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Bio-Based Fire Retardant for Coco Lumber using *Aloe barbadensis miller* (Aloe Vera), *Mangifera indica* (Mango), or *Persea americana* (Avocado) and Boron Additives

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Abstract: Accidental fires are prevalent in low-income communities and one of the solutions to decrease fire risk is to apply fire retardants on combustible materials. While extensive research were available in creating fire retardants with inorganic chemicals, further studies are needed for bio-based fire retardants. The development of bio-based fire retardants involves testing organic matter for the presence of fire-retardant compounds such as nitrogen, phosphorus, and polyphenols. This study sought to determine the effectiveness of the peels of *Aloe barbadensis miller* (aloe vera), *Mangifera indica* (mangoes), and *Persea americana* (avocados) in creating bio-based fire retardants for coco lumber. Maceration was used to get the fruit and plant extracts. Boric acid and borax were also added as additives to boost fire retarding properties. The burning behavior of the lumber was observed in a modified horizontal flammability test and a modified flame spread test and measured in terms of mass loss, smoke density, char yield, and charring rate. The results revealed that among the fruits, the mango-based fire-retardant inhibited mass loss the most ($M = 0.006$, $SD = 0.003$), while the avocado-based fire-retardant inhibited smoke the most ($M = 0.036$, $SD = 0.016$). No significant difference was found among the groups as determined by One-way ANOVA and MANOVA ($p > 0.05$). An indirect relationship was found between smoke density and char yield, which may be examined to improve the smoke suppressing ability of commercial fire retardants. Future studies may also refine the plant extracts and use standard flammability tests.

Keywords: bio-based fire retardants; mass loss of wood; smoke density; char yield of wood; charring rate of wood

INTRODUCTION

House fires commonly occur in the Philippines and disadvantaged communities are especially vulnerable to them. Light construction materials are more commonly used in impoverished residential areas due to their significant lack of income to provide better housing for their families (Ballesteros, 2010). In England, Dean et al. (2015) found that impoverished young families and urban populations experienced the most fatalities due to fire incidents. This increases the need for the implementation of cost-efficient fire prevention methods in disadvantaged communities.

One of the strategies in reducing fire risk, targeting the combustible properties of structural materials since this impacts the spread of fire, is the application of fire retardants (Wahlqvist & Hees, 2016). Fire retardant chemicals such as boron, nitrogen, phosphorus, and metals are mixed or chemically-bonded (National Institute of Environmental Health Sciences [NIEHS], n.d.; Vahabi et al., 2020). When applied, materials are subject to heat and their fire retarding properties were observed.

Several studies succeeded in making cellulosic material fire resistant by chemically binding the fire retardant onto the material (Al Hokayem et al., 2020; Xiong et al., 2020; Yan, Xu, & Wang, 2019). Alternatively, other studies have used organic materials to create fire retardants. Basak and Ali (2019) created a novel fire retardant for cotton fabric using pomegranate rind. An examination of the pomegranate rind's chemical composition revealed the presence of nitrogen, potassium, aluminum, silicon, sulfur, chlorine, calcium. Consequently, the combination of nitrogen and phosphorus created thermally stable residues (Ghomi et al., 2020). Furthermore, Basak and Ali (2017) stated that polyphenolic compounds helped improve the char formation ability of pomegranate. Similarly, Xia et al. (2018) stated that when subject to heat, polyphenols increase char formation. In addition, char formation improves the fire retardancy of the material because it serves as a protective barrier against heat and prevents the release of combustible particles in the air (Browne, 1958; Salasinska et al., 2017).

Although fruits and plants contain high levels of polyphenol, nitrogen, and phosphorus content, they have not been studied for fire retarding properties. An analysis done by Haque et al. (2014) showed that the Aloe Vera leaves contained 1.90 mg/g of phosphorus. Masibo and Qian (2008) found that polyphenolic compounds present in mangoes amount to 4066 mg/kg. In a study done by Haas (1945), the nitrogen content in avocados ranged from 0.07% to 0.56% in a fresh pulp, while the dry pulp nitrogen content ranged from 0.21% to 1.82%. The phosphorus content ranged from 509 parts per million (ppm) to 1122 ppm for a fresh pulp, and the range of a dry pulp was from 2063 ppm to 3243 ppm.

