Flammability of plant communities in arid and semi-arid ecosystems: Identifying key drivers and management implications (Postprint)

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Abstract

Arid and semi-arid ecosystems are prone to extensive fires due to specific climatic conditions, sparse vegetation cover, and high density of fine fuels. Understanding the flammability characteristics of land covers is essential for fire management and designing land restoration programs in arid and semi-arid ecosystems. This study provided a new approach to evaluate the flammability of shrublands and woodlands using flammability indices (FIs) including time to ignition (TI), duration of combustion (DC), and flame height (FH) of plant species and their relative frequencies in the Dalfard Basin of southeastern Iran. The results showed that there was a significant difference in FIs between land covers. Shrublands had higher flammability potential compared with woodlands. Plant moisture content had a negative relationship with TI ($P<0.010$) and no significant relationship with DC and FH ($P>0.050$). Artemisia spp., Astragalus gossypinus Fischer, Amygdalus scoparia Spach, and Cymbopogon jwarancusa (Jones) Schult. had the highest FI. Tree species such as Rhazya stricta Decne., and Pistacia atlantica Desf. showed greater resistance to fire. Using principal component analysis, the relationship between species and FIs was examined, and TI of wet fuel was the most important FI in relation to species. Structural equation model showed that life form ($P<0.001$) was the most important flammability driver. Precipitation ($P<0.010$) and legume species ($P<0.010$) were significantly related to the flammability in arid land. This study emphasizes the importance of managing high-risk species and using resistant species in vegetation restoration and shows that combining species FIs with their abundance is an effective tool for assessing fire risk and fuel management at the plant community scale.

Full Text

Preamble

J Arid Land (2026) 18(2): 304–321 doi: 10.1016/j.jaridl.2026.02.005; CSTR: 32276.14.JAL.20250314 Flammability of plant communities in arid and semi-arid ecosystems: Identifying key drivers and management implications Mosayeb HOJATI, Azam KHOSRAVI MASHIZI* Department of Ecological Engineering, Faculty of Natural Resources, University of Jiroft, Jiroft 7867161167, Iran Abstract: Arid and semi-arid ecosystems are prone to extensive fires due to specific climatic conditions, sparse vegetation cover, and high density of fine fuels. Understanding the flammability characteristics of land covers is essential for fire management and designing land restoration programs in arid and semi-arid ecosystems. This study provided a new approach to evaluate the flammability of shrublands and woodlands using flammability indices (FIs) including time to ignition (TI), duration of combustion (DC), and flame height (FH) of plant species and their relative frequencies in the Dalfard Basin of southeastern Iran. The results showed that there was a significant difference in FIs between land covers. Shrublands had higher flammability potential compared with woodlands. Plant moisture content had a negative relationship with TI ($P<0.010$) and no significant relationship with DC and FH ($P>0.050$). Artemisia spp., Astragalus gossypinus Fischer, Amygdalus scoparia Spach, and Cymbopogon jwarancusa (Jones) Schult. had the highest FI. Tree species such as Rhazya stricta Decne., and Pistacia atlantica Desf. showed greater resistance to fire. Using principal component analysis, the relationship between species and FIs was examined, and TI of wet fuel was the most important FI in relation to species. Structural equation model showed that life form ($P<0.001$) was the most important flammability driver. Precipitation ($P<0.010$) and legume species ($P<0.010$) were significantly related to the flammability in arid land. This study emphasizes the importance of managing high-risk species and using resistant species in vegetation restoration and shows that combining species FIs with their abundance is an effective tool for assessing fire risk and fuel management at the plant community scale.

Keywords: duration of combustion; plant moisture; fire management; structural equation model; arid ecosystems Citation: Mosayeb HOJATI, Azam KHOSRAVI MASHIZI. 2026. Flammability of plant communities in arid and semi-arid ecosystems: implications. Journal of Arid Land, 18(2): 304–321. https://doi.org/10.1016/j.jaridl.2026.02.005; https://cstr.cn/32276.14.JAL.20250314 Identifying key drivers and management

1 Introduction

Arid and semi-arid areas are considered to be among the most vulnerable ecosystems to environmental and human disturbances due to constraints such as low precipitation and irregular precipitation distribution (Singh and Chudasama, 2021). Wildfire is one of the most important natural factors in the dynamics and evolution of ecosystems and plays a dual role in regulating ecological processes (Kala, 2023). Wildfire can cause the restoration and rejuvenation of some ecosystems, meanwhile, if it occurs frequently and severely, it can lead to resource destruction, ∗Corresponding author: Azam KHOSRAVI MASHIZI (E-mail: Azam.Khosravi@ujiroft.ac.ir) Received 2025-07-12; revised 2025-11-01; accepted 2025-11-21 http://jal.xjegi.com; https://www.keaipublishing.com/en/journals/journal-of-arid-land/ biodiversity loss, and disruption of functional balance of the ecosystems (Gajendiran et al., 2024).

