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Article

Flammability of native ornamental grasses with potential for use in green roofs

Inflamabilidade de gramíneas ornamentais nativas para uso em telhados verdes

Victor Gurgel Pessoa[1,*], Vivian Loges[1], Tomás Guilherme Pereira da Silva[2], Maria Fernanda dos Santos Silva[1], Simone Santos Lira Silva[1], Ana Cecília Ribeiro de Castro[3], and Clara Correia da Silva Santos[1]

[1] Universidade Federal Rural de Pernambuco, Departamento de Agronomia, Recife-PE, Brasil.
[2] Universidade Federal Rural de Pernambuco, Departamento de Zootecnia, Recife-PE, Brasil.
[3] Empresa Brasileira de Pesquisa Agropecuária (Embrapa), Unidade Agroindústria Tropical, Fortaleza-CE, Brasil.

Abstract
Grasses are widely used in extensive green roofs due to their ecological performance, yet fire-risk assessments for these systems remain scarce. Understanding species specific flammability is essential because vegetation drying, especially under low irrigation, may increase ignition potential in urban infrastructures. This study evaluated the flammability of native and commercial grass genotypes to identify safer options for green roof applications. The experiment was conducted simulating the conditions of an extensive green roof. Genotypes of *Paspalum notatum* (BRA006513, BRA019178, BRA023558, and the cultivars Aruaí, Tiriba, and Tuim), *Axonopus parodii* (cv. Curica), and *Zoysia japonica* as a reference species were cultivated from seedlings for 365 days. Morphological characteristics, biomass moisture, fire behavior parameters, surface temperatures, and grass plate weight were measured under controlled burning. Species differed significantly in fire behavior. *Z. japonica* exhibited the highest flame height (65 cm), rate of spread (0.03 m s^{-1}), and fire intensity (24.56 kcal m^{-1} s^{-1}), whereas BRA023558 showed the lowest susceptibility to fire. Moisture content varied among genotypes but was not correlated with fire parameters. Grass species vary widely in fire behavior parameters. These results support evidence-based plant selection for safer and more resilient urban green infrastructure. Thus, the BRA023558 genotype showed lower susceptibility to fire under burning conditions.
Keywords: Fire behavior, plant combustibility, plant selection, urban fire risk, vegetated infrastructure.

Resumo
As gramíneas são amplamente utilizadas em telhados verdes extensivos devido ao seu desempenho ecológico, porém, as avaliações de risco de incêndio para esses sistemas ainda são escassas. Compreender a inflamabilidade específica de cada espécie é essencial, pois a secagem da vegetação, especialmente sob baixa irrigação, pode aumentar o potencial de ignição em infraestruturas urbanas. Este estudo avaliou a inflamabilidade de genótipos de gramíneas nativas e comerciais para identificar opções mais seguras para aplicações em telhados verdes. O experimento foi conduzido simulando as condições de um telhado verde extensivo. Genótipos de *Paspalum notatum* (BRA006513, BRA019178, BRA023558 e as cultivares Aruaí, Tiriba e Tuim), *Axonopus parodii* (cv. Curica) e *Zoysia japonica*, como espécie de referência, foram cultivados a partir de mudas por 365 dias. Características morfológicas, umidade da biomassa, parâmetros de comportamento ao fogo, temperaturas superficiais e peso da placa de grama foram medidos sob queima controlada. As espécies diferiram significativamente em seu comportamento ao fogo. *Z. japonica* apresentou a maior altura de chama (65 cm), taxa de propagação (0,03 m s^{-1}) e intensidade de fogo (24,56 kcal m^{-1} s^{-1}), enquanto BRA023558 demonstrou a menor suscetibilidade ao fogo. O teor de umidade variou entre os genótipos, mas não apresentou correlação com os parâmetros de incêndio. As espécies de gramíneas variam amplamente em seus parâmetros de comportamento ao fogo. Esses resultados corroboram a seleção de plantas baseada em evidências para uma infraestrutura verde urbana mais segura e resiliente. Assim, o genótipo BRA023558 apresentou menor suscetibilidade ao fogo em condições de queima.
Palavras-chave: Combustibilidade de plantas, comportamento do fogo, infraestruturas vegetadas, risco de incêndio urbano, seleção de plantas.

Introduction

The use of plants as green coverings on buildings has been widely explored as an environmental improvement tool, with green roofs being one of the most common implementations of this model. Beyond the aesthetic and economic benefits for buildings, this technology supports landscape ecology as well as social life in urban centers. In this context, research has demonstrated that the use of green roofs contributes to reducing water runoff (Kazemi et al., 2023), increasing building energy efficiency (Priya and Senthil, 2021), reducing atmospheric pollutants (Pessoa et al., 2022), mitigating urban heat island effects (Mazzeo et al., 2023), and enhancing biodiversity by providing natural habitat for various organisms (Wang et al., 2022).

Among the different plant groups used on green roofs, grasses have gained prominence due to their adaptability to shallow substrates, rapid establishment, and tolerance to stressful conditions typical of extensive systems. A recent global survey reported the use of grasses on green roofs in approximately 40 countries, highlighting their widespread application across diverse climatic regions (Pessoa et al., 2025). In the context, native grass species from the genera *Axonopus* and *Paspalum* have been tested with promising results for this type of application (Silva et al., 2020; Paes et al., 2023).