Another factor to consider in the creation of fire retardants are fire retardant additives. Wang et al., (2010) mentioned in their study that individually, chemicals with fire retarding properties are not sufficient in making a fire retardant. They also mentioned the need to integrate fire retardant chemicals into their base fire retardants to improve their ability to suppress smoke and flame. Boric acid and borax were used as additives due to their fire retarding properties. According to a study done by Wang et al. (2004), boric acid accelerates oxygen diluting reactions in the wood at about 100-300 degrees Celsius, which is a desirable effect in a fire retardant. Their study revealed that boric acid is usually paired with borax because it can inhibit flame spread but promotes smoldering, which boric acid can suppress. Given these results from both boron compounds, boric acid and borax were integrated into the bio-based fire retardant.

Several gaps exist in fire retardant research. First, controlled experiments cannot account for numerous variables that affect an actual fire in current fire-retardant tests. Variables such as humidity impact the flame spread rate of a material (Dietenberger & Hasburgh, 2016). Thus, the behavior of fire retardants in buildings and homes may not be accurately predicted using results from previous studies. Second, few studies have developed plant-based fire retardants for wood. Third, fire retardants, specifically created for lumber from tropical regions, are lacking.

To address these limitations, the researchers created an alternative bio-based fire retardant for coco lumber using *Aloe barbadensis miller* (aloe vera), *Mangifera indica* (mango), or *Persea americana* (avocado) and boron additives. The plant-based fire retardants were developed using mixtures and physical reactions, and their performance was judged based on mass loss-the weight loss of the wood due to combustion (Yan et al., 2019), char yield-the amount of char produced, measured by the amount of char from the burned samples in grams, smoke density- smoke density is the amount of carbon in the smoke (Champagne, 1971), and charring rate- the speed of char formation or char depth over a constant period of time (Maraveas et al., 2013). Char depth is measured using optical density, the amount of light that passes through the smoke (Wellhausen et al., 2013).

The study addressed the limitation of controlled experiments by acclimatizing the samples before performing modified tests outdoors. The standard fire tests were modified due to pandemic-related constraints. Through the development of a bio-based fire retardant, the study aimed to lower the risk of fire in domestic places to prevent people from losing one of their basic needs, which is shelter.

From the experiments, the following research questions were answered:

1. What are the effects of fire retardants made from plant/fruit skin extracts on the burning timber in terms of the following;
    a. mass loss;

b. char yield;

c. charring rate; and

d. smoke density?

2. Is there a significant difference between the mass loss, char yield, charring rate, and smoke density of fire retardants treated with different plant/fruit extracts?
3. Is there a significant difference in the mass loss, char yield, charring rate, and smoke density of the experimental group compared to the control group?

METHODOLOGY

Research Design

A one-factor research design was used to assess the effects of different types of plant/fruit extracts and an 8% concentration of boric acid and borax on the flammability of the coco lumber samples. The independent variable, i.e., plant/fruit extract, had four categorical levels: three experimental groups and a negative control group. Furthermore, a positive control group made of samples treated with a Class A fire retardant was also present. In total, five groups underwent the horizontal flammability test and flame spread test to assess their fire retardancy in terms of the dependent variables: mass loss, char yield, smoke density, and charring rate.

Research Locale and Samples

Due to the COVID-19 pandemic, particular adaptations were made in the research locale, sample size, and procurement. Material development was done in the researchers' respective homes in the cities of Cavite, Las Pinas, and Muntinlupa, while the testing procedures were conducted in Quezon City. All materials and equipment were purchased online from established shops. Each experimental group included five timber samples. The sample size was limited to five due to financial constraints, though it was within the acceptable range suggested by James et al. (2007) for experiment trials.

