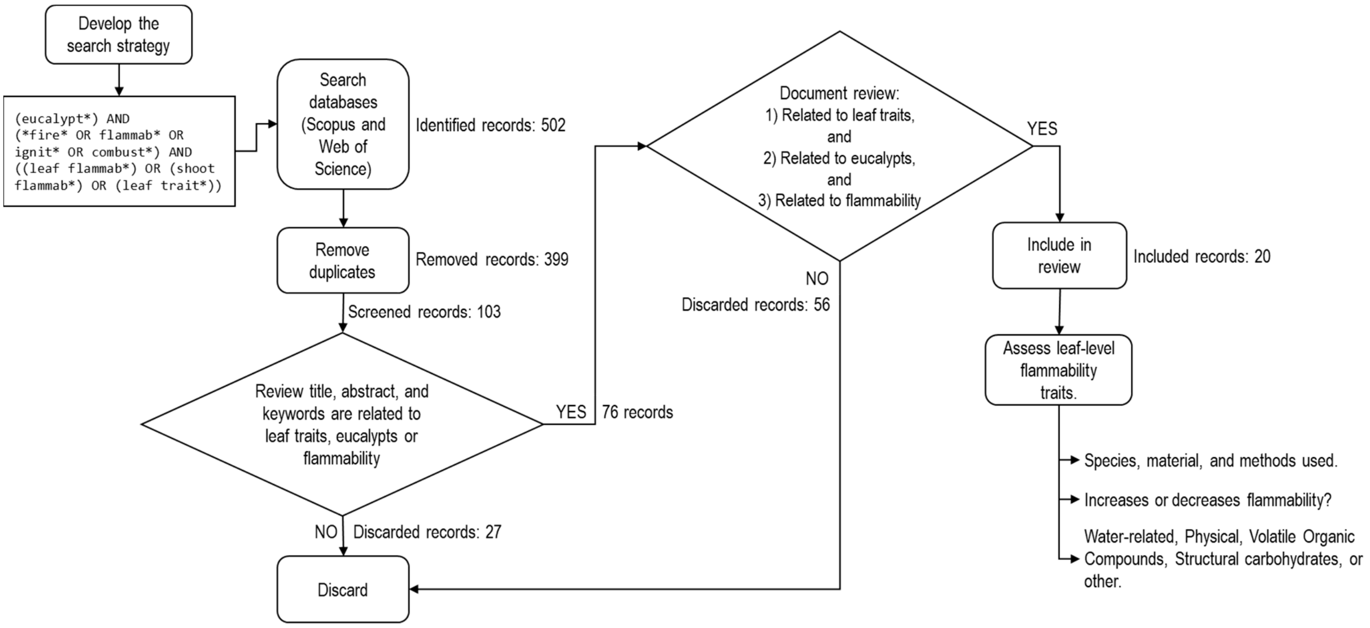

Figure 2. Workflow used to identify and select the literature records on leaf-level traits that influence eucalypt flammability.

Document Screening and Information Extraction

Duplicate results were removed using a reference manager, and we eliminated documents unrelated to leaf-level flammability traits. Afterwards, we uploaded the final 103 documents to Sysrev [34] for information extraction. We reviewed the title, abstract, and keywords of each article and applied the following two criteria for inclusion or exclusion: (1) the document had to relate at least one of the flammability components to at least one leaf-level trait, and (2) the document had to involve at least one eucalypt species in the analysis of flammability. The remaining documents (n = 76) were further analysed and 56 of them were declared ineligible (Figure 2), leaving 20 to be included in this review. We used Sysrev to manually extract preliminary information from each document before a full document review (see Supplementary Table S1). We then reviewed each document and grouped the leaf-level traits into five categories: water-related traits, physical traits, VOCs, structural carbohydrates, and other traits.

3. Linking Leaf-Level Traits to Flammability

Of the 20 peer-reviewed documents which reported the relationships between flammability and leaf-level traits in eucalypt forests, most studies (70%) were from Australia (n = 14), and 70% of the studies were published after 2010 (Supplementary Figure S1). Overall, 35 species of eucalypts were assessed in the flammability studies, but *Corymbia gummifera* (Gaertn.) K.D.Hill & L.A.S.Johnson, *Eucalyptus camaldulensis* Dehnh., *E. globulus* Labill., *E. sparsifolia* Blakely, *E. saligna* Sm, and *E. viminalis* Labill. were the most used for flammability experiments (Figure 3A). *C. gummifera* and *E. saligna* were included in most of the studies focusing on Australian vegetation, while *E. globulus*, *E. camaldulensis*, and *E. viminalis*, which are commonly used for plantations, appeared in documents from Australia and Chile, Spain and Greece, and Australia and New Zealand, respectively.

Among the 14 leaf traits measured across all studies (Figure 3B), leaf water content, leaf size (length and width [mm]), leaf area (LA, the one-sided area of a fresh leaf [mm^2]), and specific leaf area (leaf area divided by the leaf oven-dry mass [$mm^2 \cdot g^{-1}$], SLA) were the most frequently assessed. Leaf water content was measured in 19 of the studies (95%), leaf size and LA were measured in 6 studies (30%), and SLA and LA divided by leaf volume in four (20%) studies. All other traits were measured in fewer than four studies (Figure 3B). It is worth noting that some studies reported recording multiple traits; however, not all traits were used as explanatory variables for flammability. For example, many authors measured leaf thickness, but only two studies reported a relationship between leaf thickness and flammability.

Fresh leaves, dried leaves, and leaf litter were used in 90% (n = 18), 56% (n = 13), and 10% (n = 2) of the studies during combustion experiments, respectively (Table 1). Most studies assessed leaf ignitability (90%, n = 18), sustainability (60%, n = 12), or combustibility (60%, n = 12), while only 20% of the studies (n = 4) measured leaf consumability. Methods to measure the flammability of eucalypt leaves and shoots also differed greatly, with 17 studies using a single method, and three studies using two or more methods (Table 1). Commonly used methods include: a muffle furnace (n = 6 studies, 30%) which is a vessel capable of reaching very high temperatures (>700 °C) without a flame; a self-sustaining and controlled pilot flame (n = 5 studies, 25%); an epiradiator (n = 3 studies, 15%) consisting of an incandescent source that emits radiant heat; and a bomb calorimeter (n = 3 studies, 15%), which measures the heat released by combustion inside a sealed vessel. These differences in methods to measure flammability highlight the challenges in comparing results across studies [35].

In total, the studies found 35 times that leaf traits were related to measures of ignitability, 24 times to sustainability, 21 times to combustibility, and 4 times to consumability (Table 2). Most studies agreed that leaves with high water content were less ignitable and less combustible than leaves with low water content; larger and heavier leaves will sustain a flame for longer periods of time as well as being more ignitable and combustible than smaller and lighter leaves. In addition, leaves with high concentrations of VOCs and structural carbohydrates are more flammable than those with lower concentrations (Table 2).