Among the recognized advantages of using grasses in green roofs is their tolerance to water stress (Leotta et al., 2023). However, plants experiencing water deficiency increase their leaf temperature, reducing the effectiveness of green infrastructure (Elkadi et al., 2024). In extensive systems, where irrigation is generally absent, this deficiency can lead to vegetation drying, which, combined with environmental factors such as high temperatures, low air humidity, and species-specific traits, may increase the risk of vegetation combustion, requiring careful planning and vegetation management.

Fire safety has emerged as a critical concern in vegetated building systems. Green roofs typically consist of continuous vegetation layers that, under unfavourable conditions such as drought, inadequate maintenance, and high thermal radiation, may facilitate fire ignition and spread (Gerzhova et al., 2019; Gerzhova et al., 2022). Thermal radiation is considered one of the main drivers of fire propagation in vegetated systems, as it allows heat transfer without direct contact between fuel sources (Buchanan and Abu, 2017). As a result, understanding the fire behavior of plant species used on green roofs is essential for the safe design and management of urban green infrastructure.

***Corresponding author:** victor.pessoa@ufrpe.br | https://doi.org/10.1590/2447-536X.v32.e323076 | Editor: Lúcia Maria de Siqueira Cavalcanti Veras, Universidade Federal de Pernambuco, Brasil | Received: Feb 04, 2026 | Accepted: June 30, 2026 | Available online: Aug 24, 2026 |

Fire behavior in vegetated systems is commonly assessed through flammability, defined as the ability of biomass to ignite and sustain combustion. Flammability is influenced by multiple components, including ignitability, combustibility, consumability, and sustainability, which together determine fire intensity and duration (Pausas et al., 2017). Grasses often exhibit traits associated with higher flammability, such as fine leaf architecture, low moisture content during dry periods, and the accumulation of senescent biomass (Gao and Schwilk, 2022). Consequently, species selection and vegetation management practices are key strategies for reducing fire risk in green roofs (Gerzhova et al., 2022).

Despite the rapid expansion of green roofs worldwide, studies assessing the flammability of plant species used in these systems remain scarce. Most flammability research has focused on forest ecosystems or grasslands, while empirical data for green roofs are limited. Reports indicate a growing number of fire incidents in vegetated building systems over recent decades, underscoring the need for fire risk assessment and evidence-based vegetation selection in urban environments (Ni et al., 2024).

In this context, the present study aimed to evaluate the flammability of grass species with potential use in extensive green roofs, considering their morphological traits and combustion properties. It was hypothesized that flammability differs among species and cultivars, allowing the identification of grasses more suitable for use in green roofs from a fire risk management and environmental safety perspective.

Material and Methods

Study area and experimental conditions

Tray-based experimental units were used to simulate extensive green roofs, as this approach reliably reproduces the physical conditions of real systems (Silva et al., 2020; Paes et al., 2023). The trays were placed under full sun on an impermeable cobblestone surface, and the experiment was conducted from October 2022 to October 2023. No fertilization was applied during the cultivation period, and no mowing or pruning was performed. These management conditions were adopted because extensive green roofs are generally designed as low-maintenance systems, requiring minimal inputs and interventions (Bullock et al., 2026; Pessoa et al., 2026). Vegetation was evaluated after 365 days of cultivation, when grasses had reached maturity, ensuring representative biomass for destructive flammability testing.

The evaluated parameters are described in the following section.

Plant material and experimental design

The experiment followed a randomized block design with eight treatments and four replications. Treatments consisted of grass genotypes with potential use on green roofs: *Paspalum notatum* accessions (BRA 006513, BRA 019178, BRA 023558) and cultivars (Aruaí, Tiriba and Tuim), *Axonopus parodii* cv. Curica, and *Zoysia japonica* used as a reference species due to its widespread use in turfgrass systems. Plant material was obtained from the Active Germplasm Bank of Embrapa Southeast Livestock (São Carlos, Brazil).

Seedlings (~10 cm height) were transplanted into polyethylene (14 x 37 x 60 cm) containing 8 cm of substrate. Plants were grown in a commercial substrate suitable for shallow vegetated systems, commonly used in green roof applications. Trays were placed on an impermeable surface to simulate extensive green roof conditions and cultivated for 365 days after planting.

Supplementary irrigation was applied only during periods of pronounced water deficit, with the sole purpose of preventing plant mortality and ensuring minimum functional performance. No regular or continuous irrigation was adopted, in accordance with international guidelines for extensive green roof systems, which recommend occasional supplementary irrigation exclusively under prolonged dry conditions to sustain vegetation establishment and survival (Green Roof Organization, 2021).

Plant morphological and moisture traits

Morphological and fuel-related traits were assessed immediately before fire tests. The following variables were measured: Grass height (GH, cm): vertical distance from substrate surface to the tallest green leaf; Ground cover (GC, %): estimated from digital images analyzed using ImageJ software through image binarization (et al., 2016); Moisture content (MC, %): determined separately for aboveground (MC-AG, %) (leaves and stolons) and belowground biomass (MC-BG, %) (roots and rhizomes) following oven-drying procedures (Detmann et al., 2021); Proportion of dry leaves (PDL, %): visually estimated by trained evaluators using a five-point hedonic scale (Chaves and Sproesser, 1993).

Fire behavior assessment

The fire behavior parameters used in this study are widely applied in fire ecology and fuel hazard assessments to evaluate ignition, fire spread, and heat release (Vasconcelos et al., 2020). Green roof surfaces were simulated using turf trays containing intact plant–substrate systems placed on fiber-cement roofing sheets, a material commonly used in Brazil (Durante et al., 2022).