Development of fire-retardant-treated timber

The development of fire-retardant-treated timber consisted of four stages. First, the fire-retardant additives were prepared. Boric acid and borax were mixed in boiling water in a ratio of 1:1:8 until they were fully dissolved. Second, plant extracts were obtained using maceration. The fruit peels were cleaned using distilled water and cut into small pieces (Albrigi, n.d.). The cut pieces were then oven-dried at a temperature of 50°C, until they reached a moisture content of 10% (Safdar et al., 2016). Once the moisture content of the peels reached 10%, they underwent maceration by storing the dried fruit/plant rind in an airtight water-filled container for three days with frequent shaking (Waghmare & Deshmukh, 2017). After three days, the mixture was filtered via straining to remove insoluble materials from the liquid. Third, the fire retardants were formulated. Ninety-two percent plant extract and eight percent boron additives were rapidly blended according to the optimal ratio studied by Ayrilmis et al. (2012). The fire retardants were then stored in sanitized and airtight glass jars during transport to the research area. Fourth, coco lumber was prepared and treated with the fire retardants. A 330 x 50 mm. board was used for the horizontal flammability test, a modification made from the UL94 Horizontal Flammability Tester (TESTEX, n.d.). A 4 x 0.26 ft. board was used for the flame spread test, which was proportionate to the size used in the Steiner Tunnel Test (Eickner, 1977). The sample groups were coated with five (5) fire retardants and dried outdoors for 24 hours. The negative control group received a boric acid and borax treatment and was acclimatized with the other groups for 24 hours. The positive control group was treated with a Flame Shield, Class A fire retardant, and was dried outdoors according to the instructions specified on the product.

Instruments and Data Gathering Procedures

For data collection, the samples' mass loss, smoke density, char yield, and charring rate when burned were measured in the horizontal flammability and flame spread tests.

Five sample groups were tested based on the factorial design of the research. Table 1 shows the contents of each group and how the independent variable was separated into categorical levels, with a control variable of 8% concentration of boric acid and borax.

Table 1

Experimental groups with levels of plant/fruit extract and FR additives

Plant/fruit extract	Boric acid + Borax Concentration of 8%
None	Negative Control Group
Aloe Vera	Experimental Group 1
Mango	Experimental Group 2
Avocado	Experimental Group 3
Class A fire retardant	Positive Control Group

Smoke density, mass loss, charring rate, and char yield were measured to determine the fire retardants' effectiveness. Ten (10) samples from each experiment group, standard group, and control group underwent the horizontal flammability test and the modified flame spread test; five (5) underwent the former test while the other five (5) underwent the last test.

The Horizontal Flammability Test was used in this study to collect data on mass loss, char formation, and smoke density. According to the article Flammability Test Methods (n.d.), the horizontal flammability test is a procedure that examines how easily a material would catch fire and how they behave when introduced to fire. The material was positioned above the bunsen burner horizontally, which allowed the researchers to distinguish whether the material will remain burning after the test flame was removed. The rate at which the materials burn could be determined as well. A simplified version of the horizontal flammability test was constructed using horizontal support and a butane torch, based on TESTEX (n.d). The horizontal support was used to keep the specimen in place throughout the experiment or adjust the specimen when burning. Adjustment of the sample was made to increase or decrease the concentration on any part of the material. The butane torch was used to ignite the wood to start the burning process and collect the needed data for the dependent variables.

Conducting the horizontal flammability test involved several steps. First, the sample was suspended above the ground using horizontal support with a butane torch placed over it. Second, the light intensity and the weight of the sample were measured using the light meter and weighing scale before the test. Third, the sample was burned for thirty seconds (30 sec.). Light intensity was measured again during the test. Fourth, once the test was completed, char was scraped off the wood to weigh the sample and the char for mass loss and char yield. Accordingly, the procedure of the horizontal flammability test is complete, illustrated in Figure 1:

Figure 1

Modified Horizontal Flammability Test

The modified flame spread test, adapted from the Steiner Tunnel Test, was used to observe the charring rate of the wood samples. The Steiner Tunnel measures how far and how fast flames spread across the 25 ft length of the test sample, ending after 10 minutes (Eickner, 1977). Due to financial constraints, the wood's dimensions were reduced to 4 x 0.26 ft, and the test only lasted 2.20 minutes. In this study, the researchers constructed the tunnel using concrete, a fire-resistant material (CLM Fireproofing, n.d.). However, the structure of the tunnel was modified to accommodate the dimensions of the wood samples. The tunnel was 4 ft. long, and the inner chamber was 12 x 18 inches. Openings on either end of the tunnel measured 12 x 18 inches to properly ventilate the chamber. The wood sample was attached to the chamber ceiling, with a butane torch placed at one end of the specimen.

The flame spread test started once the flames came into contact with one end of the sample. The sample was burned for 2.20 minutes. Using a measuring tape, char length was taken after the test, and this data was processed to get the charring rate of the sample. Figure 2.2 shows an illustration of the modified flame spread test.