This issue is especially important in arid and semi-arid ecosystems that have fragile vegetation. In these areas, the occurrence of fires with quick speed and extent can have devastating consequences on ecological and economic functions, including reduced vegetation cover, increased soil erosion, threats to wildlife, and risks to adjacent human communities (Guo et al., 2025). Climate change, with increasing temperatures, increased droughts, and changes in the spatial and temporal patterns of precipitation, has increased the likelihood and severity of fires in arid and semi-arid areas, and as a result, has exacerbated the loss of species diversity (Jenkins et al., 2023). Change in plant composition is the obvious result for the responses of plant communities to fire (Grau-Andrés et al., 2024). After a fire, sensitive species with low regeneration capacity are significantly reduced, while fire-resistant or invasive species are given the opportunity to establish and expand, which causes changes in the composition and structure of vegetation cover (Meza et al., 2023). Also, the decrease in vegetation density as a result of fire reduces the capacity of soil stabilization, moisture retention, and natural regeneration, and disrupts key ecosystem processes such as nutrient cycling and primary production (Alcañiz et al., 2018). In summary, the synergy between climate change and fire can accelerate the process of vegetation loss and sustainable land degradation in these areas, and identifying these processes is essential for the ecological management and restoration of arid and semi-arid ecosystems.

Plants act as the main fuel in nature, and their flammability properties directly affect the ignition and fire behavior (Prior et al., 2018; Jian et al., 2024). Plant flammability is an important trait that affects the survival and reproduction of plants in fire-prone environments (Popović et al., 2021). In this regard, understanding the behavior of plant fuels and analyzing flammability indices (FIs) is a fundamental step for effective fire management and protection of natural resources. Flammability is the degree to which a plant or plant community can burn and is influenced by a set of morphological, physiological, chemical, and climatic factors (Dickman et al., 2023; Jian et al., 2024). Among the most important of these factors are the amount and type of biomass, moisture content, size and shape of organs, volatile plant compounds (such as essential oils and resins), and vegetative form (Gnanasekaran et al., 2023). In addition, human activities such as agriculture, livestock grazing, and land use changes can increase the risk of fires in rangelands (Davies et al., 2022; Huang et al., 2022). Therefore, accurate assessment of the flammability of different plant species is not only essential for fire prevention, fire risk assessment, and fire behavior prediction, but also an important aspect of fire ecology studies (Popović et al., 2021; Jian et al., 2024).

Based on previous studies, we used three indices, i.e., ignition time (TI), flame height (FH), and duration of combustion (DC) to determine and compare the flammability of species in arid areas (Hachmi et al., 2011; Jaureguiberry et al., 2011). TI helps to identify species that react more quickly to a heat source and can initiate a fire, so it is very useful for predicting the initial susceptibility of species to fire (Su et al., 2024). FH is important for estimating fire strength and its ability to spread to surrounding vegetation patches due to its direct relationship with the intensity of burning reaction and energy transfer (Cornwell et al., 2015; Pausas et al., 2017). DC indicates the extent to which species can act as a sustainable source of energy and contribute to the intensification and persistence of a fire over time (Cornwell et al., 2015). The simultaneous use of these three indices provides a comprehensive picture of the potential behavior of biofuels and allows natural resource managers in drylands to identify high-risk species and benefit from vegetation management, reduction of flammable fuels, and design of fire prevention strategies (White and Zipperer, 2010; Pausas et al., 2017). Although species-level flammability provides valuable information about the fuel behavior and fire responses of individual plants and can help natural ecosystem managers to select fire-resistant or fire-prone species (Wyse et al., 2018), community-level analysis is more essential for accurate assessment of fire potential at the ecosystem scale (Mitsopoulos et al., 2019). The actual fire behavior in an area depends not only on individual species characteristics, but also on the spatial structure, composition of vegetation forms, thin-to-thick fuel ratio, moisture status, horizontal and vertical continuity of vegetation JOURNAL OF ARID LAND 2026 Vol. 18 No. 2 cover, and interspecific interaction (Airey-Lauvaux et al., 2022). Community-level flammability assessment allows for better prediction of fire behavior and severity, larger-scale risk analysis, and the development of more effective strategies for fire management, vegetation restoration, and ecological damage reduction (Schertzer and Staver, 2018). Therefore, complementing species- level studies with multi-species assessments within the plant community framework is a crucial step towards sustainable land management in fire-prone areas.

Currently, there is no universally accepted standard for measuring plant flammability. Accurate and comprehensive assessment of plant flammability remains a challenge. Burning experiments probably provide a better reflection of plant behavior during combustion (Jian et al., 2024). The burning method is an efficient and standardized method for assessing the flammability severity of plant species under controlled laboratory conditions (Balde et al., 2023). This method is easy to implement, highly reproducible, and allows for inter-species comparison, especially in studies investigating the properties of plant fuels (Dimitrakopoulos and Papaioannou, 2001; Penman et al., 2011). The burning allows for a more detailed analysis of the fuel behavior of species and provides a better understanding of the role of vegetation composition in fire risk. This method has been used in different parts of the world, such as North America (Airey-Lauvaux et al., 2022), South America (Bianchi and Defosse, 2015), Africa (Dehane et al., 2017; Essaghi et al., 2017), Australia (Alam et al., 2020; Scarff et al., 2021; Cawson et al., 2023), Europe (Dimitrakopoulos and Papaioannou, 2001; Curt et al., 2011), and Asia (Fares et al., 2017), and its effectiveness has been reported for different climatic regions. The wide application of this method in different ecosystems indicates its high adaptability and importance in ecological studies and fire risk management.