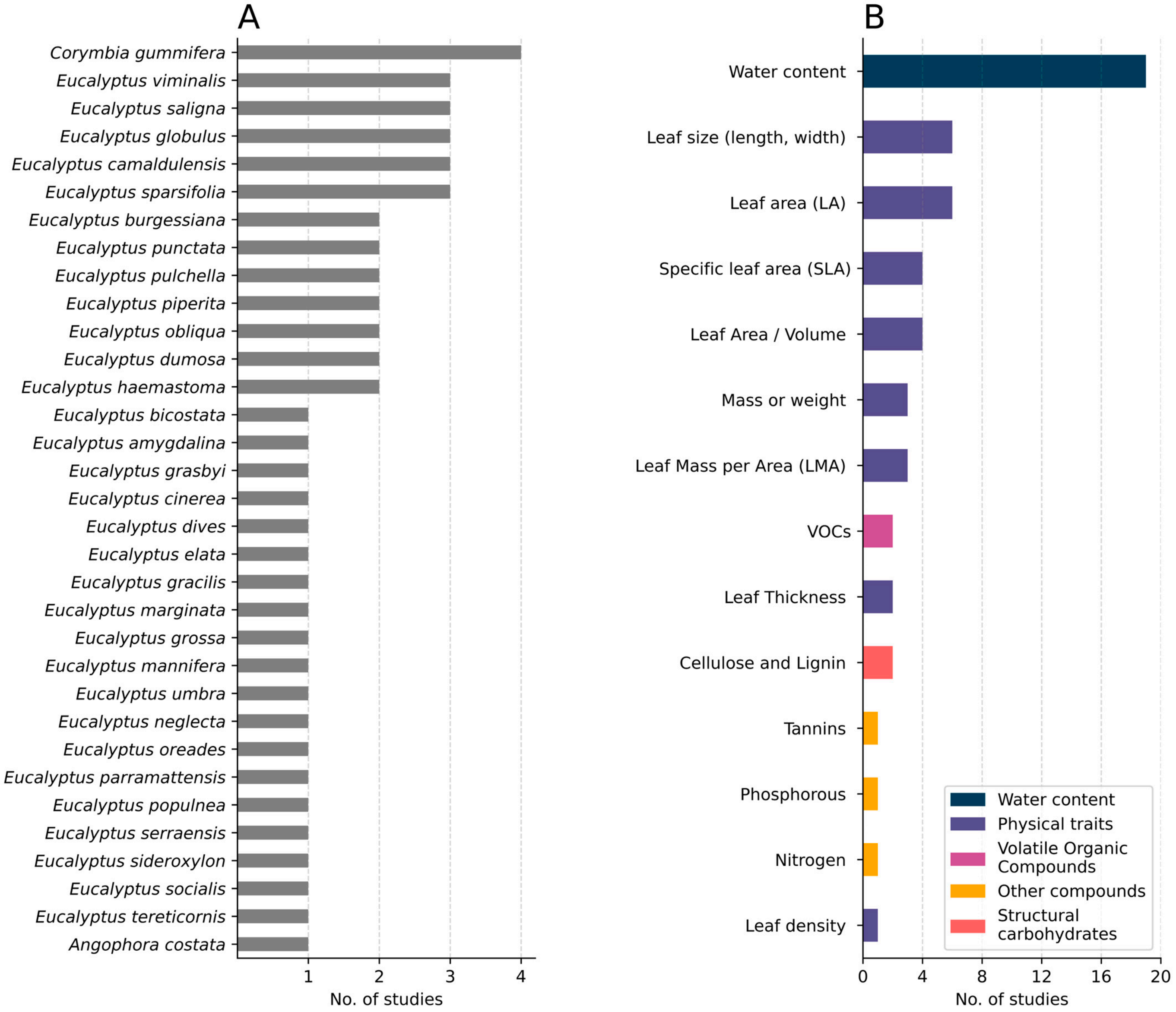

Figure 3. Summary of the studies considered in this review. Panel (**A**) shows the species used in all studies. Panel (**B**) shows the leaf traits measured in all studies, where different colors represent the five groups analysed in Section 3.

Table 1. Summary of the methods used in flammability experiments in the studies assessed in this review. FL = fresh leaves; DL = dried leaves; LL = leaf litter.

Scale of Experiment	Material Used	Heating or Ignition Source	Reference
Leaf	FL, DL	Pilot flame	[36]
	FL, DL	Pilot flame	[37]
	FL, DL	Pilot flame, bomb calorimeter	[38]
	FL, DL	Radiator cone	[39]
	FL, DL	Muffle furnace	[29]
	DL	Pilot flame	[40]
	FL, DL, LL	Muffle furnace	[30]

Table 1. *Cont.*

Scale of Experiment	Material Used	Heating or Ignition Source	Reference
Leaf	FL, DL	Bomb calorimeter, Cleveland open-cup tester	[41]
	FL, DL	Epiradiator, bomb calorimeter, Cleveland open-cup tester	[42]
	FL	Muffle furnace	[43]
	FL	Muffle furnace	[44]
	FL	Muffle furnace	[45]
	FL	Epiradiator	[46]
	FL	Epiradiator	[47]
	FL, DL	Muffle furnace	[48]
	FL, DL	Mass-loss calorimeter	[49]
	FL, DL	Cone colorimeter	[50]
	FL, DL	Cone colorimeter	[51]
	LL	Pilot flame	[52]
Shoot	Shoot	Grill	[16]

Table 2. Relationships between leaf-level traits and flammability components. (+) indicates that larger values increase flammability. (-) indicates that larger values decrease flammability. An asterisk (*) indicates the absence of a relationship between the leaf traits and flammability components. Color coding is the same as Figure 3B. FL = fresh leaves; DL = dried leaves; LL = leaf litter.