Figure 2

Modified Flame Spread Test

Data Analysis Procedures

Equations 1 and 2 were used to obtain the mass loss value (Zamboni, 2020):

Mass loss percentage = final mass / initial mass (Eq. 1)

Average mass loss = initial mass average - final mass average (Eq. 2)

The ratio between the weight of char and the initial weight of the sample was calculated to obtain the char yield value (Guizani et al., 2017). This equation was used to obtain light intensity values for smoke density (Meredith & Massey, 1977):

Light intensity = initial light intensity / final light intensity (Eq. 3)

The data was then analyzed using the Jamovi software to determine the most effective fire retardant. First, descriptive statistics determined the general increase or decrease in the dependent variables per group. Subsequently, significant differences between the sample groups according to mass loss, smoke density, char yield, and charring rate were drawn using One-way ANOVA and its non-parametric alternative, the Kruskal-Wallis H test. Lastly, significant differences between the experimental and control groups were compared using One-way ANOVA and MANOVA. From this data analysis procedure, the researchers will determine the optimal bio-based material and fire retardant by choosing the treated group with the most significant positive effects compared to the negative control group and the most negligible difference compared to the positive control group.

RESULTS AND DISCUSSION

Effects of fire retardants on burning timber

In terms of mass loss

When a material undergoes combustion, mass is lost in the process (Yan et al., 2019). Therefore, mass loss is used to determine the ability of fire retardants to prevent thermal decomposition or convert the mass into char (Karaseva et al., 2019).

To treat the wood and test for mass loss, the plant extracts of aloe vera, avocado, and mango peels were obtained using maceration. Boric acid and borax were diluted in water at 100°C, in a 1:1:8 ratio. The plant extract and boron solution were then blended together and coated on a 330 x 50 mm board of coco lumber. Mass loss was measured using the modified horizontal flammability test, wherein the board was suspended above the ground horizontally and subjected to heat for 30 seconds. The weight of the board was measured before and after it was burned. These two variables were then used to calculate the mass loss of the wood (see Equations 1 and 2).

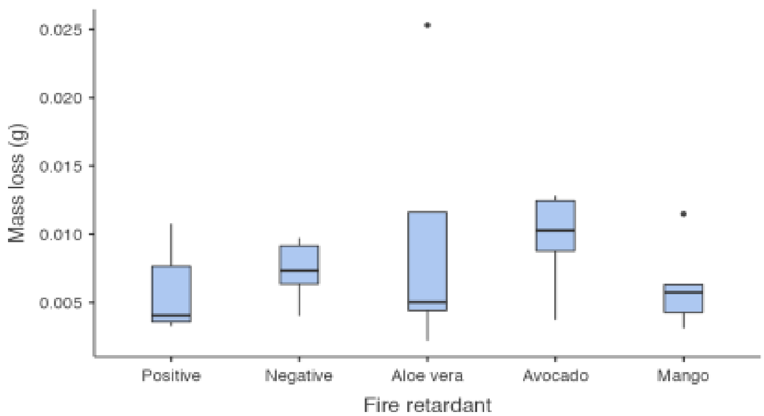

Figure 3

Mass Loss among the Sample Groups

Figure 3 presents the mass loss of the treated wood. Aloe vera (M = 0.01, SD = 0.009) had the highest mass loss and was closest to the negative (M = 0.007, SD = 0.002) , while mango (M = 0.006, SD = 0.003) had the lowest mass loss and was closest to the positive (M = 0.006, SD = 0.003).

Among the fruits, the mango-based fire-retardant significantly lessened mass loss because it was closest to the results of the positive control group. Yan et al. (2019) notes that mass loss decreases when the char yield increases because it acts as a barrier, protecting the material from any damage. In addition to char formation, the polyphenols, as well as the boron compounds from the additives, improved the thermal stability of the wood, which prevented mass loss. These compounds were also observed to lessen the mass loss in previous studies (Karaseva et al., 2019; Xu, et al., 2018).

In terms of smoke density

Smoke emissions is one of the properties that fire retardants aim to suppress due to their life-threatening effects on the human respiratory system (Environmental Protection Agency, n.d.) For this study, smoke density was measured using optical density, which is the amount of light that can pass through smoke despite the obstruction of the light path by the fumes (Wellhausen et al., 2013). By measuring the smoke density or the concentration of smoke particles produced, the researchers can determine if a particular fire retardant or fire prevention method is effective in fire suppression.