Despite the widespread use of burning method in studies related to plant flammability, most of these studies have focused on tree species and forest ecosystems, especially in Mediterranean, savannah, and temperate forests (Burton et al., 2021; Popović et al., 2021). The occurrence of fires and their consequences in other ecosystems are often overlooked (Pagadala et al., 2024).

However, experimental studies using flammability method in arid and semi-arid ecosystems, especially rangelands, are very limited (van Etten et al., 2021). Rangelands, with a different composition of vegetation forms, especially grass species and broad-leaved herbaceous plants (forbs), have different fuel characteristics and ignition patterns compared with forest ecosystems.

However, these features have rarely been investigated in controlled experiments, and as a result, the available information on the intensity and pattern of flammability in rangeland species remains inadequate (Wyse et al., 2016). This research gap can lead to inaccurate assessments of fire risk and ineffective design of management strategies in dryland ecosystems. Therefore, it is essential to conduct targeted studies on the flammability of plant communities using standard methods such as tip burning, especially in fire-prone areas. The objectives of this study are: (1) to investigate the flammability of species using TI, BD, and FH indices; (2) to investigate the flammability of plant communities in arid and semi-arid areas by combining the flammability of species and their relative coverage in plant communities; (3) to investigate the relationship between FIs and plant species in arid and semi-arid areas; (4) to classify plants based on flammability intensity; and (5) to investigate the most important drivers of flammability of plant communities in arid and semi-arid areas.

2.1 Study area

The study is conducted in the Dalfard Basin of southeastern Iran (28°30′–29°28′N, 57°00′–57°49′E). The area of the Dalfard Basin is 4211 km2 with an elevation range of 633–3672 m a.s.l.

Downstream of the Dalfard Basin is located in a very arid area with 105 mm average precipitation and upstream of the Dalfard Basin is located in a semi-arid area with 357 mm average precipitation. Upstream landscape is mostly included rangelands with the dominant plant type of Mosayeb HOJATI et al.: Flammability of plant communities in arid and semi-arid···Artemisia aucheri Boiss_{Astragalus} gossypinus Fischer (Table 1 ; Fig. 1 [FIGURE:1]). These rangelands receive the highest precipitation in the study area. Rhazya stricta Decne. Woodlands are located in the plains, which receive the least precipitation (Table 1). Variation in precipitation and temperature due to elevation changes in the study area has created complex plant communities, and the area is made up of several distinct shrub and woodland plant communities (Table 1).

Given that the study area experiences several fires annually in the spring and summer seasons, experts and local managers have been concerned about the size and frequency of recent fires.

Table 1 Environmental and plant characters in the Dalfard Basin, Iran Plant type Abbreviation Elevation (m) Minimum Maximum Precipitation Temperature Artemisia aucheri Boiss_{Astragalus} gossypinus Fischer Ar_{As} Pistacia atlantica Desf._A. gossypinus Amygdalus scoparia L._A. gossypinus A. scoparia_{Ebenus} stellate Boiss.

Pi_{As} Am_{As} Am_{Eb} A. scoparia_{Cymbopogon} jwarancusa (Jones) Schult.

Am_{Cy} Tecomella undulata (Sm.) Seem Rhazya stricta Decne.

Fig. 1 Study area (a) and distribution of plant types in the Dalfard Basin, Iran (b). Am_{As}, Amygdalus scoparia L._A. gossypinus; Am_{Cy}, A. scoparia_{Cymbopogon} jwarancusa (Jones) Schult.; Am_{Eb}, A. scoparia_{Ebenus} stellate Boiss.; Ar_{As}, Artemisia aucheri Boiss_{Astragalus} gossypinus Fischer; Pi_{As}, Pistacia atlantica Desf._A. gossypinus; Rh, Rhazya stricta Decne.; Te, Tecomella undulata (Sm.) Seem.

2.2 Flammability measurements

Based on empirical approaches, ignition, combustibility, and sustainability of fire are three main components of plant flammability (Pausas et al., 2017). They play a key role in fire behavior at scales ranging from individual plants to landscapes and are important in assessing fire risk in natural ecosystems. Ignitability indicates how easily a plant or its parts (such as leaves, stems, or branches) can be ignited by a heat source. TI is used to test the ignitability. Shorter time means a species is more susceptible to ignition (Su et al., 2024). Combustibility refers to the ability of a fuel to ignite and produce heat. In thermal experiments, FH is commonly used as an index of the intensity of combustion reaction and the transfer of energy to environment (Cornwell et al., 2015).

JOURNAL OF ARID LAND 2026 Vol. 18 No. 2 FH can be an indicator of the species'ability to facilitate fire spread within plant units or between plant patches in the landscape (White and Zipperer, 2010; Pausas et al., 2017). Sustainability refers to the length of time a plant burns and produces heat after ignition. This property is characterized by DC and indicates whether the species acts as a stable fuel source in a fire (Cornwell et al., 2015). Species with high DC produce more heat over time and can potentially contribute to the intensification and persistence of fires.

