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Fire-Resistant Plants: A Review of Plant Morphology, Tissues, Habits, Ecological Adaptations, and Other Factors Contributing to Bioderived Environmental Solutions and Technologies

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Abstract

This review represents an investigation of fire-resistant plants through the areas of materials and characterization, discussing and exploring the implications of their unique properties in several applications, materials solutions, pollution, and perspectives on these plants. The main goals are identifying promising fire-resistant plants from published research with potential applications in engineering and exploring their potential properties in engineering applications including biomimetics. First, Carrot2, results search clustering engine was used to create inclusion criteria and categories for examining the past five years of fire-resistant plant research, materials science-related and otherwise. From these papers analyzed nearly half of research was agricultural or environmental science in nature, with topics and applications in chemistry, engineering, materials science, representing less than 10% each. The unique properties and mechanisms of fire-resistant plants can be classified in areas such as plant architecture, microstructure, and constituent materials, which were discussed. Specifically, the relevance of silica, trichomes (plant hairs), tissue organization, biopolymers, and indigenous knowledge of plants are examined, with an eye towards biomimetics and as inspired structures for engineering as well as in solving pollution/waste disposal and housing/sustainable architecture. Practical considerations, hypotheses to be tested, and conclusions are synthesized, always keeping in mind the intersection of fire-resistant plants and materials science.

Keywords: Fire-resistant plants; Silica; Hairs; Biopolymers; Tissue structure; Materials.
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1. Introduction

There is an increasing concern over the preservation of some species in two very different and iconic regions of South America, the Andes and Amazonia. Due to multiple reasons that include global warming,[1] invasive plants in the context of land management,[2] weather,[3] and deforestation,[4] wildfires are one of the major forces currently devastating native forest ecosystems worldwide, even threatening to change the Amazon rainforest from a net carbon sink to a net carbon source.[5]

Millions of years of evolution have produced some amazing plant species able to survive wildfires, plants that, even when largely destroyed by the action of fire, somehow can resist high temperatures and/or resprout soon after fire exposure, showing that the plant has survived the effects of high temperatures.[6] The resistance of plants, and particularly of trees, to fires, depends on several factors, such as fire type, trunk characteristics, and bark thickness.[6] There are also fire-resistant plants that are now used to protect landscapes and reduce the risk of wildfire.[7]

Fire-resistant plants and plants exposed to fire have been studied, but the topic is far from completely understood due to the complexity of the factors involving diverse plant species. It has been reported from even Cretaceous fossils that some leaves and flowers may be protected and provide protection from direct heat during the fire, due to their hairy texture,[8] a hypothesis that should be investigated in the multifunctional hairy leaves from *frailejón* (*Espeletia* spp.).[9] Also, many species have been identified as resistant to fire in various parts of the world, the result of complex natural selection and adaptation, including convergent evolution, which certainly

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can be very useful to understand their preservation and importance today.[10] The complex microstructure of these plants not only may explain fire resistance but also have direct applications in the fabrication of ceramics, such as silica in bamboo stems,[11] *moriche* palm fibers,[12] or rice husk,[13] which could explain some of their fire-resistant and mechanical properties. Although the case of rice husk complicates this, as it is used as a fuel, showing that the effect of plant materials on fire resistance is context-dependent and involves a complex interaction between structure, inorganic and organic composition, as well as the fire- and fuel-related variables involved at a macro scale. In fact, the very characteristics of plant materials that make them fire-resistant (e.g., combustibility, rapid rate of fuel consumption, high ignition temperature, elevated pyrolysis temperature range) in habitat may also cause them to be attractive as fuels in certain situations.[14]

This article used the Scopus database to analyze the current trends, limitations, and science related to fire-resistant plants, particularly from the last 5 years, a time interval selected because of the high number of articles to analyze and in the interest of prioritizing more recent research. It was also limited to research and review articles, excluding conference papers and other document types, mainly because this selection usually includes more elaborated research. It presents a detailed literature review, metrics, and statistics to provide basic information about prior research on fire resistance in plants and which areas of basic research could use more attention/work. Also, it addresses indigenous and traditional knowledge as well as ecological and morphological findings in terms of suggesting new lines of research as a driver of fire-resistant plants and its potential importance for mitigating wildfires and inspire new engineering solutions for fire-resistant materials. Finally, it also integrates a broad-ranging view of this issue, incorporating local, practical, and social concerns about the topic.

2. Literature review methods

For this review, bibliographic searches were carried out in the Scopus database, for the area of fire-resistant plants (see Table 1). From these keywords, initially, 761 documents were found. Then, applying filter 1, a total of 590 documents were determined. Thereafter, by applying filter 2, a total of 185 documents were found. Moreover, by applying the two filters in the same search, 160 documents were established. Finally, excluding keywords such as plant disease, genetics, and agricultural and biological sciences, only 71 documents were selected.

Carrot2 software open-source search clustering engine was used to understand the areas found in the search. This software automatically clusters collections of documents, in our case research and review papers, into thematic categories, from the Scopus database search. This was particularly useful because it shows much more specific areas, allowing a different classification and analysis.

2.1 Literature review: results and analysis

Figure 1 shows some of the search statistics obtained from Scopus, where the number of documents in the last years increased significantly, Fig. 1a; only 5% of the documents targeted are review papers, Fig. 1b; the main research areas are agricultural and biological sciences, and environmental science, Fig. 1c. The funding sponsors are led by agencies in China and the USA, respectively.

Figure 2 shows a tree map generated by the tool Carrot2, with 51 results classified in clusters of fire-resistant plants (5), materials (5), and other topics (9), among others. This graph shows by size the number of studies by area available with Scopus and with the Carrot2 software, which is important to understand the different subjects related to the fire-resistant

Table 1. Search algorithms.