Smoke density is measured during the modified horizontal flammability test. The sample lies between a light source and a light meter. As the sample is being burned, the light meter measures the amount of light that penetrates the smoke emissions. Smoke density is then calculated using Equation 3.

Figure 4

Smoke Density among the Sample Groups

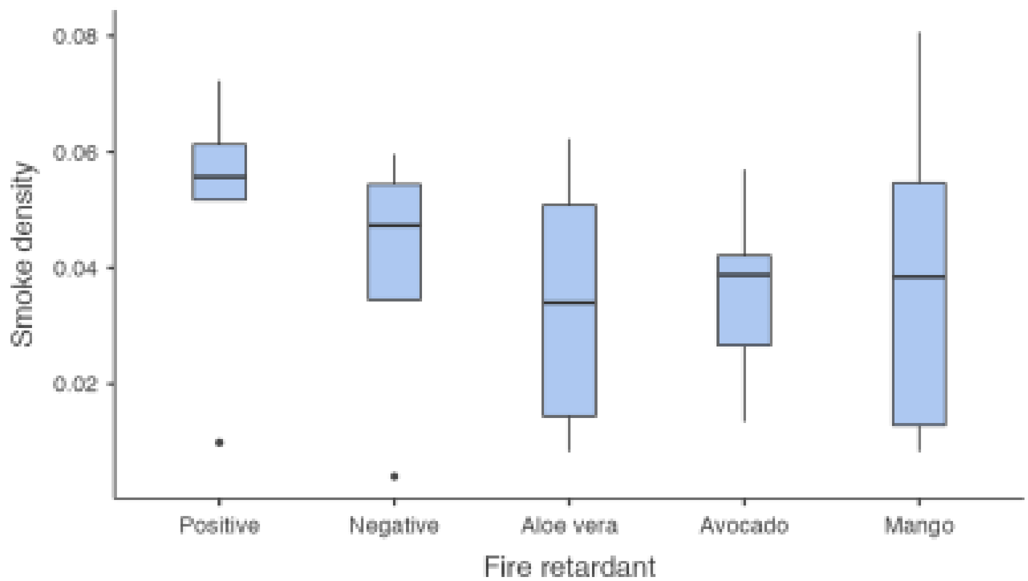

Figure 4 presents the smoke density values of samples treated with different fire retardants. The positive control group (M = 0.050, SD = 0.024) had the highest smoke density value, while the aloe vera fire retardant (M=0.034, SD = 0.023) exhibited the smallest smoke production. Avocado (M = 0.036, SD = 0.016) had the second-lowest smoke density but is considered more effective due to its smaller standard deviation.

The plant-based fire retardants were found to suppress smoke density the most and create the most char yield compared to the control groups. These results are aligned with the increased char yield theory because the char layer traps smoke particles, causing lower smoke density (Browne, 1958). The polyphenol, nitrogen, and phosphorus content of the plant/fruits may have encouraged char growth since similar results were observed in other studies that focused on these elements (Basak and Ali, 2019; Karaseva et al., 2019).

In terms of char yield

Char formation is a crucial variable in the development of fire retardants. Several studies have found that the char layer protects the wood from heat and further decomposition (Mariappan et al., 2017; Salasinska et al, 2017); Al Hokayem et al., 2020). Char formation was measured using char yield, which is the percent weight of char formed after burning the wood in the horizontal flammability test.