FI was measured using the following three indices: TI, FH, and DC. First, each component was standardized using normalization between minimum and maximum observed values so that different scales could be compared. Then, the components were combined into a single equation with specific weight. The weight of each component was determined using the analytic hierarchy process (AHP) method to consider the relative importance of each indicator in assessing flammability. The formula of FI is as follows:

DC DC FH FH , (1) where DCmax and DCmin are the maximum and minimum of DCi, respectively; TImax and TImin are the maximum and minimum of TIi, respectively, and FHmax and FHmin are the maximum and minimum of FHi, respectively; i is the species; and α, β, and γ are the weights of FIs.

In order to evaluate the fuel characteristics and determine the FI of plant species, we applied sampling at the end of growing season (late summer) in 2024. Sampling was carried out from each of the vegetation forms, including forbs, grasses, shrubs, semi-shrubs, and trees. Collecting data was carried out from the aerial parts of the plant (including branches, leaves, seeds, etc.) in dry conditions (no rainfall for at least 72 h before) to maintain the natural moisture content of the plants. For each species, samples were taken from at least 5 separate plants and on a surface with uniform coverage to be truly representative of the biomass of that species. From each species, 500 g of fresh biomass was collected. This amount of biomass was collected in a combined and homogeneous manner from the branches of the plants to be representative of entire species.

Samples were immediately placed in well-ventilated paper bags after collection to prevent excessive transpiration and moisture changes. Samples were transported to the laboratory at ambient temperature and used in the flammability test within 48 h. Plant moisture content before combustion was also recorded using the pre- and post-drying weighing method.

To measure the flammability of plants, we used the methods described by Jaureguiberry et al. (2011). A simple and effective portable device that allowed the measurement of flammability properties of plant biomass under field conditions was used (Jaureguiberry et al., 2011). The device consisted of a steel barrel with a diameter of 60 cm and a length of 85 cm, horizontally cut in half and placed on four stable metal supports. The structure was designed to provide sufficient airflow for burning the sample, while maintaining user safety. Our plant sample burning oven was designed and implemented. First, the gas burner was turned on and the burning device (modified metal grill) was heated to 150°C. This temperature was controlled and recorded using a K-type thermocouple in the center of chamber. The burning process was carefully monitored and the characteristics of TI, DC and FH were recorded. Testing was performed for both wet and dry fuels of any plant species. For each species, at least 5 replicates were tested, and for species with high variability in leaf or stem traits, up to 10 replicates were included to ensure reliable estimates.

2.3 Species diversity and canopy cover

In each land cover type, a total of 50 plots with an area of 20 m$×20mweresystematicallyrandomized, whereint
shrubswererecordedwithin1m×2mplots, andtheabundancealongwithcanopycoverageofherbaceousspecieswas
m plots. The assessment of species diversity (D) was conducted utilizing Simpson' s index (Simpson, 1949):

Mosayeb HOJATI et al.: Flammability of plant communities in arid and semi-arid···where pi is the relative abundance of species i to the total; and S is the total number of species.

2.4 FI of plant community (FIt)

FIt was calculated as follows: where N is the number of plant species observed in plant communities; Ci is the relative canopy cover of species i; and FIi is the FI of species i. Ci value indicates the contribution of each species to the total community coverage. Species that contribute more to the total coverage will have a greater impact on the FIt. This method allows both specific characteristics of each species in terms of flammability and the influence of their abundance in vegetation to be included in a single integrated index. In this way, the flammability potential of plant community can be assessed and used for fuel management and fire risk prediction in arid and semi-arid ecosystems.

2.5 Data analysis

Analyses of variance (ANOVA) alongside least significant difference (LSD) test were utilized to systematically compare varying land covers and life forms with respect to canopy cover and FI.

Pearson' s correlation coefficient was employed to evaluate the relationships between moisture content and FI. Both direct and indirect determinants of flammability were scrutinized through the application of structural equation modeling (SEM) framework. Recently, SEM—a sophisticated statistical approach that integrates confirmatory factor analysis with regression techniques—has been applied to elucidate the complex direct and indirect interactions among ecosystem components (Awang et al., 2015). Utilizing smartPLS v.2.0 software, the robustness and validity of SEM were examined through the metrics of composite reliability (CR) and average variance extracted (AVE), respectively (Ringle et al., 2015). Principal component analysis (PCA) was employed to explore the patterns of FI across various plant species. We applied clustering methodologies to categorize species according to their flammability potential. To classify vegetation group, we calculated the similarity matrix of sampling units based on Bray-Curtis index. Then hierarchical clustering was performed using the Ward' s method (Murtagh and Legendre, 2011). In order to determine the optimal number of clusters, we examined the resulting dendrogram and used the pseudo-F criterion to evaluate the appropriate cut point. Finally, the sampling units with the highest similarity in species composition were placed in one class, and thus the plant classes were separated from each other (Kent, 2012).

3 Results

Relationship between plant moisture and FI was investigated using Pearson' s correlation (Fig. 2 [FIGURE:2]).