Search	All results	Only filter 1 (document type: article or review)	Filter 2 (last 5 years)	Two filters
TITLE-ABS-KEY (fire AND resistant AND plants)	761	590	185	-
(("TITLE-ABS-KEY (fireAND resistant AND plants) AND (LIMIT-TO (PUBYEAR, 2022) OR LIMIT-TO (PUBYEAR, 2021) OR LIMIT-TO (PUBYEAR, 2020) OR LIMIT-TO (PUBYEAR, 2019) OR LIMIT-TO (PUBYEAR, 2018)) AND (LIMIT-TO (DOCTYPE, "ar") OR LIMIT-TO (DOCTYPE, "re"))				160
(EXCLUDE (EXACTKEYWORD, "Erwinia Amylovora") OR EXCLUDE (EXACTKEYWORD, "Genetics") OR EXCLUDE (EXACTKEYWORD, "Plant Disease")				126
AND (EXCLUDE (SUBJAREA, "AGRI")) Agricultural and Biological Sciences				71

Where TITLE-ABS-KEY is Title-Abstract-Keywords, and PUBYEAR is publication year, all data taken from the analyzed article. DOCTYPE is document type, EXACTKEYWORD is the exact keyword, and SUBJAREA is subject area.

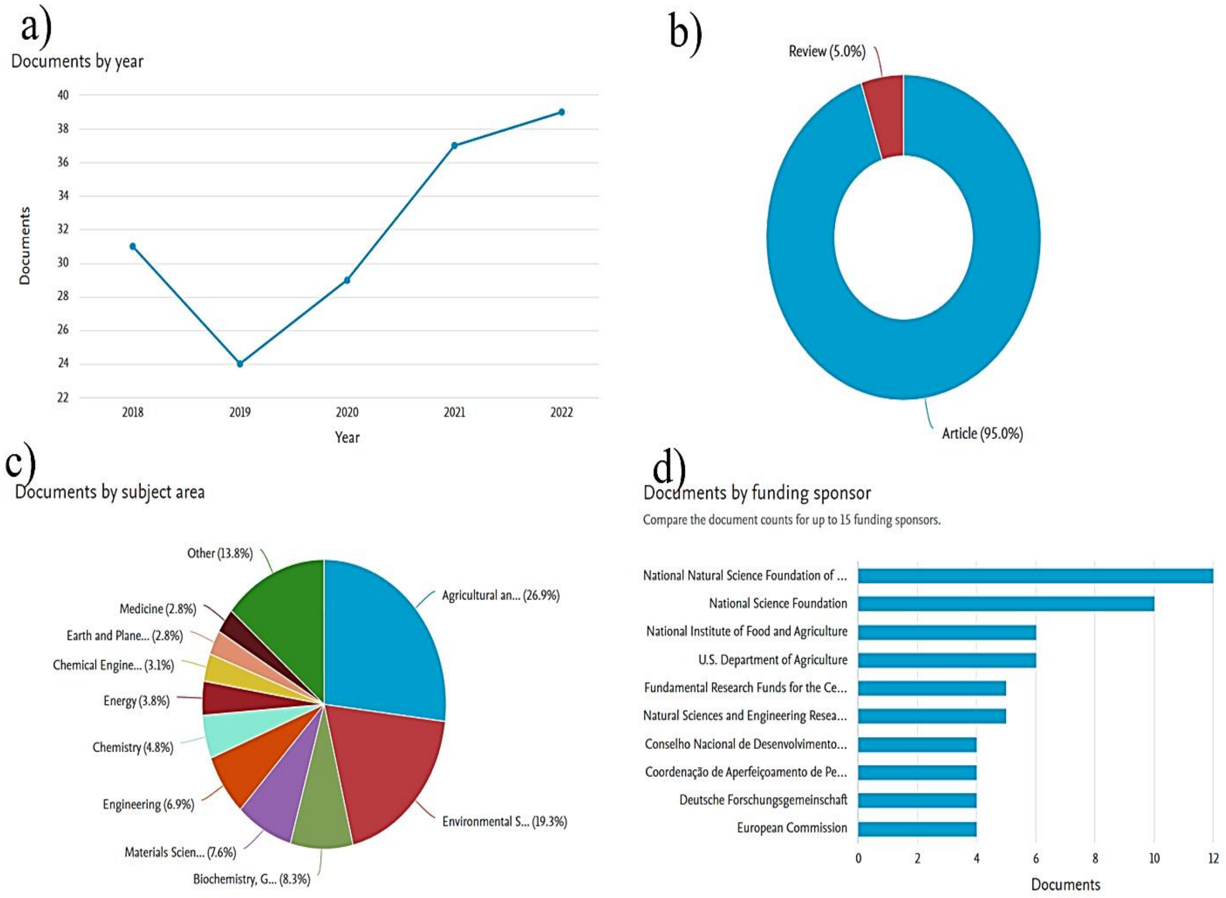

Fig. 1 Scopus statistics regarding the search algorithms from Table 1.

plants. The subject fire-resistant plants also appear, but it is mostly related to biology or environmental aspects. Other areas are more related to applications and materials.