Figure 5

Char Yield among the Sample Groups

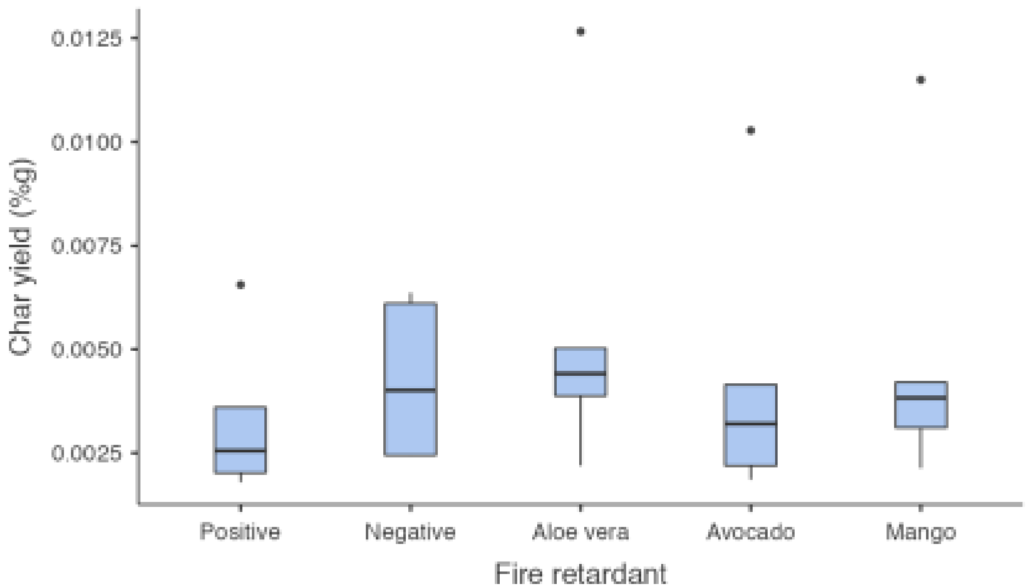

Figure 5 presents the char yield of the treated wood. Aloe vera (M = 0.006, SD = 0.004) had the highest char yield and was closest to the negative (M = 0.004, SD = 0.002), while avocado (M = 0.004, SD = 0.003) had the lowest char yield and was closest to the positive (M = 0.003, SD = 0.002).

Intumescent char, which swells under heat to protect the underlying wood from thermal decomposition (Kandola et al., 2020), was one of the expected observations in the experiments. Unfortunately, the char residues of all experimental and control groups were not intumescent because char almost accounted for all mass loss. As both groups use boric acid and borax, a contradiction is found with previous studies that state that the two additives were observed to form intumescent char (Ghomi, 2020; Xu et al., 2018). This may imply that the properties in the char cannot suppress mass loss. The rate of air change was found to have a direct relationship with the rate of mass loss, leading to the conclusion that mass loss rate relies on air flow and oxygen concentration.

In terms of charring rate

Maraveas et al. (2013) defines charring rate as char depth over a constant period of time. The researchers found that charring rate was an important indicator of the structural strength of the wood because char cannot support any additional load. To measure charring rate, wood samples (4 x 0.26 ft) were coated with the fire retardants, placed in a concrete tunnel, and burned at the edge for 2.20 minutes. The length of the char was taken after the test, and charring rate was presented as the length of the char over 2.20 minutes.

Figure 6

Charring Rate among the Sample Groups

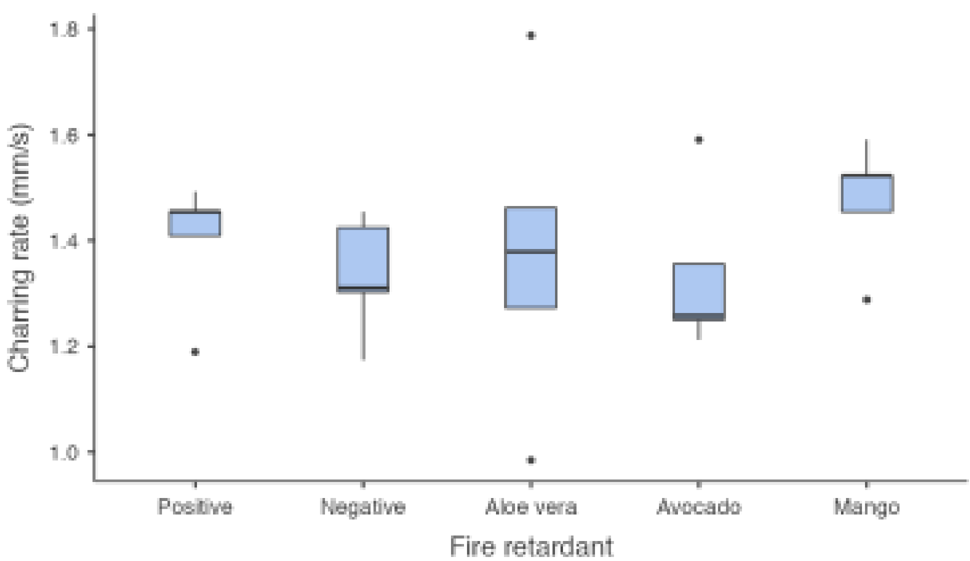

Figure 6 presents the charring rates of the treated wood. Mango-treated wood (M = 1.476, SD = 0.116) had the fastest charring rate, followed by the positive group (M = 1.400, SD = 0.121). The negative group (M = 1.333; SD = 0.111) had the slowest charring rate, with the second slowest being the avocado-treated wood (M = 1.333, SD = 0.153).