Category	Trait Name	Material Used	Ignitability	Combustibility	Sustainability	Consumability	Reference
Water content	Water content	DL	(-)	(-)	(-)		[40]
		FL	(-)		*	*	[43]
		FL	(-)	(-)	(+)		[44]
		FL	(-)				[45]
		FL	(-)		(-)		[46]
		FL	(-)	(-)	(-)		[47]
		FL	(-)	(-)		(-)	[16]
		FL, DL	(-)		*		[36]
		FL, DL	(-)	(-)	*		[37]
		FL, DL	(-)				[39]
		FL, DL	(-)				[29]
		FL, DL	(-)				[41]
		FL, DL	(-)		(+)		[42]
		FL, DL	(-)				[48]
		FL, DL	(-)	(-)		(-)	[49]
		FL, DL	(-)	(-)	*	(-)	[50]
		FL, DL	(-)	(-)			[51]
		FL, DL, LL	(-)				[30]
		FL, LL		(-)			[38]
Physical traits	Leaf area (LA)	FL	(+)		(+)	(+)	[43]
		FL	(-)	(+)	(+)		[44]
		FL			(+)		[45]
		FL, DL	*				[37]
		FL, DL	(+)				[48]
		LL		(+)			[52]
	Leaf area/volume	FL, DL		(-)			[36]
		FL, DL	(+)				[29]
		FL, DL, LL	(-)				[30]
		LL		*			[52]
	Leaf density	LL		*			[52]
	Leaf Mass per Area (LMA)	FL	(-)		(+)	(+)	[43]
		FL	(-)	(+)	(+)		[44]
		FL	(-)		(+)		[45]

Table 2. *Cont.*

Category	Trait Name	Material Used	Ignitability	Combustibility	Sustainability	Consumability	Reference
Physical traits	Leaf size (length, width)	FL	(+)		(-)		[46]
		FL	(+)				[47]
		FL, DL	*				[37]
		FL, DL	(+)				[48]
		FL, DL, LL			(+)		[30]
		LL		(+)	(+)		[52]
	Leaf thickness	FL, DL	*				[48]
		FL, LL	(-)				[38]
	Mass or weight	DL	*	(+)	(+)	(+)	[40]
		FL, DL, LL	(+)		(+)		[30]
		FL, LL		(+)	(+)		[38]
	Specific leaf area (SLA)	FL, DL					[37]
		FL, DL	(+)				[48]
		FL, DL, LL	(+)		*		[30]
		LL		*			[52]
Volatile Organic Compounds	VOCs	FL, LL		(+)			[38]
		FL, DL	(+)		(+)		[42]
Structural carbohydrates	Cellulose and lignin	FL, DL, LL	(+)		(+)		[30]
		LL		*			[52]
Other compounds	Nitrogen	FL, DL, LL			(-)		[30]
	Phosphorous	FL, DL, LL			(-)		[30]
	Tannins	FL, DL, LL			(+)		[30]

3.1. Water Content

Water content in leaves has long been promoted as the main driver of forest and leaf-level flammability [25,40], but there are discrepancies in how it is calculated and measured (see also Section 4.1). Fuel Moisture Content (FMC) is defined as the ratio between the mass of water and the dry mass of a leaf (Equation (1), [53]).

$$\mathrm{FMC} = \left(\frac{\frac{m_{fresh} - m_{dry}}{Area}}{\frac{m_{dry}}{Area}} \right) = \frac{m_{fresh} - m_{dry}}{m_{dry}} \tag{1}$$

where m_{fresh}, m_{dry}, and *Area* are the fresh mass, dry mass, and area of the leaf, respectively.

The studies reviewed here, however, described different ways of measuring moisture content (MC). For example, some studies [43,48,50] used two different definitions of MC (Equations (2) and (3), respectively), while other studies did not explicitly state the methods used to quantify MC.

$$\mathrm{MC} = \frac{m_{fresh} - m_{dry}}{m_{fresh}} \tag{2}$$

$$\mathrm{MC} = \frac{m_{fresh}}{m_{dry}} \tag{3}$$

As a result, there is a lack of consensus on how to quantify the amount of water in leaves, making it challenging to compare studies without the raw data (see also Section 4.1). In this paper, we use FMC to describe the amount of water in eucalypt leaves because it is a term commonly used in the context of fire management activities.

FMC affects flammability in three ways. Firstly, water acts as a heat sink in the leaves; in doing so, water changes from liquid to gaseous state. During the heating process, water consumes more energy than other leaf components, thereby preventing the pyrolysis of the leaf. While pyrolysis and evaporation can occur simultaneously [50], water affects both the ignitability and the overall heat of combustion. Intuitively, when FMC is high, more energy is spent in heating the water rather than igniting and pyrolyzing other leaf components [49]. As a result, the energy released by the pyrolysis reaction is lower when FMC is high, delaying and reducing the ignitability, combustibility, and consumability of eucalypt leaves [36,38,41,42,48,50].

Secondly, FMC reduces flammability through evaporative cooling. When water evaporates, it reduces the temperature of the leaf surface; therefore, more energy is needed to ignite the leaf and ignition is delayed [44,49,50]. Thirdly, when leaf water evaporates, it dilutes the gases in the combustion zone and displaces the oxygen molecules, leaving fewer oxygen molecules available for ignition and combustion [49,50]. This dilution of gases reduces the sustainability, consumability, and combustibility of the leaves; thus, higher water content makes leaves less flammable.

The relationship between FMC and ignitability seems to be linear, with higher FMC leading to longer time to ignition (i.e., reduced flammability) [40]. Researchers [51] found that higher FMC in fresh leaves and dead leaves (i.e., litter) led to reduced ignitability regardless of the intensity of the heat flux. Specifically, it was found that fresh eucalypt leaves required significantly higher temperatures of ignition (472 °C vs. 377 °C) and heat fluxes (24.5 kWm^{-2} vs. 15.5 kWm^{-2}) when compared with dry leaves. These linear relationships were also reported by [39], suggesting that FMC is a crucial factor for eucalypt flammability. Interestingly, other researchers [48] found that fresh leaves of native Australian species (including eucalypts) had lower water content than exotic species, but both native and exotic plants exhibited similar ignitability, suggesting that there were other traits influencing leaf flammability. This observation was also made by [30], who found that FMC was a key factor in overall leaf flammability but SLA was the main predictor of ignitability.

Despite the influence of moisture content on leaf flammability, few studies have continuously recorded data over prolonged periods of time (>1 year) and most studies have conducted short field campaigns (days to weeks). Several studies reported FMC values between 80–120% for fresh eucalypt leaves; however, FMC values in trees affected by drought heatwaves can fall well below 80% [54]. To develop predictive models that support operational fire management, it is important to capture the widest possible range of moisture content values, including values throughout the fire season and immediately before prescribed burns or wildfires. Despite this, we found that most studies reported only the mean value for FMC, rather than all measurements taken and their respective dates. The main caveat of reporting only the mean water content of leaves is that it removes the ability to track flammability changes over time and determine when and where leaves and trees are more likely to ignite (see also Section 4.2).