Burn experiments were performed between 8:00 and 11:00 a.m., with meteorological conditions recorded on-site (Table S1). During the experiment, air temperature increased progressively from 26.94 ºC at 8 h to 29.50 ºC at 11 h, while relative humidity showed a corresponding decrease, ranging from 59.25% to 47.25%. Wind speed measured at 2 m height remained relatively stable throughout the experimental period, varying between 4.47 and 4.70 m s^{-1}. Overall, the mean temperature, relative humidity, and wind speed were 28.31 ºC, 52.51%, and 4.54 m s^{-1}, respectively.

Ignition was initiated using a standardized flame source simulating an accidental high-intensity heat point. Combustion was recorded for posterior analysis (Fig. 1).

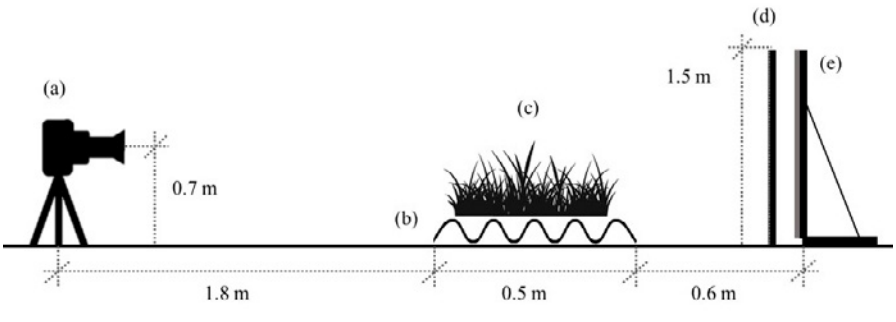

Fig. 1. Side view of the burning process. Note: (a) video camera; (b) fiber-cement roofing sheet; (c) grass panel; (d) ruler to assist flame height measurement; (e) black panel to facilitate flame observation.

The following fire behavior parameters were evaluated: Ignition frequency (IF): indicates the number of times ignition was attempted with the flame thrower to initiate combustion; Ignition time (IT, s): refers to the time that the fuel material (above ground plant part) took to ignite; Burn duration (BD, s): represents the time during which the flame of the fuel material remained lit; Flame height (FH, cm); Vegetation combustibility index (VCI): classification ranged from VCI = 1 (very low - flame height < 10 cm) to VCI = 5 (very high - flame height > 120 cm) (Vasconcelos et al., 2020); Rate of spread (ROS, m s^{-1}): indicates the time it took for the fire to consume 2220 cm^2 (grass area) of all the grass (Botelho and Ventura, 1990); Fire intensity (I, kcal m^{-1} s^{-1}) (Rothermel and Deeming, 1980); Heat per unit area (HA, kcal m^{-2}) (Soares and Batista, 2007); Flammability value (FV): classification ranged from FV = 0 (weakly flammable) to FV = 5 (extremely flammable) (Valette, 1990).

Thermal and mass variation before and after burning

Before and after combustion, turf trays were evaluated for: Surface temperature on the upper and lower layers using an infrared thermometer positioned 0.65 m above the surface; Tray mass, including substrate and vegetation, using a precision digital scale (100 g). These measurements allowed assessment of immediate thermal effects and biomass loss caused by combustion.

Before and after combustion, the turf trays were evaluated for: (i) surface temperature of the upper and lower layers, measured with an infrared thermometer positioned 0.65 m above the surface; and (ii) total tray mass, including substrate and vegetation, measured with a precision digital scale (100 g). These measurements enabled the assessment of immediate thermal effects and the biomass loss resulting from combustion.

Statistical analysis

All data were subjected to analysis of variance (ANOVA), and means were compared using Tukey's test ($p \leq 0.05$) with SISVAR software (Ferreira, 2019). Temperature and mass values before and after burning were compared using paired Student's t-tests.

Pearson's correlation analysis was performed between plant traits (GH, GC and MC) and fire behavior variables using MINITAB 17, with correlation strength classified as weak (<0.4), moderate (0.4-0.5) or strong (>0.5).

Results

Significant differences in fire behavior were observed among grass species and cultivars, indicating that plant type and morphological traits influenced combustion dynamics under simulated green roof conditions.

Grass height varied markedly among the evaluated materials, with the cultivar Curica being 87% taller than the cultivar Tuim (Fig. 2A). This difference reflects the strong intraspecific variability among *Paspalum notatum* cultivars. In contrast, ground cover did not differ significantly among species or cultivars, with an overall mean coverage of approximately 81% (Fig. 2B).

Moisture content (MC) of the materials, considering both shoot and root portions, ranged from 63% (BRA006513) to 75% (BRA023558) (Table 1).

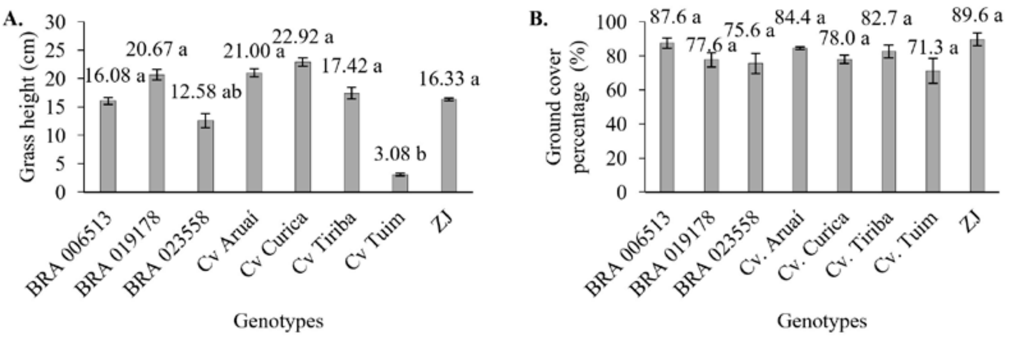

Fig. 2. Aboveground height (A) and ground cover percentage (B) of ornamental grasses with potential for use under extensive green roof conditions. Means followed by different lowercase letters indicate significant differences among accessions/species by Tukey's test at 5% probability. Vertical bars represent standard error of the mean. Note: Cv. = cultivar; ZJ = *Zoysia japonica*.