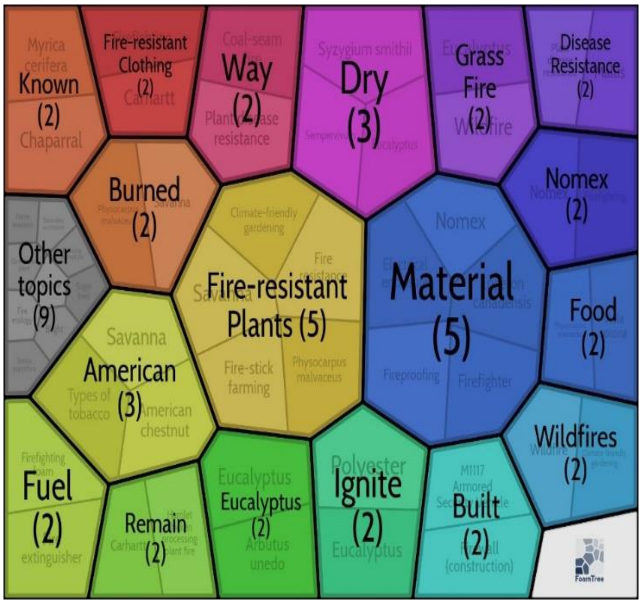

Fig. 2 Clustering with more specific topics (search.carrot2.org).

2.2 Materials characterization technologies

From the above classification, several papers that are analyzed below, used diverse advanced materials characterization technologies, opening the understanding of fundamental mechanisms and their associated micro- and nanostructures of plants that contribute to their more significant properties. Among these technologies are Fourier-transform infrared spectroscopy (FTIR), differential scanning calorimetry (DSC), thermogravimetric and differential thermal analysis (TGA, DTA), X-ray photoelectron spectroscopy (XPS), and scanning electron microscopy (SEM). One study focused on the production and characterization of fire-resistant epoxy composites from plant-derived-ferulic acid used FTIR[15] spectra for chemical bond identification; DSC, DMA (Dynamic Mechanical Analysis), TGA, and TDA for storage modulus and thermomechanical properties; SEM for microstructure identification; and XPS for elemental composition. Another research application has investigated leaves capturing fire smoke particles,[16] involving IR and SEM techniques to understand the smoke composition and compound concentration, as well as microstructure, respectively. Phosphorylated cellulose[17] has been used as an admixture for fire-resistant lyocell fibers, characterized via TGA, SEM, and FTIR techniques. Clearly, much basic research regarding fire resistance in plants and its practical applications requires many of the same advanced characterization techniques. Table 2 summarizes some of the most important characteristics for the fire-resistant plants found in this literature review. First, considering the number

Table 2. Fire-resistant plants parameters.

Plant species	Fire or temperature exposure	Part studied	Application	Materials characterization techniques	Country´s plant	Ref.
Ferula asafoetida, rattletop, spina date	40-700 °C from TGA	Leaves, fibers, and seeds, respectively with epoxy resin	fire-resistant epoxy thermosets	TGA-DTA, SEM	China	[18]
Seagrass (*Zostera marina* leaves, *Posidonia oceanica* leaves, and wood)	Flame test ISO 5660-1 (over 300 °C), and Cone calorimeter	Leaves and fibers, with polymeric binder	Insulating materials	OM, thermal conductivity	Germany	[19]
Cunninghamia lanceolata and *Schima superba*	Portable burner set up 300 °C	Leaves	Wildfires prevention and/or conservation	SEM, IR	China	[20]
Lyocell cellulose (semisynthetic fibers)	Room temperature to 700 °C from TGA, Cone calorimeter, burning tests	Fibers	Fire resistant fibers	FTIR, TGA, SEM-EDS	China	[21]
Banana peel powder (*Musa acuminata*) (BPP), coconut shell (*Cocos nucifera*) extract (CSE) and pomegranate rind (*Punica granatum*)	Flamability tests and TGA up to 700 °C	Extracts and fabric	Fire resistant fabrics	TGA, FTIR, SEM-EDS, mechanical tests	India	[22]
Savanna trees (*Crossopteryx febrifuga* and *Piliostigma thonningii*)	Fire exposure up to 620 °C	All plant	Wildfires prevention and/or conservation	None	CoÃte d'Ivoire (West Africa	[23]
Eucalyptus spp. and *Callitris intratropica*	Modified wick-fire technique	Bark	Wildfires prevention and/or conservation	None	Australia	[24]
Several, including: pitch pine, balsam fir, eastern hemlock, beech, sugar maple and chestnut oak	Thermal conductivity	Bark	Wildfires prevention and/or conservation	Thermal conductivity	USA	[25]
Cabbage palms (*Sabal palmetto*)	Direct and controlled fire on site, over 300 °C	All plant	Wildfires prevention and/or conservation	None	USA	[26]
Many, including: annuals, and turf.	Not reported	All plant	Wildfires prevention and/or conservation	None	USA	[27]
Many, including: *Ajuga reptans* and *Achillea* spp.	Not reported	All plant	Wildfires prevention and/or conservation	None	USA	[28]
Many, including: *Myrica rubra*, and *Camellia oleifera*	Not reported	All plant	Wildfires prevention and/or conservation	None	China	[29]

of plants interesting for studying this behavior, the number of species with serious studies is very low, and there are even fewer studies using materials sciences techniques to understand important aspects of plant materials and microstructure. Only a few papers include thermogravimetric analysis (TGA) for precise thermal degradation and quantification, scanning electron microscopy (SEM), or Fourier Transform Infrared Spectroscopy (FTIR). In terms of plant parts, mostly the leaves and bark are the subject of these few studies, and even more limited are the number of countries which have researchers that have undertaken these studies.

Besides these studies and considering the number of species worldwide, this review shows amazing opportunities for research and development in this area.