3.2. Physical Traits

Considering that LA, leaf size (length, width [mm]), and leaf weight or mass are directly related to SLA and leaf mass per area (leaf dry mass divided by leaf area [$\text{g}\cdot\text{mm}^{-2}$], LMA), we refer to LA, SLA, and LMA as the physical traits that drive flammability. Several studies suggest that LA, SLA, and LMA are the physical traits that exert the greatest influence on flammability. Researchers [29] analysed the leaves of 11 eucalypt species and found that leaf flammabililty was driven by SLA and moisture content, with the former explaining up to 80% of the variance in ignitability for some species. Almost two decades later, a study [30] was conducted that included various eucalypt species and concluded that leaves with high SLA ignited faster than those with lower SLA (Table 2). In that study, SLA showed a strong relationship with ignitability ($\geq$59% explained variance) in fresh plant material, while water content showed a weaker relationship (16% explained variance), thereby emphasising that morphological traits played a more important role in driving flammability than water content. Other researchers [43] also reported that higher LA and LMA resulted in faster ignition times (i.e., ignitability) and higher mass loss rates (i.e., combustibility). Similarly, it was observed [48] that fresh, larger leaves of Australian native species were more easily ignited than smaller leaves, and it was found [30] that LA and SLA were strong predictors of ignitability in fresh leaves, dried leaves, and leaf litter ($r^2 \geq 0.59$, 0.70, and 0.68 respectively) in native species including eucalypts. Using leaf litter from varied Australian tree and shrub species, researchers [52] found that larger leaves created more gaps in the litter beds, thus allowing better oxygen flow through the litter bed that increased the heat release rate (i.e., combustibility).

The relationships between physical traits and flammability are strong; however, not all physical traits affect every flammability component. On the one hand, larger leaves (i.e., high LA) generally have more mass available to burn, and each leaf can burn for longer; therefore, their consumability and sustainability are higher [36,44,45]. In addition, the layer of air immediately surrounding the leaves (known as the boundary layer) may change the temperature of the leaves and thus their flammability; for example, larger leaves often have thicker boundary layers and higher temperatures throughout the year compared with smaller leaves [44,48,55]. Moreover, the boundary layer may protect the leaves from abrupt temperature changes (e.g., a fire) by absorbing some of the radiant heat before it reaches the leaves; however, this hypothesis remains untested and may be negligible under operational fire management situations where biotic and abiotic factors play more important roles [55].

Conversely, leaves with high LMA and high density have greater thermal mass. This increased thermal mass implies that more energy is required to change the temperature of a leaf by a specific magnitude (e.g., 1 °C), thus reducing the ignitablity of the leaf. Leaves with high LMA need longer exposure times to a heat flux to ignite, or exposure to increased heat fluxes, as suggested by [38] and demonstrated by [45].

There are other compounding effects to consider in the context of flammability traits. Water content also plays a role in the overall thermal mass of the leaves. Given the same LMA, leaves with high water content should require more energy to ignite compared with leaves with low water content; however, we were unable to find experimental examples that support this hypothesis. It appears that water content and physical traits drive flammability but in opposite directions (Table 2). It is worth stating that findings obtained in controlled environments may not be directly applicable in large-scale fires, where other factors such as type of fire (e.g., surface, crown), wind speed, and topography may play a more significant role [56]. However, larger and heavier eucalypt leaves contribute to increased combustibility and sustainability by providing a greater fuel load available to burn and potentially holding higher concentrations of volatile organic compounds.

3.3. Volatile Organic Compounds

Volatile organic compounds (VOCs), essential oils, and extractives are terms that are used interchangeably in the literature and are related to polar compounds found in many plant species. These compounds include terpenes (e.g., monoterpenes, sesquiterpenes), organic acids, aldehydes, ketones, esters, and alcohols, which can be emitted by plants during most stages of biomass combustion [57–59]. Measurement and quantification of VOCs is often attained through gas or liquid chromatography and mass spectrometry, which can be expensive and requires specialised equipment; as a result, they are rarely measured. Terpenes represent the largest and more extensively studied group of compounds found in eucalypt leaves; therefore, this section mainly focuses on this group of VOCs, although the underlying principles also apply to other chemical groups.

Terpenes are unsaturated hydrocarbons derived from turpentine oil that contribute to the distinctive odour of eucalypt trees. In general, terpenes consist of chains of isoprene units (C_5H_8) biosynthesised from mevalonic acid, which are divided into monoterpenes (e.g., limonene, α-pinene) and sesquiterpenes (e.g., aromadendrene). Specialised glands in eucalypt leaves store these compounds, with younger leaves showing fewer, smaller glands than mature leaves [60]. The relationship between tree age and oil gland abundance implies that older trees likely store and secrete more VOCs, and these emissions vary with diurnal temperature, species, tree age, and tissue (e.g., leaves or flowers) [61]. The composition of VOCs in eucalypt trees has been thoroughly described and is known to vary from species to species [58], but their role in affecting flammability remains unstudied and largely a matter of speculation.

Researchers [38] have suggested that physical traits and water content alone cannot explain all the observed differences in leaf flammability. In that study, the authors indicated that eucalypts are more flammable than other species due, in part, to their high concentration of oils. Similarly, Other studies [48,52] have speculated that higher concentrations of oils resulted in leaves and leaf litter being more easily ignited than those with lower oil concentrations. While the effects of terpenes on flammability have been explored in other species (e.g., [62]), this hypothesis was only recently tested in eucalyptus leaves [42] and it was demonstrated that high concentration of VOCs (mainly terpenes) reduced the time to ignition of *E. globulus* leaves, making them more flammable than other species.

Terpene concentrations and emissions alter eucalypt flammability in two ways: firstly, terpenes often have low flash points and low flammability limits. A low flash point means that they can ignite at low temperatures (e.g., 49 °C for 1,8-Cineole) and a low flammability limit means that ignition is possible even at low concentrations in the air. These two characteristics increase the ignitability of eucalypt leaves [61,63]. Under different experimental conditions and using different plant materials [30], it was found that terpene emissions increased with higher heat fluxes in a process comparable to distillation. For example, compounds with low flash points were emitted at ambient temperature, but when leaf temperature increased (e.g., due to a heatwave or a nearby ignition source) compounds with higher flash points were released to the atmosphere, increasing the flammability of the leaf boundary layer. While some studies argue that terpene concentration is proportional to leaf area [44], oil yields vary with species and are not necessarily dependent on leaf size [58,64].

Secondly, terpenes, and other oily compounds (e.g., cuticular waxes) have high calorific values, meaning that they can release more energy during combustion, hence increasing the combustibility of eucalypt leaves. Researchers [38] described the calorific values of live and dead leaves from a range of species found in Tasmanian forests and found that eucalypts had the highest calorific values out of all species tested. The results of other studies [41,42] also suggest that during combustion, *E. globulus* leaves released larger amounts of energy when compared to Chilean native species, due, in part, to the concentration of oils and terpenes in the leaves.