Table 1. Moisture content of the aerial part and roots of ornamental grasses with potential for use in extensive green roofs conditions.

Genotypes	Aboveground biomass (%)	Belowground biomass (%)	SEM	*p*-value
BRA006513	57.16aA	67.89aA	9.3245	0.5651
BRA019178	70.97aA	68.73aA	1.6639	0.4110
BRA023558	73.61aA	75.82aA	0.8905	0.1766
Cultivar Aruaí	62.08aA	74.35aA	7.7410	0.3440
Cultivar Curica	68.60aA	71.60aA	4.1197	0.6412
Cultivar Tiriba	72.68aA	69.80aA	4.4810	0.6802
Cultivar Tuim	74.28aA	71.49aA	2.3265	0.4595
Zoysia japonica	62.83aA	75.51aA	6.4501	0.2585
SEM	5.2499	4.5952		
***p*-value**	0.2364	0.8651		

SEM: Standard error of the mean. Means followed by different lowercase letters in the same row and different uppercase letters in the same column differ significantly according to Tukey's test at the 5% probability level.

The proportion of dry leaves exceeded 75% in all materials except cv. Curica, which showed intermediate values (50%-75%). No significant correlations were detected between moisture-related traits, grass height, ground cover, and fire behavior parameters (Table 2).

All materials showed high ignitability, characterized by low ignition frequency and ignition time, with combustion initiated after a maximum of two ignition attempts and ignition times below 2 s (Table 3).

Table 2. Pearson's correlation coefficient matrix between plant characteristics, fire behavior parameters, weight and temperature of ornamental grass panels with potential for use in extensive green roofs conditions before and after burning.

	GH	GC	MC-AG	MC-BG	IF	IT	BD	FH	ROS	I	HA	BWB	LTB
GC	0.135^{ns}												
MC-AG	-0.061^{ns}	-0.322^{ns}											
MC-BG	0.073^{ns}	-0.010^{ns}	-0.143^{ns}										
IF	0.167^{ns}	-0.005^{ns}	-0.142^{ns}	0.087^{ns}									
IT	0.070^{ns}	-0.116^{ns}	-0.267^{ns}	0.088^{ns}	0.821*								
BD	0.192^{ns}	0.024^{ns}	0.044^{ns}	-0.075^{ns}	0.499*	0.344^{ns}							
FH	-0.026^{ns}	0.218^{ns}	0.068^{ns}	-0.154^{ns}	-0.540*	-0.587*	-0.643*						
ROS	0.130^{ns}	0.204^{ns}	-0.163^{ns}	0.020^{ns}	-0.271^{ns}	-0.276^{ns}	-0.445*	0.546*					
I	-0.009^{ns}	0.237^{ns}	0.051^{ns}	-0.145^{ns}	-0.510*	-0.555*	-0.602*	0.987*	0.582*				
HA	-0.092^{ns}	0.144^{ns}	0.145^{ns}	-0.188^{ns}	-0.246^{ns}	-0.312^{ns}	-0.157^{ns}	0.368*	-0.418*	0.319^{ns}			
BWB	0.046^{ns}	0.094^{ns}	0.096^{ns}	-0.312^{ns}	-0.157^{ns}	-0.030^{ns}	0.089^{ns}	-0.029^{ns}	-0.185^{ns}	0.010^{ns}	0.097^{ns}		
LTB	-0.093^{ns}	-0.222^{ns}	-0.029^{ns}	-0.232^{ns}	0.034^{ns}	-0.035^{ns}	-0.113^{ns}	0.192^{ns}	-0.137^{ns}	0.177^{ns}	0.249^{ns}	0.242^{ns}	
UTB	-0.154^{ns}	-0.079^{ns}	0.026^{ns}	-0.099^{ns}	-0.295^{ns}	-0.307^{ns}	-0.461*	0.305^{ns}	0.297^{ns}	0.253^{ns}	0.060^{ns}	-0.069^{ns}	0.478
LTA	0.075^{ns}	-0.227^{ns}	0.124^{ns}	-0.240^{ns}	0.115^{ns}	-0.004^{ns}	-0.119^{ns}	0.088^{ns}	0.074^{ns}	0.075^{ns}	-0.054^{ns}	0.204^{ns}	0.664
UTA	0.212^{ns}	0.058^{ns}	0.018^{ns}	-0.140^{ns}	-0.472*	-0.450*	-0.313^{ns}	0.345^{ns}	0.171^{ns}	0.297^{ns}	0.139^{ns}	0.053^{ns}	0.283
BWA	0.058^{ns}	0.065^{ns}	0.154^{ns}	-0.250^{ns}	0.024^{ns}	0.038^{ns}	0.188^{ns}	-0.103^{ns}	-0.252^{ns}	-0.068^{ns}	0.089^{ns}	0.866*	0.196

*= Significant by the F-test at 5% probability; ns = not significant at 5% probability. GH = Grass height; GC = Ground coverage percentage; MC-AG = Aboveground biomass moisture content; MC-BG = Belowground biomass moisture content; IF = Ignition frequency; IT = Ignition time; BD = Burn duration; FH = Flame height; ROS = Rate of spread; I = Fire intensity; HA = Heat per unit area; BWB = Biomass weight before combustion; BWA = Biomass weight after combustion; LTB = Lower temperature before combustion; LTA = Lower temperature after combustion; UTB = Upper Temperature before combustion; UTA = Upper temperature after combustion.