3. Plant mechanisms for fire-resistance

The unique properties and mechanisms of fire-resistant plants can be grouped into factors such as plant architecture, material composition, and microstructure. Moreover, there are several parts of the plants that must be preserved so that they can be easily regenerated after a fire: the vascular cambium, the axial or apical shoots, as well asthe phloem in adult woody vascular plants. However, in many cases it may not be known the exact mechanisms by which tissues are protective for their plants – in which case the fire-resistant properties need to be explained by way of further research, the driving purpose behind this review. In this review it was found that some plants contain silica or hairs, for instance, as components of protective tissues that lead to improved fire-resistance that enables them to withstandwildfires. Even when some parts of the plants are destroyed, many species have an amazing regeneration capacity involving resprouting among other mechanisms.

3.1 Silica

One major mechanism for fire resistance in plants that has been broached but that deserves further attention and analysis is related to their silica content. Rather than a main chemical mechanism for fire retardation and resistance, it is proposed that the structural characteristics and physical distribution of silica particles within a plant or in a material are the actual basis for the mechanism.[30] The effectiveness of this flammability reduction is based on certain microstructural characteristics deriving from the physical and physicochemical properties of silica particles, including pore size, particle size, surface silanol concentration, surface area, density, and viscosity.[30] In particular, if the silica particles accumulate near the sample surface, based on the additive's surface area, density, and viscosity, it seemingly is more likely to perform as a thermally insulating layer for the polymer or composite of interest.[30] This could be an under investigated factor in materials where, for instance, hemp fiber is serving as an additive in hempcrete and other composite materials with inorganic binders, since the non-glandular cells of hemp are only silicified on the outer wall surface, and in the case of one study of hemp fiber-reinforced polyester, ignition temperature was increased by the volume fraction of fiber in a density-independent manner.[31,32] Many sources suggest that hemp's contribution of perceived fire-resistant properties to composites may be more related to the amelioration of their cracking behavior,[32–39] such that the binder itself (e.g., lime) is more responsible for direct fire resistance, and further suggesting that hemp in these materials may primarily be acting much as a fiber temper does in ceramics. This perhaps deserves its own separate analysis, however, and it is not the end of the story where silica and silicified plant tissues, especially where trichomes and epidermal cells are concerned. Anecdotal evidence suggests that in the case of *Curatella americana*, a fire-resistant shrub that yields various leaf epidermal and hair cell phytoliths (silicified plant remains often corresponding to the shapes of cells and intracellular spaces) present in the archaeological and sedimentary records of Panama, as well as its close relative, *Davilla aspera*, with similar cellular morphology, these silicified structures are responsible for both the ethnographic use for scrubbing pots and polishing wooden items and also seemingly for their thermal and fire-resistant properties, as is the case with the hyperaccumulating, silicon-dependent scouring rushes/horsetails (*Equisetum* spp.).[40,41] Phytoliths derived from the ash of tree bark, amorphous silica corresponding to the cellular and intracellular spaces of these tissues, have been considered as a separate category of tempering material in their own right from the outset in the 20th-century development of ceramic science.[42] Certainly, it may be worth considering that there are chemically based fire resistance effects due to silica as well, albeit not necessarily based so much on the natural physiology of plants, given the studies of wood impregnation with silica and titanium dioxide,[43] among other substances. If there are elemental and inorganic biomarkers for fire resistance in plants related to mere concentration rather than microstructure though, including silica, they have yet to be identified with certainty. Thus, there are several complex factors that make a plant resistant to fire, and the microstructure may play an important role in the responses. Fig. 3 shows in two images the microstructure of *moriche* palm obtained from scanning electron microscopy, still poorly understood but known by its resistance to fire by ancestral communities from the Amazon region.

Figure 4 shows a complex microstructure in plants with hairy and grain configuration and with known fire-resistant properties. Their chemical composition contributes as well.

3.2 Hairs (trichomes)

A couple of papers concerning the genus *Phylica* (Rhamnaceae) and its ancient relatives were published in the past couple of years, which made interesting, if largely anecdotal, claims about the lineage's ancient adaptation to fire, given the conserved structure and thick covering of trichomes supposedly protecting budding flowers.[44] Possibly more conclusive are the cases of trichome-coated leaf axils and epicormic structures in a couple of myrtaceous genera –

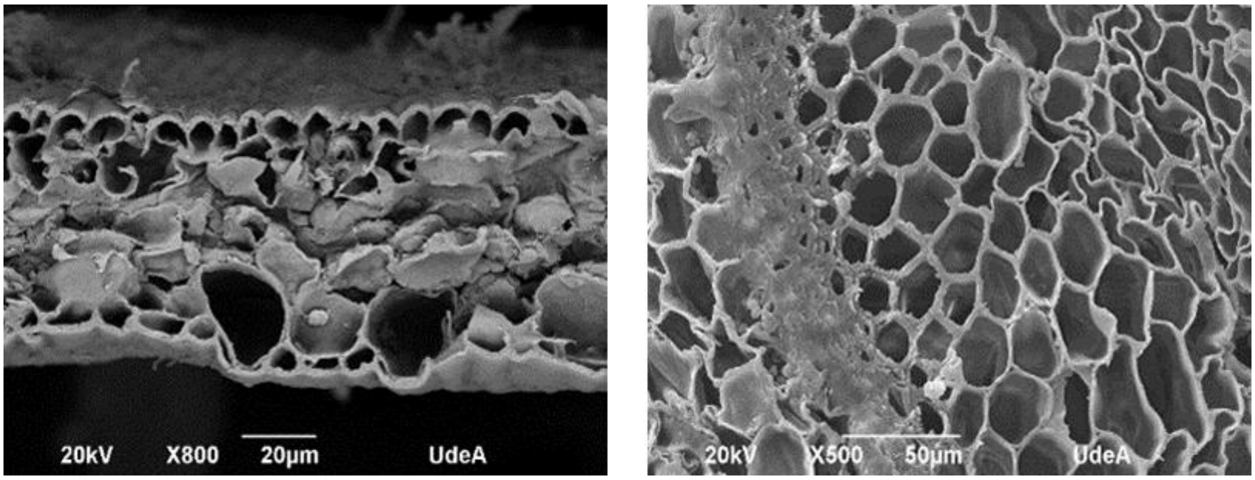

Fig. 3 Microstructure of a fire-resistant plant *Mauritia flexuosa* (*moriche* palm) from Colombia.