3.4. Structural Carbohydrates

Structural carbohydrates (cellulose, hemi-cellulose, and lignin) are the main components of plant cell walls and leaf dry mass (Section 3.2). Cellulose and lignin are polymers thought to affect the sustainability and combustibility of leaves, as well as in the formation of char or charcoal. Cellulose and lignin can easily be extracted from leaf material using solvents and acid digestions. While these methods are straightforward to implement, they are time-consuming and require the use of hazardous chemicals, resulting in low adoption rates. Only two of the studies reviewed made direct comparisons between structural carbohydrates and the flammability of eucalypt leaves, while other documents provided only suggestions about the role of these substances during combustion. It was reported [30] that lignin had a small but significant positive effect on the ignitability and sustainability of eucalypt leaves; similarly, other researchers [52] stated that lignin had a small effect on flammability, but this effect was negligible when compared with the influence of leaf physical traits.

Some by-products of lignin and cellulose pyrolysis include phenols and other compounds with high calorific values (see Section 3.3). Researchers have explained [52] that when leaves are exposed to a flame, the structural carbohydrates can transform into gases, tars (condensable gases), or char (charcoal), depending on the amount of oxygen available. When oxygen is abundant, more gases are expected to form; otherwise, char formation is favoured. Gases and tars readily ignite, providing fuel for the flame front and transferring heat from the flame source to the leaves, facilitating flame propagation [65,66]. Char, on the other hand, reduces leaf flammability by creating a carbon-rich layer on the surface of the leaves that reduces the transfer of heat and oxygen to the inner layers of the leaf. In addition, char formation limits the availability of cellulose and lignin for the pyrolysis reactions to take place; that is, char formation reduces the amount of fuel available to burn [59,66,67]. The influence of lignin and cellulose on the flammability of eucalypt leaves was quantified by researchers [30] who concluded that higher lignin content explained up to 3% of the ignitability in fresh leaves and up to 8% of flame sustainability in dry and senesced leaves. Related work [52] suggested that physical traits affected flammability much more than lignin and did not reveal a significant relationship between lignin and leaf flammability. In summary, findings from these studies suggest that structural carbohydrates play a minor but non-negligible role in eucalypt flammability, underscoring the need for further research in this area.

3.5. Other Compounds

Compounds such as phosphorous and tannins have received less attention in the existing literature compared with other traits. Phosphorous is often used in the production of industrial flame retardants [68] and may play a similar role in trees and leaves. For example, in experimental and simulation work [66,69], it was demonstrated that phosphates reduced the ignitability and combustibility of leaves. In both cases, the authors used samples of pure cellulose (Whatman filter paper No. 40) treated with 1 mL of 10.1 g/L $(NH_4)_2HPO_4$ to simulate the foliar concentration of phosphates across a wide range of trees and shrubs. The authors found that phosphates inhibited the production of tar and favoured the production of char on the surface of the leaves, resulting in a modest increase in ignition temperatures (see Section 3.4). These works [66,69] were not related to eucalypts, and were hence excluded from this review, but they highlight possible effects of phosphorous on eucalypt leaf flammability and the need for further research.

In the current review, only a single study [30] investigated the role of phosphorous, tannins, and nitrogen in eucalypt flammability, highlighting an important knowledge gap. Specifically, the authors found that higher phosphorous and tannin concentrations in dried leaves and leaf litter reduced flame duration (i.e., combustibility), but no effect was detected on fresh leaves. Additionally, the study revealed that tannins explained 5–9% of the variation in smoulder duration and seemed to increase char production, thus increasing the sustainability of combustion in this case. Conversely, nitrogen was found to reduce the flame duration, impacting combustibility in both dried and senesced leaves, while it had no significant effect on the ignitability of the leaves.

4. Discussion

We compiled information about how and why leaf-level traits affect the flammability of eucalypt leaves (Figure 4). We found that published studies often combine the flammability traits of eucalypts with those of other vegetation families and few disaggregate the results by genera or species. Studies that aggregate flammability traits by family or phyla provide a good understanding of flammability in broad terms; however, data aggregation makes it impossible to decouple the effects of individual leaf traits on the flammability of eucalypts from the flammability and traits of other species. Moreover, there is no standardised set of methods, traits, and flammability components (Figure 3, Table 1); as a result, comparison between studies and species was unviable.

Understanding flammability at the genera and species level becomes more important when eucalypts are planted and grown outside of their native range, where they are blamed for their disproportionate contribution to fires that affect people and communities [70,71]. Due to the limited availability of quantitative data to support such claims, there is a clear need for a continued investigation of the flammability traits of eucalypts in Australia and elsewhere.

This literature review revealed that the key leaf-level drivers of flammability in eucalypts are water content and the physical traits of leaves, and thus, they should be prioritised for assessing forest fuel flammability across Australia and other regions where eucalypts grow. Consistent with the literature, we found that physical traits (LA, SLA) and water content were the most studied factors of leaf-level flammability in eucalypts compared with other biophysical components (Table 2). Recent reviews [31,32] also found that water content and physical traits were important drivers of flammability in live and dead fuels, but did not take in-depth look at eucalypt trees.