The results showed that there was a significant and negative relationship of plant moisture with DC and TI indices (P<0.010). There was also a significant and negative relationship between plant moisture and FIt (P<0.050). There was no significant relationship between plant moisture and FH (P>0.050). By combining FI and relative canopy cover of species, FIt was estimated (Fig. 3 [FIGURE:3]). The results showed that TI of wet fuels varied between 10 and 183 s. The DC of wet fuel also varied between 45 and 265 s. In terms of FH, wet fuels also varied between 30 and 65 cm (Fig. 3).

For wet fuel, ANOVA and LSD showed that R. stricta had the highest TI and DC values among the studied plant types with an average of 150 (\$$\pm 42) and 243 (\pm 56) s, respectively. The highest FH with an average of 65 (\pm 14) cm belonged to the type A. scoparia_A$ belonged to the type A. aucheri_A. gossypinus (Fig. 4 [FIGURE:4]). The results showed that TI of dry fuels varied between 5 and 93 s. FH of dry fuels varied between 30 JOURNAL OF ARID LAND 2026 Vol. 18 No. 2 Fig. 2 Relationship between plant moisture content and flammability indices (FIs). (a), DC (duration of combustion); (b), TI (time to ignition); (d), FH (flame height); (e), FIt (FI of plant community). *, P<0.050 level; **, P<0.010 level.

Fig. 3 Spatial distribution of FIs in the Dalfard Basin, Iran. (a), DC_D (dry fuel); (b), DC_W (wet fuel); (c), FH_D; (d), FH_W; (e), FIt_D; (f), FIt _W; (g), TI_D; (h), TI_W. and 132 cm, DC of dry fuels varied between 25 and 140 s (Fig. 3). ANOVA and LSD showed that R. stricta had the highest TI and DC values among the studied plant types with an average of 85 (\$$\pm 34) and 120 (\pm 54) s, respectively. The highest FH with an average of 103 (\pm 42) cm belonged to the type Amygdalus$ (Fig. 5 [FIGURE:5]). The contribution of each vegetative form in the studied plant types was also calculated (Fig. 5).

Mosayeb HOJATI et al.: Flammability of plant communities in arid and semi-arid···Fig. 4 Comparison of FIs among different plant types. (a), TI_W; (b), DC_W; (c), FH_W; (d), FIt_W; (e), DC_D; (f), TI_D; (g), FIt_D; (h), FH_D. Different lowercase letters indicate significant differences among plant types at P<0.050 level. Bars are standard errors.

Fig. 5 Comparison of canopy cover in different plant types (a) and different life forms of plants (b). Different lowercase letters in Figure 5a indicate significant differences among different plant types at P<0.050 level. Bars are standard errors.

The results of LSD showed that there was no significant difference in plant moisture between forbs and grasses, but they had significant differences with other forms (P<0.050; Fig 6 [FIGURE:6]). The JOURNAL OF ARID LAND 2026 Vol. 18 No. 2 highest DC of wet and dry fuels belonging to the tree form was 142 ($±42)and88(±10)s,respectively,whichwassignificantlydifferentfromothervegetativeforms(P < 0.050).ThelowestTIofwetanddrysamplesbelongingtothegrassformwas5(±2)and2(±0)s,respectively,whichu 0.050).ThehighestFHforthesemi−shrubformwas61(±1)and105(±52)cm,respectively,whichwassignificant 0.050).ThehighestFItforthegrassformwas0.562(±$0.031), respectively, which was significantly different from other vegetative forms (P<0.050).

Fig. 6 Comparison of FIs among different life forms of plants. (a), plant moisture content; (b), DC_W; (c), FH_W; (d), TI_W; (e), FIt_W; (f), TI_D; (g), FH_D; (h), DC_D; (i), FIt_D. Different lowercase letters indicate significant differences among different life forms of plants at P<0.050 level. Bars are standard errors.

Using PCA analysis, the relationship between plant species and FIs was examined (Fig. 7 [FIGURE:7]). The first PCA axis explained 76.27% of the data variance and the second PCA axis explained 15.59% of the data variance. In total, the first and second axes explain 91.86% of the data variance.

Positive and negative loadings indicated the direction of contribution of each index to the principal component. TI_W (wet fuel) and DC_W were the most important FIs.

The distribution of species in relation to FIs showed that Trifolium pretense L. and Medicago sativa L., which are herbaceous species of legume family, had the highest correlation with plant Mosayeb HOJATI et al.: Flammability of plant communities in arid and semi-arid···Fig. 7 Distribution of plant species in relation to FI based on principal component analysis (PCA). Ar_{au}, Artemisia aucheri Boiss; Ar_{si}, Artemisia sieberi Besser; As, Astragalus gossypinus Fischer; Pi, Pistacia atlantica Desf.; Am, Amygdalus scoparia L.; Cy, Cymbopogon jwarancusa (Jones) Schult.; Conv, Convolvulus arvensis L.; Ds, Descurainia sophia (L.) Webb ex Prantl; Eb, Ebenus stellata Boiss.; Pt, Pteropyrum aucheri Jaub.&Spach subsp. aucheri; Ro, Roemeria argemone (L.) C. Morales R. Mend.&Romero García; Ac, Acantholimon glandulosum Hand.-Mazz.; Tr, Trifolium pratense L. subsp. pretense; Ec, Echinops aucheri Boiss.; Me, Medicago sativa L.; Al, Allium jesdianum Boiss.&Buhse.; Fi, Ficus carica subsp. rupestris (Boiss.) Browicz; Ep, Ephedra ciliata Fisch.&C. A. Mey.; St, Stipa haussknechtii Boiss.; Junc, Juncus inflexus L.; Ae, Aerva javanica (Burm. f.) Juss.; Ac_c, Acantholimon chlorostegium Rech. f.&Schiman-Czeika; Be, Berberis integerrima Bunge; Ta, Tamarix androssowii Litv.; Zi, Ziziphus spina-christi (L.) Desf. Ju, Juniperus excelsa M.Bieb.; He, Heliotropium aucheri DC.; De, Descurainia sophia (L.) Webb ex Prantl. Th, Thymus daenensis subsp.