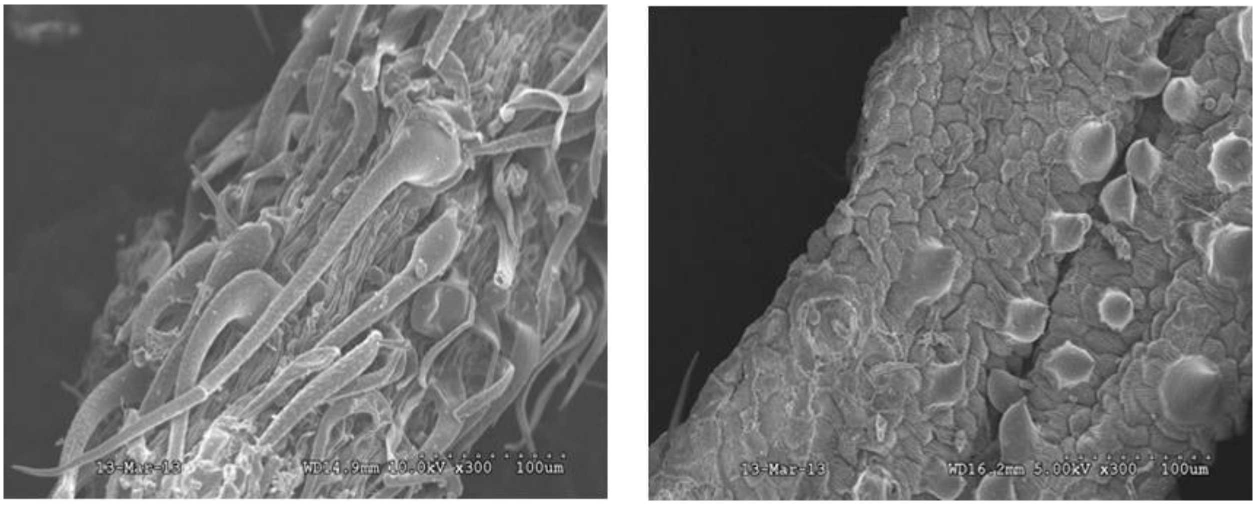

Fig. 4 Non-glandular silicified hairs (left) and calcium carbonate-containing cystoliths (right) in *Cannabis sativa* L., source of hemp and cannabis; only the outer wall surface of these two types of non-glandular trichomes is silicified.

Syncarpia and *Tristaniopsis* – with fire resprouting properties, as well as the presence of taxa with buds protected by a covering of trichomes as a distinct and effective strategy in fire-disturbed habitat, given the more systematic ecological and morphological investigations in these cases.[45,46] The principles here may be relevant to *Espeletia* spp. (Asteraceae), *Dendrosenecio* spp. (Asteraceae), and *Lobelia* sect. *Rhynchopetalum* (Campanulaceae), among others, all alpine pachycaul plants, although much more, by comparison, has been written about how their convergent evolution in hairy leaves and Bauplan are related to protection from the cold and from UV rays with higher solar irradiance in montane habitats as well as acquisition and conservation of water.[9,47] Evidence from the study of *Lychnophora diamantinana* (Asteraceae), with similarly hairy leaves and habit to alpine pachycauls, in the Brazilian side, show that, at least in this specific case, the cell walls of non-glandular trichomes may physically degrade and deposit a hyaline layer of mostly pectin that is hygroscopic and protects the plant from desiccation.[48] While there is no guarantee that hairs are functionally providing fire-resistance in the same way they are supporting its survival in dry, sunny habitats, it is interesting to note that the plants are additionally endemic and adapted to fire-disturbed areas. On the one hand, it is suggested that *Lychnophora* spp. may be mostly resprouters and post-fire germinators and that the tops, including leaves, are destroyed during wildfires or that the fires are not particularly powerful when the aerial parts do survive.[49,50] Not only the leaves are covered with hairs, however, but the stems as well are covered with a thick tomentum composed of trichomes, suggesting that this adaptation attributed primarily and traditionally just to dry environments with high insolation could confer fire resistance as well,[51] a possibility worth at least further and more in-depth exploration either way.

3.3 Biopolymers and other materials

To understand the composition of plant materials, fuels, and biomass (and possibly composites and bioinspired materials developed from them), at least one of two main, related techniques should be employed, among others depending on the study: TGA-GC-MS[52] and py-GC-MS.[53] The first, thermogravimetry coupled with gas chromatography-mass spectrometry analysis, allows the scientist to observe the mass percentage to a precise level and volatile chemical composition that evolves with heating at a known temperature program and interpret the results in terms of the sample's phase transitions and thermal decompositions in concert. This is a powerful tool in terms of understanding the combustion and pyrolysis as well as the initial composition of the material of interest. Ash, cellulose, hemicellulose, lignin, and volatile components and contributions to mass percentage can be monitored, along with those of individual sugar residue types from the decomposition of biopolymers.[52] The second, pyrolysis-gas chromatography-mass spectrometry, is used to quickly decompose and volatilize a sample with a pyrolyzer at elevated temperature and then analyze it[53]. Equally, one can perform a thermal desorption step beforehand to analyze volatiles and semi-volatiles only and then produce a separate pyrogram that corresponds just to the material's decomposition.[53] Either way, chemical information that would not be recoverable from microscopic and other analytical techniques can be produced and contribute to an understanding of fire-resistant properties.