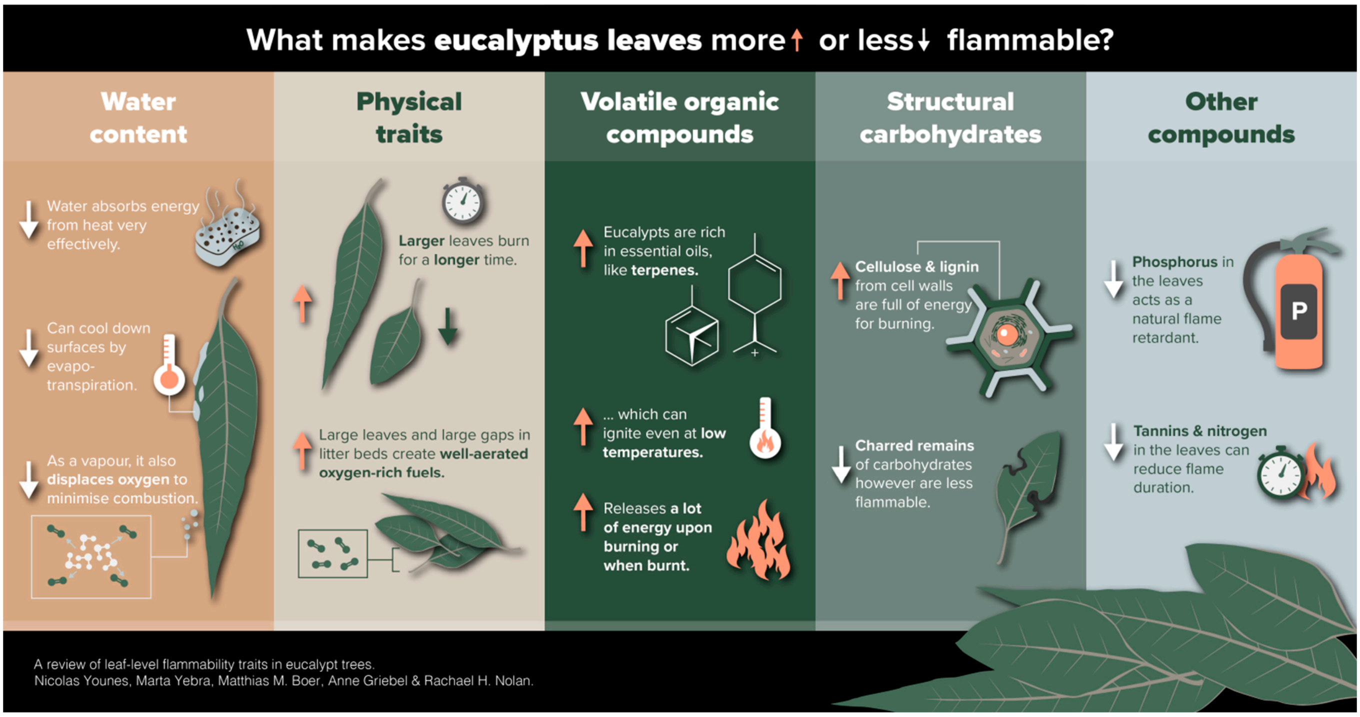

Figure 4. Summary of the leaf-level traits that make eucalypt leaves more or less flammable.

Importantly, our findings and those of others must be interpreted with caution because traits that are simple to measure are overrepresented in the literature and may be perceived as more important than traits that require complex and time-consuming protocols. Physical traits and water content are straightforward to measure and interpret, as they do not require specialised equipment or large amounts of resources compared with structural carbohydrates and VOCs. For example, measuring the leaf area plus fresh and dry weights often allows the derivation of leaf length, width, and perimeter as well as FMC, SLA, and LMA. There have been few in-depth investigations into the role of structural carbohydrates and VOCs in flammability [62,72], and these are often non-existing for eucalypt species (see Section 3.3). Due to their strong potential to act as ignition accelerants, comprehensive assessments of VOCs and structural carbohydrates for eucalypts and other species are needed to improve fire risk assessments around communities and critical infrastructure.

4.1. Different Ways of Measuring Flammability Traits Prevent Direct Trait Comparisons

Studies differ in the definition and measurement of flammability traits in fresh leaves and litter, thus impeding direct comparisons (see Section 3.1). For example, our findings indicate that the most common methods to assess the flammability of eucalypt leaves include the use of a pilot flame, a muffle furnace, or a calorimeter (Table 1). Despite this, recent studies suggest there is a trend towards assessing the flammability of shoots, rather than individual leaves, using a grill [16,35,73–75]. The proposed grill method allows the assessment of the effects of fuel arrangement (i.e., fuel continuity, density, and structure) on the flammability of the sample, which should better represent real-world scenarios but complicates comparison with leaf-level studies due to differences inherent in the experimental design, highlighting the need for standardised protocols and procedures (Figure 3, Table 1).

Much of the recent literature follows established procedures to measure some leaf traits, but older publications do not. Reference [73] lists and describes ways to measure plant and leaf traits related to flammability (e.g., morphology)but it does not include protocols for measuring water content, or structural carbohydrates. Given that water content is an important driver of flammability, there is a critical need for standardisation and an opportunity for future studies to implement a single, consistent protocol for measuring water content. We found 15 different combinations of temperature and drying time to measure moisture content in eucalypt leaves and litter (Table 3), a fact not discussed in references [31,32]. When combined with Equations (1)–(3) it is evident that comparing studies becomes problematic, and a standardised approach is urgently needed.

Table 3. Differences in drying methods used to estimate moisture content (%). * indicates that moisture content values are reported for all species, not only for eucalypt leaves. N/A = not available; FL = fresh leaves; DL = dried leaves; LL = leaf litter.

Drying Time (h)	Drying Temperature (°C)	Moisture Content (%)	Material Used	Reference
22	95	N/A	FL, DL	[29]
24	23	90–200	FL	[49] *
24	40	~3-35	DL, LL	[49] *
24	75	77–87	FL	[49] *
24	80	N/A	FL, LL	[38]
24	105	72–103	FL, DL, LL	[30] *
24	110	N/A	FL, DL	[41,42]
48	60	4–120	FL, DL	[50]
48	65	0–162	FL	[16]
48	75	40–48	FL, DL	[48] *
48	80	~3-14	DL	[37] *
48	80	4–120	FL	[44] *
48	80	0–162	FL, DL	[51]
48	105	N/A	FL	[38]
48	105	5–100	FL, DL	[39]
72	65	67–230	FL, DL	[37] *
72	70	80–113	FL	[46,47]
72	80	70–330	FL	[43] *
72	80	N/A	FL	[45] *
N/A	N/A	80–120	FL	[36] *

In fire management activities, water content is quantified by dry weight (Equation (1)); therefore, we recommend adopting the calculation of FMC (Equation (1)) as the standardised method to derive water content across all fuel types. Regarding the drying times and temperatures, reference [76] recommends drying leaves 24 h at 105 °C, which is higher than the temperatures used in many studies (Table 3). It was found [76] that such drying temperature results in a closer approximation of true moisture content, and that it reduces the effect of ambient humidity on the final moisture content measurements. The main caveat to drying leaves at 105 °C is that this process also removes some VOCs, resulting in an overestimation of leaf water content. In contrast, lower temperatures may prevent VOC volatilisation at the cost of not removing all water from the leaves; therefore, more research is needed to determine the effects of drying temperatures and times on VOC and water emissions. Along these lines, reference [76] found that differences in drying temperatures and times result in 0.9–3.5% changes in the measured moisture content, in turn, directly affecting fire behaviour and rate-of-spread predictions. These changes in moisture content could be the result of VOC emissions that were not quantified by the authors. Nonetheless, we recommend following [76] for determining the water content of live and dead fuels, due to its importance as driver of flammability, and we further encourage researchers to also quantify and report the concentration of VOCs in live and dead fuels.

Lastly, following [77], we recommend collecting the samples at least 48 h after the last rain event and as close to the middle of the day as possible, regardless of the fuel type (i.e., live or dead), vegetation structure (e.g., closed-canopy forests, savannas, grasslands), and topography, as well as recording additional environmental factors such as relative humidity to provide an overview of the environmental conditions at the time of sampling [78]. Having standardised protocols for measuring and reporting flammability and trait data will allow the comparison of present and future studies on eucalypt flammability, which is especially relevant under changing climate conditions.