lancifolius (Celak.) Jalas; Co, Cornulaca monacantha Delile. moisture. Grass species Cymbopogon jwarancusa (Jones) Schult. and Stipa barbata Desf., shrub species Artemisia sieberi Besser, A. aucheri, and A. gossypinus had the highest correlation with TI. Tree and shrub species Ficus carica Linn., R. stricta, Ziziphus spina-christi (L.) Desf., Tamarix androssowii Litv., Pistacia atlantica Desf., and Berberis integerrima Bunge were most closely related to DC. Shrub species such as Acantholimon glandulosum Hand.-Mazz., Pteropyrum aucheri Jaub.&Spach subsp. aucheri, and Ebenus stellata Boiss. were most closely related to FH. PCA results also showed that TI and DC of wet fuel were the most important indices of flammability of species (Table 2). Using clustering analysis, we classified the studied species based on FIs (Fig. 8 [FIGURE:8]). The results showed that C. jwarancusa, S. barbata, A. sieberi, A. aucheri, A. gossypinus, A. scoparia, Trifolium pratense L. subsp. pretense, Allium jesdianum Boiss.&Buhse., and M. sativa had high flammability, and species R. stricta and P. atlantica had very low flammability.

Table 2 Principal component analysis (PCA) loading for flammability indices (FIs) using the first two axes Index Plant moisture FIt_W Axis 1 Axis 2 Index FIt_D Eigenvalue Variance (%) Axis 1 Axis 2 Note: The significant value is shown in bold. DC, duration of combustion; TI, time to ignition; FH, flame height; FIt, FI of plant community; D, dry fuel; W, wet fuel.

JOURNAL OF ARID LAND 2026 Vol. 18 No. 2 Fig. 8 Clustering plant species in very low, low, moderate, and high classes of FIs Relationships of plant characteristics and environmental factors with flammability were investigated using SEM model. Two indices, CR and AVE, were used to validate the model, with CR greater than 0.700 and AVE of all parameters greater than 0.500, indicating the reliability and validity of the model being evaluated (Table 3). Overall, life form was the most important drivers affecting flammability (P<0.010). The next parameters affecting flammability were precipitation, legume species, and C4 species (P<0.010).

Table 3 Average variance extracted (AVE), composite reliability (CR), and total impacts of plant traits and environmental factors related to flammability using structural equation model (SEM) Variable Canopy size Species height Legume species C4 species Leaf life span Life form Temperature Precipitation Species family Elevation Canopy cover Species diversity Flammability Impact 0.276* 0.375** 0.369** -0.296* -0.487*** 0.152* 0.389** 0.241* 0.162* 0.173* 0.190* Note: *, P<0.050 level;* ***, P<0.010 level;*** , P<0.001 level. ' '-' ' indicates no value.

4.1 Flammability of plant communities

The results of this study showed that rangelands had higher flammability compared with woodlands. Vegetation structural composition of rangeland, the higher proportion of herbaceous plants and forbs, and the higher density of fine and surface fuels in rangelands can be considered Mosayeb HOJATI et al.:

Flammability of plant communities in arid and semi-arid···as the reasons for the high flammability of this ecosystem (Pilliod et al., 2017). While vegetation on woodlands typically has denser canopy cover, coarser fuels, and higher relative humidity in the understory, which can reduce fire intensity and spread (Pellizzaro et al., 2007; Baruch et al., 2022).

Also, vegetation on rangelands is more susceptible to rapid ignition and horizontal fire spread due to its openness and the presence of annual and perennial herbaceous plants, while in forest lands, vertical fire transfer and flammability are more influenced by more specific conditions, such as the presence of flammable materials in the canopy or under severe drought condition (Pilliod et al., 2017; Maestas et al., 2023). These findings indicate that in fire management and restoration planning of damaged areas, it is essential to pay attention to the type of plant community and its structural characteristics, and rangelands should be considered as areas with higher risk potential for fire spread.