A relevant study was undertaken in Puerto Rico to determine the carbon, nitrogen, and other essential element resource use and allocation for biopolymers in the metabolism of two species of Neotropical palms was triggered by the excitement about traditional knowledge on the timing of palm frond harvest for thatching, using *Sabal mauritiiformis* (Arecaceae),[54] during the lunar cycle in Latin America. Examination of the palm fronds showed that their composition during the full moon accordingly demonstrated peak levels of lignification and production of hemicellulose, with the opposite being true for the new moon.[54,55] This is seemingly also verified in the context of wood quality as well since rural Zapotec farmers know to harvest branches for the hafts of axes and the handles of other such implements like hoes as well as structural beams at the full moon in order to ensure their durability and prevent them from being infested by termites.[56] As stated by the authors of the palm frond harvest paper, the best-supported hypothesis, for now, is that these plants' increased lignification is a response to the higher degree of insect activity and feeding behavior under levels of maximum lunar illumination.[54,55] Yearly, seasonal, lunar, and diel cycles in plants, while they may be known anecdotally or from further observation and scientific study, are not necessarily at all yet attributable to ecological relationships nor to other environmental stimuli.[54] For instance, in the opium poppy (*Papaver somniferum*), Western empiricism has only recently been able to explain the millennia-old tradition of morning harvest of latex, when the alkaloidal content is highest, physiologically in terms of the plant's daily modulation of water allocation throughout its laticiferous tissue,[54,57,58] and so in certain cases biologically relevant cycles may be more a matter of metabolism instead. It will be well worth appreciating the potential existence and impact of these cycles to identify, reproduce, and understand their effects on the composition and durability of harvested plant tissues, as fuels and as materials in general.

3.4 Tissue structure and habit

While chemical and microstructural compositions of tissues may account for some of the fire-resistant properties of plants, higher-level tissue organization and ultimately the habits of plants in their ecological contexts may also account for such adaptations. For *Mauritia flexuosa*, the *moriche* palm, for instance, at least some populations seem to be in continuous, long-term interaction with fire, and so long as the individuals are not subjected to wildfire events that kill the apical meristem and/or their belowground biomass, they will likely survive and regenerate.[59] Water retention by leaf sheaths/petiole bases and around the apical meristem keeps *moriche* palms wet, with fuel moisture being the primary regulator of fire in these environments, in which case they will live through wildfires and grow additional, new green tissue within days.[59] It is entirely possible with *Espeletia* spp. (*frailejones*) that the characteristics that make them remarkable as plants in terms of their tissue organization, including stomatal crypts on the undersides of leaves and thickened primary meristems at the shoot apices along with their highly villous leaves, mostly attributable to their high, dry, and cold environments,[9] also may convey fire resistance in some manner. This has yet to be explored, however. Interestingly, it is known that wildfire will sometimes remove the marcescent leaves of *Espeletia* spp., dead leaves that are retained on plants for decades and even up to and including more than a century, while leaving the rest of the tissues intact.[60] This might suggest that they can serve a protective and preventive role in these cases, for preserving the living giant rosette leaves, stems, and meristematic tissue. Other examples that might be worth studying in greater depth include the lignified outer pericarp of *Adansonia* spp. (baobabs and boabs; Malvaceae) that serves a role in protecting the fruits from harm during savanna wildfires in sub-Saharan Africa and Australia and seems to help increase the germination rate of seeds after fire exposure;[61] the tissue structures of desiccation-tolerant arborescent monocots such as certain taxa of Boryaceae, Cyperaceae, and Velloziaceae to determine fire resistance;[62] and the contributions of tissue structure, especially the process and composition of trunk formation, as well as the thickened cuticles of the epidermis, to fire resistance in Australian *Macrozamia* spp. growing in frequently fire-disturbed environments, as well as the dicots (members of the Ericacaeae [Epacridoideae], Fabaceae, Myrtaceae, and Proteaceae) in the same plant communities with notable fire-resistant traits.[63]

Evidence suggests that *Schoenoplectus* spp. (Cyperaceae) in the Americas are an excellent example of this fire resistance based in tissue structure (Fig. 5). Multiple studies have shown that *Schoenoplectus americanus* thrives in fire-disturbed wetlands, being at least in certain cases the only observed plant with aboveground stems that survive such fire events and with

Fig. 5 Collection of *Schoenoplectus* sp. (courtesy of Virginia McRostie) from the mouth of the Loa River in northern Chile. Prominently displayed are the rhizomes (surrounded by the thinner, tinier, and more numerous roots), responsible for asexual propagation, including in response to fire, and the triangular stems full of aerenchymatous tissue protected by a lignified, waxy epidermis, which together produce the favorable fire-resistant and structural characteristics of these traditionally used sedges.

a faster recovery than other species based on multiple metrics, given the level of asexual reproduction and regeneration through rhizomatous growth.[64,65] At the high end, its congener *Schoenoplectus californicus* exhibits thermal conductivity equivalent to layers of wool or wood fiber (0.55–0.66 W/mK) in construction materials, with good fire resistance including short ignition and extinction cycles, and layers composed of whole canes having greater flexural strength.[66] Traditionally, a South American subspecies of *S. californicus*, known as *totora*, was used by bundling, braiding, and weaving stems to build the floating houses and islands where the Uros of Lake Titicaca lived as well as their *balsas* (boats)[62] and the watercraft for indigenous Peruvian coastal fisherman, known as *caballitos de totora*.