4.2. Short-Term vs. Long Term Data Collection

Few studies in this review measured leaf-level flammability traits throughout the year or for extended periods of time (>1 year). As a result, detecting and assessing spatiotemporal changes in eucalypt flammability has often been carried out using proxies of flammability and modelling techniques such as remote sensing [79]. One of the few examples of long-term monitoring of flammability traits in eucalypt trees [80] demonstrated that water content in *E. globulus* can vary significantly within and between years; despite this, that study did not relate FMC values to flammability and was excluded from this review. To our knowledge, there have been neither studies examining temporal changes in VOCs, structural carbohydrates, or physical traits in eucalypt forests, nor studies on how leaf biochemistry and thus, flammability, are driven by phenology [81]. Recently, researchers [19] demonstrated that there is a strong relationship between SLA and water content in eucalypt trees, and that this relationship is driven, in part, by tree phenology and environmental conditions. Similarly, but in a different environment, it was argued [82] that seasonal changes in leaf-level flammability traits may have a significant effect in landscape-scale fires. Thus, it seems critical to start monitoring the spatial and temporal changes in eucalypt flammability to develop predictive tools to inform fire management policies and strategies.

Some of the new technologies to track changes in leaf-level flammability traits will come in the form of satellites. Current satellites are often used to measure vegetation 'greenness' or to locate active fires, but none has been designed to measure fuel flammability. Moreover, current spaceborne sensors have wide spectral bands that are ill-suited for discerning the spectral attributes distinctive of biophysical flammability traits, which manifest in narrow spectral bands [83,84]. Out of the 20 articles reviewed here, only one [37] reported the usage of satellite imagery, although the images were used to estimate canopy cover and vegetation greenness, not for estimating forest flammability. Spectral, biochemical, and flammability data from different species, geographies, and seasons are crucial for accurately modelling and estimating landscape-scale flammability, especially to understand how drought and future climate conditions will affect forest flammability [85,86]. Subtle changes in the canopy of evergreen forests can be captured with satellite images [87] and may be used to detect changes in landscape-scale flammability, but long-term on-the-ground observations of leaf-level flammability traits are also required to validate satellite-derived estimations. Accurate validation data are instrumental in enhancing satellite-derived products, which, in turn, have great potential to contribute to more effective firefighting efforts.

4.3. Linking Species and Leaf-Level Flammability to Fire Behaviour

The relationship between leaf-level flammability and fire behaviour is complex and depends on biotic and abiotic factors that work at different spatial and temporal scales (e.g., [13,14,74,88]). In their simplest form, leaf-level traits determine the ignitability, sustainability, combustibility, and consumability of live and dead leaves (Table 2); these traits also influence the flammability of shoots and litter beds [16,50,51,89] (Figure 5). Leaf-level studies suggest that the importance of water content and physical traits is disproportionately large when compared with other traits (e.g., [30,36,52]). However, a formal quantification of the relative importance of each trait is still lacking. Researchers [81] have demonstrated that water content and physical traits are directly related to one another, while others [19] found that SLA could be used to predict leaf water content in eucalypt forests. These studies highlight the need for more research into the interaction of individual vegetation traits on the flammability components of vegetation to predict fire behaviour at different spatial and temporal scales.

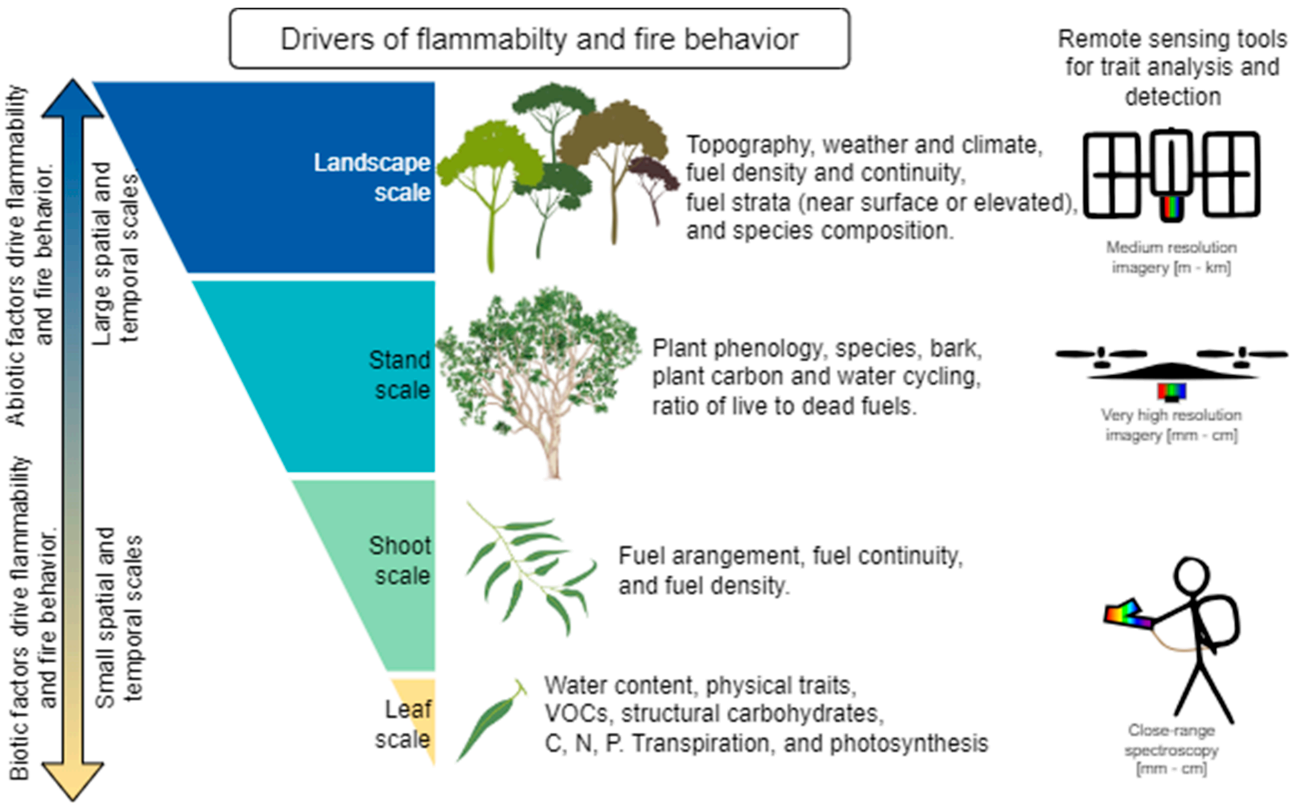

Figure 5. Drivers of flammability and fire behaviour and spread depend on the spatial and temporal scale of assessment. Remote sensing tools to monitor vegetation also change with scale.