Table 3. Fire behavior parameters of ornamental grass panels with potential for use in extensive green roof conditions.

Genotypes	IF	IT (s)	BD (s)	FH (cm)	ROS (m s^{-1})	I (kcal m^{-1} s^{-1})	HA (kcal m^2)
BRA006513	2A	1.75A	170.00A	47.50AB	0.007B	13.15AB	1716.46A
BRA019178	2A	1.75A	186.25A	50.00AB	0.009B	14.83AB	1754.32A
BRA023558	1A	1.75A	122.25A	37.50B	0.008B	8.17B	1344.13A
Cultivar Aruaí	1A	1.00A	226.25A	40.00AB	0.013AB	8.83B	823.97A
Cultivar Curica	2A	1.75A	113.50A	55.00AB	0.018AB	17.85AB	1023.80A
Cultivar Tiriba	2A	2.00A	205.25A	42.50AB	0.009B	11.55AB	1103.69A
Cultivar Tuim	1A	1.50A	122.75A	50.00AB	0.014AB	14.49AB	1112.24A
Zoysia japonica	1A	1.00A	71.75A	65.00A	0.030A	24.56A	970.81A
SEM	0.3477	0.4136	45.5105	5.3902	0.0042	3.0090	342.4528
***p*-value**	0.2594	0.5898	0.2788	0.0367	0.0179	0.0218	0.4524

IF = Ignition frequency; IT = Ignition time; BD = Burn duration; FH = Flame height; ROS = Rate of spread; I = Fire intensity; HA = Heat per unit area; SEM: Standard error of the mean. Means followed by different uppercase letters within columns differ significantly according to Tukey's test at 5% probability.

Marked differences were observed in flame development and energy release. *Zoysia japonica* exhibited significantly greater flame height, rate of spread and fire intensity than most native *Paspalum* accessions and cultivars (Table 3), being the only material classified as highly combustible (VCI 4), whereas the remaining grasses were classified as moderately combustible (VCI 3).

Rates of fire spread in *Paspalum* accessions and cv. Tiriba were 70%-76% lower than those observed for *Z. japonica* (Table 3). Similarly, *Z. japonica* released substantially more energy per unit time and per unit area than native grasses, with differences exceeding 60% compared to some accessions and cultivars.

Temperature analysis revealed distinct patterns between the upper and lower surfaces of the grass plates. The lower temperature of the grass plate from accession BRA006513 decreased by 5% after burning compared to pre-fire values, indicating heat dissipation through the substrate. On the other hand, the upper temperature increased by 27% in the Aruaí cultivar and 25% in *Z. japonica* (Table 4), suggesting that the upper layer retained more energy during combustion.

Table 4. Temperatures on the upper and lower surfaces of ornamental grass panels with potential for use in extensive green roof conditions before and after combustion.

Genotypes	Temperature (ºC) Lower surface		*p*-value	Temperature (ºC) Upper surface		*p*-value
	Before	After		Before	After	
BRA006513	26.25±0.51aA	24.93±0.51bA	0.017	28.57±1.57aA	38.58±5.56aA	0.091
BRA019178	25.95±1.39aA	25.48±1.30aA	0.082	26.52±0.63aA	32.25±2.02aA	0.071
BRA023558	24.61±0.54aA	24.39±0.22aA	0.572	27.48±1.19aA	34.94±2.80aA	0.065
Cultivar Aruaí	24.52±0.50aA	24.80±0.20aA	0.446	26.64±1.60bA	36.38±2.92aA	0.032
Cultivar Curica	26.45±0.70aA	26.96±1.10aA	0.763	28.87±1.68aA	36.81±5.89aA	0.171
Cultivar Tiriba	25.08±0.34aA	27.31±0.89aA	0.755	27.98±1.35aA	33.13±2.09aA	0.150
Cultivar Tuim	25.62±0.83aA	25.33±0.46aA	0.519	28.43±0.94aA	32.04±2.01aA	0.065
Zoysia japonica	25.09±0.90aA	25.01±0.80aA	0.833	28.30±0.49bA	37.60±2.54aA	0.050
***p*-value**	0.2328	0.4314		0.5351	0.7032	

Means followed by different lowercase letters in the same row differ significantly according to the Student's t-test at 5% probability. Means followed by different uppercase letters in the same column differ significantly according to Tukey's test at 5% probability.

Before burning, the temperature on the base of plant of accessions BRA023558 and the Tuim cultivar was approximately 10% higher than the temperature on the top of plant (Fig. 3A). After burning, surface temperatures increased for most genotypes, with post-fire increases ranging from 21% (cv. Tuim) to 35% (accession BRA006513) relative to lower surface temperatures (Fig. 3B).

Changes in grass mat mass were minimal, with only one accession showing a reduction below 2% (Table 5), indicating limited combustion of substrate and belowground biomass.

The combustion mainly affected the aerial part of the plant, with no visible consumption of substrate or root system (Fig. 4).