4. Indigenous perspective

Indigenous peoples from all around the world have an extensive knowledge not only of medicinal plants,[67] but also of natural fibers to produce elements used in hunting[12] (such as bows and arrows) and palm leaves used in the construction of *malocas* and other uses.[68] For instance, indigenous knowledge from the Caribbean suggests that palm fronds harvested during the new moon decay within a couple of years while those collected at or around the full moon last for 12–2 years, such that a strategy based on using indigenous knowledge to develop ecologically sustainable harvesting practices is worth considering.[55] Certainly, the knowledge of jungle plants acquired over millennia by ancestral communities is very valuable, and unfortunately it has not been sufficiently studied, which is why it is necessary that joint research be considered in the future that includes this type of cultural knowledge. Indigenous experts can makeimportant technical contributions, particularly if their insights are combined with analytical instrumentation capacity and engineering principles.

5. Bioinspired and Potential applications

While hempcrete and other hemp-based materials have been studied and promulgated as potential fire-resistant and renewable sources of construction materials and structural fabrics,[32,33,35–39] similarly behaving materials such as kenaf bast fiber[69] as well as bamboo[70–72] and the composites derived at least partially from them have also been discussed. These ample, renewable botanical sources of raw materials all have in common that they can be to some extent grown in tropical, subtropical, and warm temperate environments and are non-timber forest products (NTFPs). In a brief review of all three materials, in the context of cement formulation, however, it was only noted that hempcrete formulations could prevent crack propagation, and at this time no particularly advantageous fire resistance has been noted,[73] even though research and development continue. Moreover, fique, a native fiber derived from *Furcraea macrophylla* and other congeneric botanical sources, has been preliminarily shown to have the potential for its thermal and other physical properties as a wearable fabric,[74] and it already does find use in indigenous handicrafts and locally made heat protectors/koozies for hot beverages in Colombia.[75]

In the context of kraft paper formulation, treatment with ammonium phosphite led to covalent (phosphoester) modification of the sugar residues in the cellulose present, which produced an increased limiting oxygen index, decreased char length, as well as a lower initial decomposition temperature with increased remaining residue that maintained the initial carbonized frame and crystal structure of the raw material.[76] More general principles of the contribution of phosphorus and phosphorus-containing compounds as flame retardants in the context of biofibers and biocomposites, along with other additives, have been reviewed,[30] as has the potential of native and modified cellulose, hemicellulose, and lignin from botanical feedstocks.[77] Moreover, comparatively minor biopolymer constituents of certain plant materials, including cutin and suberin, not only confer hydrophobic properties to surfaces but may also be responsible for fire resistance and temperature insulation of materials where incorporated, without the same pollution and health hazards of off-gassing toxic degradation products.[78,79] Tannic acid and tannins have also been shown to have very promising fire-retardant properties, which may be due in part to their low thermal conductivity and to the formation of "foaming graphite" layers in the context of charring.[79,80]

All in all, these characteristics of fire resistance in plant-based biomaterials including for construction materials, wearable fabrics, and other utilitarian purposes, especially with renewable resources, will prove invaluable for producing environmentally friendly useful materials in the context of a warming world with an exponentially increasing human population. Potential applications including for consumer electronics and technologies as well as batteries and energy generation/storage should also be investigated (e.g., fire prevention or quenching, heat resistant/dispersing components, *etc*.), as these are personal, infrastructural, and environmental hazards of note.

6. Waste removal, recycling, and pollution reduction

Along with attention to detail of the fire-resistant and other useful properties of biomaterials, careful consideration for sourcing and industrial scale production must be weighed additionally against the value of preventing (or causing additional) pollution and use of existing waste streams for industrial/societal scale applications. In certain cases, materials derived from plants may have certain histories of use and traditional applications, but the data may or may not yet exist to determine the contributions of their products and by-products to environmental health hazards and in the context of anthropogenic environments.

One of the most important by-products to consider as a botanically based waste stream that is under heavy consideration for bioderived materials and technologies is bagasse. This is the lignocellulosic residue from the agricultural production of crops, including sugarcane and agave, as well as related residues from maize (corn stover) and rice (rice husk). Composites formed from bagasse are of serious interest,[81] as are valorization schemes involving the production of composites incorporating sugarcane bagasse waste streams more specifically.[82] This is important to note because the sugarcane industry is highly toxic anyway, contributing significantly to air and water pollution,[83–87] including more specifically in Colombia,[88–90] and while the production itself should be reduced in the first place, environmental harm reduction and recycling/upcycling with by-products such as bagasse can and should be pursued to the extent possible. One interesting factor of note in addition to the presence of soluble and volatile/semi-volatile components and biopolymers in the sugarcane industry and in the context of biomass burning and valorization of waste for biomaterials is that sugarcane bagasse contains significant amounts of phytoliths, biogenic silica. Not only do phytoliths contribute to the wear and tear of industrial machinery but they can constitute a health hazard when inhaled,[90] so understanding the dispositions of different inorganic and organic components of waste streams is important when considering their use as raw material for manufacture. Comparison of the organic compositions of extracts from feedstocks such as lignocellulosic sugarcane bagasse, waste from miscanthus grass, and maize/corn stover for the generation of cellulosic bioethanol, for instance, has been undertaken.[91] Certainly, weighing the potential energy intensity and the potential of waste for the production of useful materials vs. fuels (or both) should be always considered, especially when bioethanol production (e.g., for maize and sugarcane) and similar agroindustry land use is dedicated solely to that, for corporate and/or state benefit, and not to feeding people and minding the environmental cost and burden that primarily impacts them. All of that said, waste materials derived from plants represent a promising line of research in the manufacture of fire-resistant materials and products, including ceiling tiles, insulators, cements, plasters, biodegradables, and other composites,[81,82,91] and their potential to be applied as a solution for both environmental and practical human problems in tandem is tremendous. When talking about potential engineering solutions, often research refers to plant products (if not extracts precisely) rather than the plants themselves, particularly when involving applied science/engineering in the discussion. However, these considerations and original research are also applicable to wildfire management, silvicultural systems, preservation of wetlands and *páramos*, *etc*., and so the conclusions for the plants themselves are also valuable and relevant to the discussion.