We also found that among the plant types studied, A. aucheri_A. gossypinus had the highest FI values. This result can be attributed to the morphological and physiological characteristics of these species including dense bush structure, high density of aerial biomass, presence of volatile compounds such as essential oils and resins, and low moisture content of living matter compared with other plant types (Farzaneh et al., 2006; Sharifi-Rad et al., 2022). Species of these two plant types usually have larger levels of fine and flammable fuels and, in the presence of favorable climatic conditions such as high temperature and low humidity, can cause rapid ignition of fire and its spread across the area (Pausas et al., 2017). Previous study indicated that fine fuels play pivotal role in flammability of Artemisia (Pilliod et al., 2017; Bradley et al., 2018). The findings indicate that in fire risk management planning, special attention to these plant types is necessary, especially in arid and semi-arid areas, because their presence can be considered as an effective factor in increasing the risk of natural fires (Bacciu et al., 2022).

Among the land covers studied, the A. scoparia–C. jwarancusa type was also identified as one of the types that is sensitive to fire and has high flammability. The A. scoparia species, which is usually leafless, ignites quickly when a fire occurs due to its dry, brittle, and woody branches with low moisture content (Javidfar et al., 2017). The absence of leaves increases the ratio of dry fuel to the total biomass of the plant and increases the likelihood of fire initiation and spread. C. jwarancusa species, which is a C4 photosynthetic grass, also has high flammability due to its high aerial biomass production, rapid growth in the warm season, and thin and drying leaves (Fatima et al., 2021). C4 grasses, especially in arid and semi-arid areas, are known to be a major source of surface fuels that can rapidly spread fires in grasslands (Still et al., 2014). The combination of these two species in a community leads to an increase in the susceptibility of the type to ignition, indicating that not only individual species characteristics, but also their interactions at the plant community level play an important role in determining fire risk.

4.2 Flammability of species

Among plant species with high FIs, Artemisia and Astragalus were observed, along with some forbs and grasses. These groups have morphological and physiological characteristics that are prone to rapid ignition and high flammability due to high surface biomass, volatile organic compound content, and thin and drying leaves or stem structure (Cui et al., 2020). C4 species, especially under warmer conditions, with high growth rates and high biomass production, produce large amounts of fine and superficial dry fuel that can spread fire rapidly in rangelands (Still et al., 2014). Also, some forbs exhibit high flammability due to their open plant structure and thin leaves, especially when plant moisture content decreases during the dry season. The simultaneous combination of these plant groups in a community can significantly increase the risk of fire, especially in semi-arid areas where water stress and uneven vegetation cover provide conditions for rapid fire spread. Among the species studied, two tree species, R. stricta and P. atlantica, were identified as species with low flammability. A longer time to start burning was observed in these two species and their burning duration was also longer than other species. These characteristics indicate that these species have high thermal resistance to fire and do not ignite easily. The reason for this behavior can be sought in the physiological, biochemical, and structural characteristics of JOURNAL OF ARID LAND 2026 Vol. 18 No. 2 these species. For example, R. stricta is known as a species with relatively thick, leathery leaves, and high plant moisture content, and has specific chemical compounds that prevent it from flaming quickly (Alam et al., 2014; Albeshri et al., 2021). In the case of P. atlantica, the dense wood structure, the presence of high plant moisture content in the living tissue, and the deep root system that allows moisture absorption in dry conditions are considered to be the main factors in its resistance to ignition (Pourreza et al., 2008; Sadeghi et al., 2010). These results indicate that the use of fire-resistant tree species such as R. stricta and P. atlantica in vegetation management and land restoration programs in fire-prone areas can help reduce the risk and severity of fire spread (Park et al., 2024).

4.3 Relationship between FIs and species

The findings of this study showed that TI and DC play the most important roles in determining the flammability of plant species. Species that live fuel ignites later and burns longer are more resistant to fire. These results are consistent with previous studies (Weise et al., 2016; Coradi et al., 2020), indicating that plant moisture content of living parts is one of the most important factors controlling the flammability of plants. Also, the duration of live fuel burning indicates the amount of energy required to completely burn living tissues and indicates the structural resistance of the plant to thermal decomposition (Fazeli et al., 2022). Examination of other indices, such as FH and dry matter burning time, showed that although these parameters also differ among species, they alone do not provide adequate resolution to determine the fire resistance of species (Al-Tayyar et al., 2022). Accordingly, it can be concluded that indices related to living parts of the plant, especially burning time and time to start burning of fresh matter, are more accurate criteria for assessing the flammability of plant species and can be used in the selection of resistant species for the restoration of fire-prone areas and fire risk management (Pausas et al., 2017).

The results of this study showed that plant moisture has a significant and negative relationship with TI and FIt of the species. This inverse relationship can be explained by the inhibitory role of moisture in the combustion process (Emery et al., 2020). Before a plant fuel can ignite, the water in its cellular structure must evaporate, which requires the absorption of a large amount of thermal energy (Grootemaat et al., 2015; Castro Rego et al., 2021). As a result, increasing the moisture content of plant tissue delays the onset of combustion and reduces the intensity and DC (Zhao et al., 2014; Blauw et al., 2015). Therefore, increasing the moisture content of the species leads to a combined reduction of the factors affecting ignition, and ultimately to a decrease in the overall flammability. However, once combustion has begun, other factors such as plant structure, volatile chemical compounds (essential oils and resins), and tissue density play an important role in fire intensity and persistence (Pausas et al., 2017). From a management perspective, these findings emphasize that fire prediction and management should not rely solely on moisture; rather, morphological and chemical characteristics of species should also be considered. This approach can be used to select less flammable species, design safe fuel stacks, and identify high-risk areas, especially in arid and semi-arid ecosystems (Fernandes and Botelho, 2003).