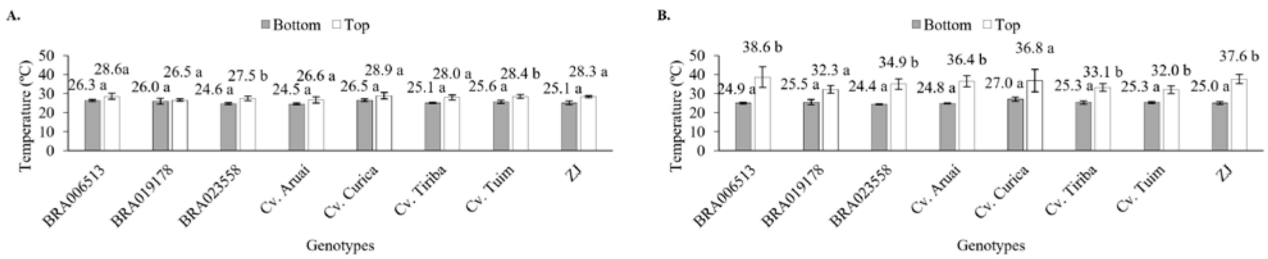

Fig. 3. Comparison of upper and lower surface temperatures of ornamental grass panels with potential for use in extensive green roofs conditions before (A) and after (B) fire. Means followed by different lowercase letters indicate significant differences between the lower and upper parts of the grass panels, by Tukey's test at 5% probability. Vertical bars represent standard error of the mean. Note: Cv. = cultivar; ZJ = *Zoysia japonica*.

Table 5. Weight of ornamental grass panels with potential for use in extensive green roofs conditions before and after burning.

Genotypes	Weight (kg)		*p*-value
	Before	After	
BRA006513	6.25±0.24aA	6.13±0.24bA	0.003
BRA019178	5.97±0.37aA	5.86±0.54aA	0.720
BRA023558	5.86±0.18aA	5.80±0.18aA	0.080
Cultivar Aruaí	6.18±0.39aA	5.81±0.24aA	0.226
Cultivar Curica	5.81±0.24aA	5.77±0.35aA	0.901
Cultivar Tiriba	6.12±0.27aA	6.03±0.25aA	0.102
Cultivar Tuim	5.36±0.39aA	5.28±0.43aA	0.182
Zoysia japonica	6.02±0.19aA	5.91±0.22aA	0.391
***p*-value**	0.6218	0.6270	

Means followed by different lowercase letters in the same row differ statistically by Student's t-test at 5% probability. Means followed by different uppercase letters in the same column differ statistically by Tukey's test at 5% probability.

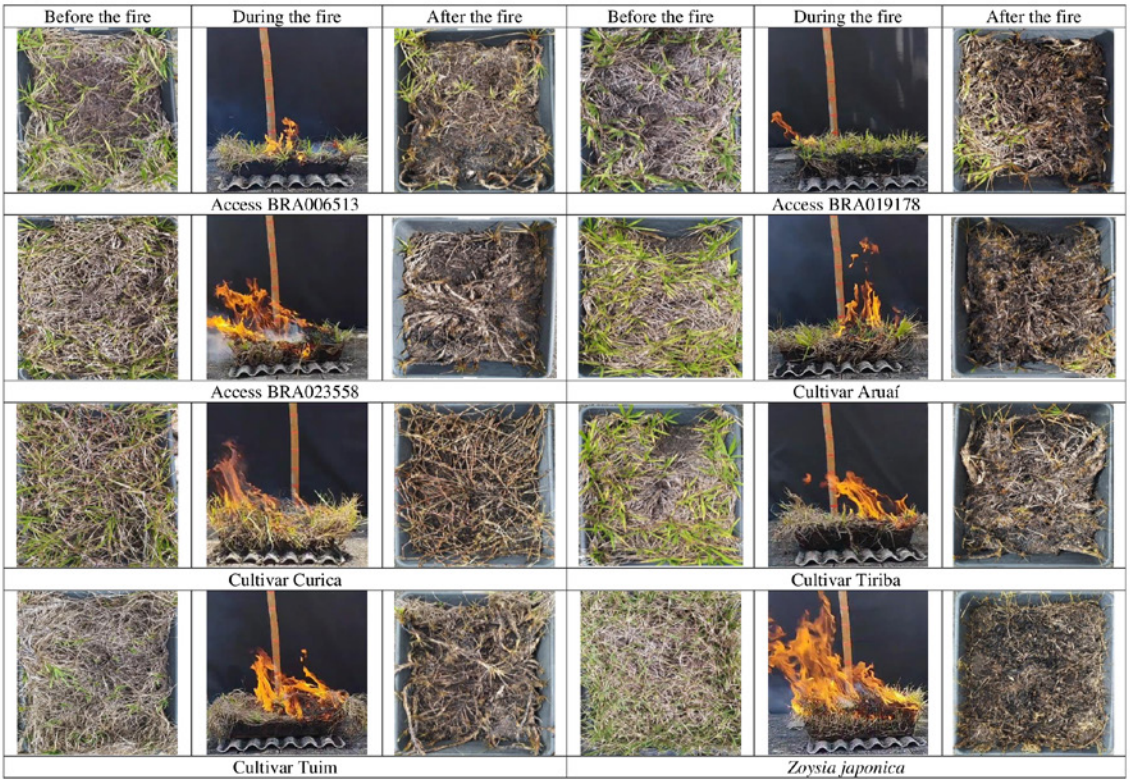

Fig. 4. Top and side views of ornamental grass panels with potential for use in extensive green roofs conditions before, during, and after fire.