7. Perspectives, challenges, and recommendations

Studies and applications must be pursued at a scale that will not produce additional ecosystem impacts, especially when plants that are vulnerable or endangered are involved (IUCN red list) and the production of materials from biomass is involved. Parallels to natural products research where overharvesting of plants (or animals, *etc*.) has occurred as a result – a good example being the Pacific yew tree (*Taxus brevifolia*) when paclitaxel was approved as a new anticancer agent in the nineties, and there were concerns the species would go extinct from human use[54,92] can be cited here as instructive examples.

One recommendation might be to conduct research into the basic and applied science at a small scale with biomass in such a way as to avoid ecosystem impact of any sort and then to scale up if necessary in at least one of two ways: 1) using substitute biomass from crops or bagasse (fibrous by-product) from an extant waste stream to produce a sufficiently similar result; 2) using the principles derived from chemical and microstructural studies to engineer similar materials with or without the use of (any) biomass.

Of course, one would hope to develop processes and materials that do not pollute or expend more energy than current practices, and the use of the aforementioned analytical chemistry techniques, such as TGA-GC-MS and py-GC-MS, along with other analyses and instrumentation, including differential scanning calorimetry, thermogravimetric analysis, evolved gas analysis, and characterization of particulates with light scattering/laser diffraction and cascade impactors will prove invaluable where the fire retardant and thermal behaviors of materials are concerned and in characterizing potential pollution. Conducting microstructural studies of materials fired in kilns, muffle furnaces, and fire test furnaces as well as under specialized conditions that better simulate wildfire or other criteria of interest is a highly interrelated activity of great importance as well, using SEM, TEM, microCT, X-ray diffraction, X-ray fluorescence, FTIR and Raman microscopy, atomic force microscopy, and pore size analysis by gas sorption, among others, to examine fuels and whole tissues as well as composite materials. Where the involvement of substantial amounts of biomass is concerned and/or the participation of communities is involved, land use considerations and genuine local collaboration, buy-in, and agency are paramount if conflict is to be avoided in these endeavors. Consider what value is or could be added in the process in terms of local infrastructure and quality of life concerns. What impacts if any, including pollution, labor issues, and factors disproportionately impacting women and children, might be anticipated, ameliorated, or improved? Any details that would show up in an IRB (institutional review board) application when thinking at a land use scale in partnership with local communities would be worth elaboration. While their perspective is important and their interest is understandable, there are clearly important contributions to be made by materials science and adjacent fields. The formation of proper interdisciplinary teams here and getting chemists and materials scientists interested in the problem in the first place may be as great a gap here as actually securing funding (which may be scarcer in the environmental sciences and basic biological science research).

Finally, the role of tissue structure in fire-resistant properties with additional examples can be given in terms of aerenchymatous tissues, bark tissue, and plant hairs/trichomes, among others. In many cases it may not be known the exact mechanisms by which tissues are protective for their plants – in which case the fire-resistant properties need to be explained by way of further research, the driving purpose behind this review, but this review brings up ideas to further explore it, such as silica/phytoliths; exudates; and natural lipophilic coatings). In this manuscript, examples in all the previous categories, were given even when a protective effect has been demonstrated for e.g., outer bark, where there is quantitative data to back fire-resistance of certain taxa in ecological contexts, even when the mechanism(s) of action are often speculative (e.g., phytochemical classes: tannins, suberins; or other physicochemical properties of bark) and/or not investigated by means of instrumental analysis and materials science methodologies. They are hypotheses that should be tested. The desire for more specifics here is no different from our call for more integrative, collaborative research into the basic and applied problems here relevant to fire resistance in plants. This work is incomplete and requires more definitive results and specific information largely because the relevant studiesstill need to be pursued.

8. Conclusions

Fire resistance in plants is a topic that is not very well researched, given its current potential importance in sustainability and wildfire prevention, and it is especially unknown from the particular perspective of materials science, which bears the far-reaching potential to impact human quality of life. Based on a preliminary survey of the extant peer-reviewed literature, most of the research (46.2%) in this vein has been undertaken by researchers in the agricultural and environmental sciences, whereas fields such as materials science have lower numbers (7.6%). This suggests that, while there may be basic data and principles that can be taken and applied from the extant body of research into agriculture, biology, and the environmental sciences, there is much material science-oriented research yet to be undertaken. Its pursuit would benefit both the basic science and applications of societal value where fire resistance in plants is concerned. Reviewing both the physical and chemical bases for fire resistance in living plants and their derived tissues and products as well as the existing research into botanically based materials with application to flame-retardant and thermally insulating products and structures, there is nearly limitless positive impact that such further interdisciplinary research would have in relation to dealing with environmental and social crises stemming from global warming and biodiversity loss. Besides the potential of advanced characterization techniques, not many investigations of any sort have been pursued, limiting the understanding of properties such as strength, composition, micro- and nanostructure, and other information that could yield material solutions to problems such as wildfires and thermal insulation, critical to social and environmental issues in a warming world. Perhaps within the complexity of the wildfires problem, in combination with global warming, deforestation, and other issues, the advantages of a materials science perspective will become evident while attempting to use these plants' properties in solvingthese planetary problems, as long as a concerted effort is made to undertake this interdisciplinary research in earnest.

Conflict of Interest

There is no conflict of interest.

Supporting Information

Not applicable.

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