4.4 Flammability drivers

Life form of plants species was the main factor affected flammability in arid and semi-arid ecosystems. The results of this study showed that forbs have the highest percentage of moisture in the fresh (wet) state compared with other vegetative forms, and therefore, flammability of their wet state showed the lowest value. This finding can be attributed to the physiological structure of forbs that usually have soft and juicy tissues and lack woody structure, which allows them to maintain high water content in leaves and stems throughout the growing season (Zhang et al., 2022). Our finding showed that flammability of the dry fuel of forbs was higher than those of other vegetation forms. This contrast between the wet and dry behavior of forbs emphasizes the importance of examining phenological conditions and fuel harvest time in flammability assessment (Afreen and Singh, 2024). Part of the fuel in ecosystems is fine, and low-density fuels that, due to good aeration and the connection between them, cause the spread of fire and increase the intensity of combustion in the ecosystem (Pausas et al., 2017). However, during seasonal Mosayeb HOJATI et al.: Flammability of plant communities in arid and semi-arid···drying or post-withering conditions, forbs lose moisture rapidly and become highly flammable fuels due to their soft texture and high surface-to-volume ratio (Wragg et al., 2018). This finding could play a key role in management decisions, especially in rangeland fire risk reduction programs and determining the appropriate time for vegetation control at the end of growing season.

Precipitation was the second most important factor influencing the flammability of plant communities. Holdrege et al. (2024) revealed importance of precipitation to predict wildfire in shrublands. Our finding indicated that there was a direct relationship between precipitation and flammability of plant species. Especially in high-altitude areas with higher annual precipitation, rangeland communities were observed to have denser vegetation cover, higher species diversity, and especially higher abundance of forb species. Consequently, although increased precipitation can generally increase moisture and reduce fire risk, in arid and semi-arid ecosystems, increased precipitation may lead to the growth and accumulation of micro-plant fuels that create a high potential for fire spread during dry season (Feldman et al., 2024). This phenomenon, known as the "paradox of productivity and fire" , has been confirmed in similar studies (Pausas and Keeley, 2009). Previous studies have also shown that this paradox is not limited to specific areas and has been observed in diverse ecosystems, from African savannas (Pellegrini et al., 2018) and Australian grasslands (Bond and Keeley, 2005) to Mediterranean forests (Pausas and Bond, 2020).

In all of these cases, the initial increase in biological productivity led to fuel accumulation and increased fire risk, but the intensity and pattern depended on the climate and management conditions of each area. The results of this study, in line with global evidence, indicate that the productivity-fire paradox is a pervasive ecological pattern that has important implications for sustainable rangeland management and fire risk prediction at regional and global scales.

Legume species were the third factor affecting flammability. Wiggers et al. (2013) emphasized the sensitivity of legumes to fire. In the study area, most of the observed legume species were forbs and were among the species with high flammability. These species are more sensitive to flammability due to their specific morphological and physiological traits, including thin leaves, high surface biomass production, and severe reduction in humidity in dry season (Wragg et al., 2018). Furthermore, the high nitrogen content of legume plant tissue may accelerate the combustion process and increase the intensity of burning (Dimitrakopoulos and Papaioannou, 2001; Pausas et al., 2017). Given that legumes play an important role in nitrogen fixation and improving soil quality, under dry conditions and with dense cover, they can potentially increase fire risk, especially when combined with other fire-sensitive herbaceous plants. Therefore, the presence of forb legumes in the vegetation composition of rangelands can be considered as a key factor in flammability risk analysis and should be considered in fuel management and the design of fire-resistant ecosystems.

5 Conclusions

This study provides a framework for identifying flammability risk at the species and community levels. FIs, particularly TI and DC for wet fuel, are useful tools for assessing fire risk in plant species. Our finding indicated that rangeland communities are more flammable than woodlands due to their higher proportion of fine fuels, forbs cover, and open structure. Among the studied species, A. aucheri and A. gossypinus showed the highest flammability, while R. stricta and P. atlantica were identified as fire-resistant. The indices TI and DC were the most reliable indicators of fire resistance, but flammability was found to depend not only on plant moisture, but also on structural and chemical traits such as tissue density and volatile compounds. Life form, precipitation, and the presence of forb legumes were major drivers of flammability. Increased rainfall promoted vegetation growth and fuel accumulation, confirming the productivity-fire paradox in arid areas. Overall, these results highlight the need for integrating species traits and climatic factors in fire management and restoration planning to enhance the resilience of arid and semi-arid ecosystems.

JOURNAL OF ARID LAND 2026 Vol. 18 No. 2 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.

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Azam KHOSRAVI MASHIZI, Mosayeb HOJATI; Writing - review and editing: Azam KHOSRAVI MASHIZI, Mosayeb HOJATI; Funding acquisition: Azam KHOSRAVI MASHIZI; Resources: Azam KHOSRAVI MASHIZI.

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Figure 14

Figure 1: Figure 14

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Figures

Source: ChinaXiv —Machine translation. Verify with original.