Despite differences in combustion intensity and fire spread, all evaluated materials were classified as extremely flammable (FV = 5), reflecting their high ignitability and short ignition times under the experimental conditions.

Discussion

Vegetation structure, dry biomass accumulation, and fire risk in green roofs

Vegetation structure is a key determinant of fire behavior in extensive green roofs, where the plant layer constitutes the primary exposed fuel. The observed variation in plant height and proportion of dry leaves among the evaluated materials highlights how species-specific traits can influence ignition potential, flame development, and fire spread under urban roof conditions. Taller canopies combined with higher amounts of dry biomass tend to favor increased flame continuity and heat release, particularly under hot and dry climates, as previously reported for grass-dominated systems (Pausas et al., 2017).

High canopy cover, as observed for all evaluated materials, is generally desirable from a green roof performance perspective due to its contribution to thermal insulation and stormwater regulation. However, from a fire management standpoint, dense vegetation can increase fuel continuity when coupled with dry biomass accumulation. This duality reinforces the importance of integrating fire risk into vegetation selection criteria for green infrastructure, especially in regions characterized by pronounced dry seasons.

The period selected for evaluating fire behavior corresponded to the most climatically restrictive phase of the experimental cycle, characterized by relatively high temperatures (31 ºC) and low precipitation (30.61 mm) compared to the mildest month (~27 ºC and 480.86 mm). Under such conditions of heat and water deficit, plants experience intensified drought stress that accelerates leaf senescence and promotes the accumulation of dead biomass, increasing the availability of combustible material (Zhang et al., 2025). These findings underscore the relevance of considering seasonal variability when assessing fire risk in green roofs and suggest that plant performance under peak stress conditions may be more informative than evaluations conducted under milder climates.

Overall, the results indicate that vegetation height, canopy density, and dry biomass accumulation interact to create differing fire risk profiles among grass species. In extensive green roofs located in hot and dry urban environments, low-growing species with limited retention of dead leaves may contribute to reducing fire hazard without compromising ecosystem services.

Moisture content and ignition behavior

Plant moisture content is widely recognized as a critical factor controlling ignition probability and fire propagation. No direct statistical relationship with fire behavior parameters was observed (Table 2). This suggests that, under the tested conditions, structural and architectural plant traits may override moisture effects, particularly in grasses with fine leaves and high surface-area-to-volume ratios.

This finding contrasts with Gao and Schwilk (2022), who identified fuel moisture as an important predictor of grass flammability. Those authors also demonstrated that the influence of moisture is strongly mediated by plant traits such as biomass, bulk density, specific leaf area, and phenological status, highlighting the multidimensional nature of flammability. However, in the present study, all materials were evaluated under similar climatic conditions and exhibited a high proportion of senescent biomass. Under these circumstances, fuel structure and dry biomass accumulation may have played a greater role in determining fire behavior than moisture content alone, which could explain the absence of significant correlations.

Grasses generally exhibit lower moisture levels than woody or succulent species, which partly explains their rapid ignition behavior (Souza and Vale, 2019; Vasconcelos et al., 2020). Even with irrigation applied 24 hours prior to testing, prevailing climatic conditions likely limited moisture retention within the biomass. This reinforces previous observations that irrigation alone may not fully mitigate fire risk in grass-dominated green roofs during prolonged dry periods (Gerzhova et al., 2022).

The absence of a clear moisture-flammability relationship highlights the need for integrated assessments that account for multiple interacting drivers, including plant architecture, biomass distribution, phenological stage, and microclimatic exposure. From a management perspective, relying solely on irrigation as a fire mitigation strategy may be insufficient, particularly in extensive systems that require limited maintenance.

Ignition potential, fire spread, and fire intensity

All evaluated materials exhibited rapid ignition and low ignition frequency, reflecting the inherently high flammability of grass fuels. This behavior is consistent with the narrow leaf morphology and effective aeration within grass canopies, which promote rapid heat transfer and ignition (Bowman et al., 2014). Compared to woody species, grasses ignite substantially faster, reinforcing their classification as high-risk fuels in urban vegetation systems (Fonseca Lucas et al., 2021).

Despite high ignition susceptibility, substantial differences were observed in fire spread rate and intensity among species. *Zoysia japonica* consistently exhibited higher flame heights, faster spread, and greater fire intensity, resulting in its classification as highly combustible (VCI = 4). In contrast, *Paspalum* and *Axonopus* genotypes demonstrated slower fire propagation and lower intensity (VCI = 3), suggesting a more favorable fire behavior profile for green roof applications.

Fire intensity and rate of spread were positively correlated (Table 2), indicating that materials producing taller flames tend to release heat more rapidly and over larger areas (Vasconcelos et al., 2020; Mariano et al., 2021). However, except for *Z. japonica*, spread rates remained within thresholds considered indicative of slow-moving and manageable fires under low-wind conditions (Fernandes et al., 2002). These findings suggest that, although grasses are inherently flammable, species selection can substantially influence fire severity and controllability in green roof systems.

Implications for safety and environmental management of green roofs

The flame heights recorded in this study were considerably lower than those reported for unmanaged or taller grass systems (Gerzhova et al., 2022), reinforcing the importance of height control and biomass management. Plant growth form emerged as a critical determinant of combustion behavior. Stoloniferous species with a high proportion of exposed aboveground biomass, in which both leaves and stolons remain above the substrate surface, such as *Z. japonica*, promoted more continuous burning and greater fire intensity. In contrast, species with a larger proportion of protected or below-ground biomass exhibited more contained fire behaviour, as observed for *Axonopus* and *Paspalum* genotypes.