At the leaf and shoot scales, fire behaviour is driven by the leaf-level traits [16,74] and fuel arrangement, whereby leaves that are closer together are more likely to burn than leaves that are further apart [90,91] (Figure 5). As the spatial and temporal scales become larger, including shoot and stand, the spatial arrangement (e.g., canopy architecture, leaf and branch retention), fuel quantity (e.g., accumulation over time), fuel density (e.g., packing ratio, leaf curl), fuel type (e.g., leaf, trunk, bark), and other properties of live and dead fuels begin to drive fire behaviour [92–96]. At the tree and stand level, the flammability of the fuel is still influenced by the leaf and shoot traits, but abiotic factors (e.g., topography and weather), as well as the characteristics of each species, begin to play a major role in the fire behaviour and spread [12,81,95,97,98] (Figure 5).

Leaves are frequently the first structures to ignite during bushfire [29] and their characteristics and arrangements play a role in fire behaviour and spread at the tree scale [14,43,90], whereas species composition and stand structure may play a major role at the landscape scale. Several studies, including [16,29,38,41,42,46,47], have demonstrated that eucalypt leaves are generally more flammable than leaves of other tree species, and that some eucalypt species are more flammable than others. For example, freshly collected leaves of *E. elata* Dehnh. ignited 21 s faster than those of *E. serraensis* Ladiges & Whiffin (11.57 versus 33.22 s to ignition respectively) [29], leaves of *C. gummifera* ignited 10 s faster than those of *E. sparsifolia* at 29.6 kWm^{-2} (25 versus 15 s respectively) [45], and the energy content of freshly collected leaves of *E. amygdalina* Labill. was 3% higher than that of *E. globulus* (22,455 Jg^{-1} versus 21,833 Jg^{-1}) [38]. While direct comparison between studies is difficult, these examples showcase that leaf-level flammability depends not only on the biophysical traits of leaves, sampling protocol, and drying protocol, but also varies significantly with species.

Linking fire behaviour at the landscape scale to leaf, shoot, and tree flammability remains a challenge. Recently, researchers [12] proposed the use of nested model frameworks to narrow the gaps between leaf and shoot flammability measurements acquired with landscape-scale fire behaviour models, whereby models can use the detailed descriptions of biophysical traits as inputs and boundaries during simulations over spatial and temporal scales that are relevant for fire management activities and operations. Scaling the effects of flammability to fire behaviour remains an area of active research that can benefit from the research priorities outlined in the next section.

4.4. Future Research

The studies included in this review examined only a fraction of the approximately 800 eucalypt species present in Australia, highlighting an important gap in our understanding of the flammability of eucalypt trees in general. With a clear understanding of the key traits that drive eucalypt flammability, research efforts should prioritise the following four areas to enhance fire risk assessments, inform prescribed burns, refine fire behaviour models, optimise suppression efforts, and support various operational and strategic fire management activities.

Priority 1: Establishing long term monitoring sites for monitoring eucalypt leaf-level flammability traits across the dominant ecosystem types in Australia that follow standardised protocols of sample collection and trait analysis. Changes in flammability can be triggered by drought, phenology, and other factors; thus, identifying spatiotemporal variations in these leaf traits is essential to understanding when the landscape becomes more flammable. Field campaigns serve as primary sources of validation data for algorithms, models, and satellite imagery; therefore, a monitoring network should be urgently implemented, adequately supported financially and coordinated at the national scale.

Priority 2: Advancing remote sensing capabilities by developing satellite missions and algorithms to detect vegetation fuel flammability prior to ignition (Figure 5). To our knowledge, there are currently no spaceborne sensors specifically designed for this purpose; however, countries including Australia are actively developing bespoke sensors such as OzFuel [99,100]. This sensor aims to detect changes in the flammability traits of forest fuels, providing valuable insights into the timing and locations of potential wildfires. Calibration and validation of satellite-derived flammability products (Priority 1) must also incorporate methodologies for upscaling of leaf and shoot flammability measurements to plot and landscape levels.

Priority 3: Thoroughly examine the relative and combined importance of each biophysical trait in influencing each of the four flammability components. Similar to previous studies [69,101], undertaking leaf-scale experiments in controlled environments will help researchers isolate the effects of each trait on each flammability component and examine potential interactions between traits. As a result, fire behaviour models could be tailored to sites with specific characteristics and species compositions. Furthermore, agreeing on a standard set of leaf-level flammability traits and methods would enable direct comparison between studies, as well as calibration and validation of fire behaviour models and satellite imagery (Figure 5).

Priority 4: Develop new models and algorithms to forecast flammability from leaf to stand level and at the landscape scale. Biophysical models could leverage long-term field observations of key plant traits related to flammability from the monitoring network suggested in priority 1 and link these with climate variables like soil moisture, vapour pressure deficit, and potential evapotranspiration. Through combining satellite imagery with biophysical data, it should become possible to forecast flammability across a range of spatial and temporal scales [19] (Priority 2). While attempts have been made to forecast flammability at continental scales [79], challenges related to model optimisation, calibration, and validation remain. Our four priorities for future research are closely aligned with the recommendations raised by recent national and international reports on the current and future risk posed by fires to people, the environment, and critical infrastructure [6,9]. Therefore, prioritising these efforts is crucial to enhance Australia's resilience and response to future fires.

5. Conclusions

Through reviewing the published literature on leaf-level traits that influence the flammability of eucalypt species, we revealed that, water content, leaf area, and specific leaf area are the main drivers of flammability in eucalypt-dominated forests. Understanding the relative importance of each trait in the flammability of plant matter across scales remains an important challenge in Australian ecosystems, which can be addressed with protocol standardisation, long-term vegetation monitoring, and experimentation. Importantly, the absence of standardised protocols for measuring the four components of flammability, plant traits, and water content impedes the comparison of flammability characteristics across species and challenges our ability to develop biophysical models to monitor and forecast flammability at the landscape scale. Hence, we suggest adopting a consistent approach, including waiting at least 48 h after rain to collect fuel samples, drying the fuel at 105 °C for at least 24 h, and reporting water content as FMC to facilitate inter-study comparisons. Future monitoring efforts should target the assessment of biophysical traits as main indicators for monitoring and forecasting the four components of flammability. Advancing remote sensing capabilities to detect vegetation flammability prior to ignition will increase our understanding of flammability at leaf-level scales, allowing us to develop predictive models for stand- and landscape-level flammability and to derive new flammability proxies that can be quantified using spaceborne measurements.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/fire7060183/s1, Figure S1: Number of studies per country per year that related leaf-level traits with flammability in eucalypt trees; Table S1: Description of the information manually extracted using Sysrev.

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