Wind speed during testing was low, favoring homogeneous combustion and limiting horizontal flame propagation. However, wind exposure in real urban settings, especially on high-rise buildings, can be substantially greater and may amplify fire spread risk. This discrepancy highlights the importance of conservative safety margins when selecting vegetation for rooftops exposed to strong aerodynamic effects.

Heat release values observed for the tested grasses were consistent with those reported for extensive green roof systems and remained substantially lower than those associated with conventional roofing materials such as concrete or ceramic tiles (Le et al., 2018). Nevertheless, even moderate heat release from vegetated roofs represents an additional thermal load that must be considered in fire risk assessments for dense urban environments.

Although vegetation flammability is an important criterion for species selection, it should be considered alongside other factors that influence the long-term performance and safety of green roofs, including structural load, maintenance requirements, root development, and interactions with waterproofing and drainage components. Therefore, vegetation selection should be based on a multidisciplinary assessment that integrates ecological, engineering, and fire safety considerations.

Temperature measurements at the lower surface of the green roof modules indicated limited heat transfer to underlying layers, suggesting that the vegetation–substrate system functioned as an effective thermal barrier under the tested conditions. The dense development of the root system likely contributed to restricting oxygen availability and preventing the downward spread of fire, consistent with previous studies on fire behavior in green roofs (Gerzhova et al., 2019).

Limitations, management implications, and future research

This study provides one of the first experimental evaluations of fire behavior in tropical grasses proposed for extensive green roofs, generating practical insights for vegetation selection and risk mitigation. However, the findings are constrained by the controlled nature of the experiments, which did not simulate high wind speeds, or the interaction with non-vegetative roofing components that may act as additional fuels.

Additionally, fire behavior in green roofs may be influenced not only by vegetation characteristics but also by the materials that compose the roofing system, including drainage layers, geotextiles, waterproofing membranes, and support structures. Interactions between vegetation and construction materials deserve further investigation to improve fire risk assessments under real operating conditions.

An additional limitation relates to the cultivation method adopted in the experimental units. Plants were grown in trays without mowing or fertilization, allowing each species to express its natural growth pattern under low-maintenance conditions typical of extensive green roofs. Because no mowing or uniformity cuts were performed, differences in canopy architecture, sod density, and senescent biomass accumulation may have been accentuated among species. These characteristics are directly related to fuel continuity and can influence fire behavior. Although vegetation structure under these conditions may differ from that observed in green roofs established with pre-grown sod or subjected to more intensive maintenance regimes, the adopted methodology provides a standardized framework for comparing species-specific flammability traits. Therefore, the results should be interpreted primarily as a comparative assessment among grass species rather than as a direct prediction of fire behavior under all green roof installation and management scenarios.

Furthermore, the experiments were conducted under a specific set of environmental conditions characterized by seasonal drought, elevated temperatures, and low wind speeds during the testing period. Since fuel moisture dynamics, biomass senescence, and fire behavior are strongly influenced by climatic conditions, the relative performance of the evaluated grasses may differ under other environmental scenarios. Therefore, caution should be exercised when extrapolating the results to regions with different climatic regimes or management conditions.

Future research should incorporate variable wind regimes, and full-system fire testing that includes drainage layers, geotextiles, and waterproofing materials, which are also potential fuels in fire situations (White et al., 2024). Additionally, integrating regional fire danger indices and building-specific factors, such as roof slope and height, would allow more accurate risk modeling.

From a management perspective, the results support prioritizing grass species with lower flame height, reduced fire intensity, and slower spread, combined with practices that limit the accumulation of dry biomass. These findings are directly relevant to policymakers seeking to balance the environmental benefits of green roofs with fire safety requirements.

Finally, it is recommended that the analysis be extended to other urban vegetated structures, such as slopes, median strips, airports, and roadside edges, where the use of grasses is also common.

Conclusions

Under the evaluated experimental conditions, it was found that the tested grasses exhibit different levels of flammability, with *Zoysia japonica* standing out for its greater propensity to burn and more critical fire parameters. Among the genotypes analyzed, the BRA023558 accession proved to be less susceptible to fire, indicating potential for safer use in urban green roofs.

These findings highlight that vegetation selection for green roofs should consider not only aesthetic and ecological attributes but also fire performance. The results reinforce that morphological characteristics, biomass accumulation, and environmental conditions interact to influence fire behavior and, therefore, should be evaluated in an integrated manner when designing urban green infrastructure.

From a scientific perspective, this study contributes to the still limited knowledge on the flammability of ornamental grasses under tropical conditions and provides evidence that native genetic resources may offer viable alternatives to commonly used exotic species. From a practical perspective, the findings support the development of vegetation selection criteria and management strategies that reconcile the environmental benefits of green roofs with urban fire safety, contributing to safer and more resilient cities.

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Author contributions

VGP: Investigation, Conceptualization, Data Curation, Data Analysis, Writing – Original Draft, Writing – Review & Editing. **VL:** Conceptualization, Methodology, Supervision, Data Curation, Funding Acquisition. **TGPS:** Investigation, Methodology, Data Curation. **MFSS:** Investigation, Methodology, Data Curation. **SSLS:** Methodology, Writing – Review & Editing. **ACRC:** Methodology, Writing – Review & Editing. **CCSS:** Investigation, Methodology, Data Curation.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability Statement

Data will be made available upon request to the authors.

Declaration of generative AI and AI-assisted technologies in the writing process

The authors declare that no generative AI or AI-assisted technologies were used in the writing or preparation of this manuscript.

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