The charring rate of wood is affected by the amount of heat applied on the material (Maraveas et al., 2013), therefore fire retardants must reduce the charring rate by heat dissipation or absorption according to the thermal theories (LeVan, 1984).

The negative control group composed of borax and boric acid exhibited the lowest charring rate compared to the positive control group, followed closely by the avocado. The positive effect of the negative control group and avocado may be due to the boron additives increasing its thermal stability, as observed in a study done by Ghomi et al. (2021). Browne (1958) also said that borax may absorb heat into its water crystals, which may aid the negative control and avocado groups in decreasing the charring rate.

When testing the fire retardants on the burning timber, it was found that the different plant/fruit extracts showed different effects. Mango was the most efficient in inhibiting mass loss, avocado had the lowest smoke density, and aloe vera created the most char, while the negative group had the lowest charring rate.

The mass loss, smoke density, char yield, and charring rate values of the different treated timber groups reflected some deviation from the conceptual framework. For instance, aloe vera was not consistent in the results, unlike the other groups. This may mean that it had no effect on the timber, and results were instead affected by the wood density and weather variables. Due to some limitations, precise tests and instruments were not used, which may have caused inconsistencies in the data. Hagen, et al. (2009) states that techniques such as the cone calorimeter test and the thermogravimetric analyzer may be used to obtain precise flammability and degradation properties of substances; however, these are inaccessible due to the pandemic. Furthermore, during the process of maceration and filtration, the plant/fruit extract was not as refined after the pulverizing process because laboratory equipment was not accessible. This reduced the solubility of the powdered plant/fruit in maceration. Ideally, maceration is conducted until bioactive compounds are completely solubilized in the solvent (Garcias-Salas et al., 2010).

Examination of significant difference between the mass loss, char yield, charring rate, and smoke density of fire retardants treated with different plant/fruit extracts

Table 2

Kruskal-Wallis H Test Results on Mass Loss among the Groups

	χ^2	df	p	ε^2
Mass loss (g)	3.2271	*4*	0.521	0.13446

Table 2 shows the statistical significance of the plant-based fire retardants in terms of mass loss. The fire retardant found to have the most mass loss was aloe vera (M= 0.010, SD= 0.009), closely followed by avocado (M= 0.010, SD= 0.004), and finally the mango fire retardant (M= 0.006, SD= 0.003). There was no significant difference between the three fire retardants based on the Kruskal-Wallis H test, H(4) = 3.227, p = 0.521.

Table 3

One-way ANOVA Results on Smoke Density among the Groups

	F	df1	df2	p
Smoke density (lux) Fisher's	0.36252	4	20	0.832

Table 3 shows the statistical significance of the plant-based fire retardants in terms of smoke density. The fire retardant found to have the highest smoke density was mango (M= 0.039, SD= 0.030), then avocado (M= 0.036, SD= 0.016), and aloe vera (M= 0.034, SD= 0.023). The difference between the smoke density of all the fire retardants was insignificant based on One-way ANOVA, F(4)= 0.363, p= 0.832.

Table 4

Kruskal-Wallis H Test Results on Char Yield among the Groups

	χ^2	df	p	ε^2
Char yield (%g)	2.4886	4	0.647	0.10369

Table 4 shows the statistical significance of the plant-based fire retardants in terms of char yield. The fire retardant that had the greatest char yield was Aloe Vera (M= 0.006, SD= 0.004), followed by Mango (M= 0.005, SD= 0.004), then Avocado (M= 0.004, SD= 0.003). There was no significant difference between the three fire retardants based on the Kruskal-Wallis H test, H(4) = 2.489, p = 0.647.

Table 5

One-way ANOVA Results on Charring Rate among the Groups

	F	df1	df2	p
Charring rate (mm/s) Fisher's	0.58017	4	20	0.680

Table 5 shows the statistical significance of the plant-based fire retardants in terms of charring rate. The fire retardant with the fastest charring rate was Mango (M= 1.476, SD= 0.116), followed by Aloe Vera (M= 1.377, SD= 0.292), then Avocado (M=1.333, SD= 0.153). The difference between the charring rate of all the fire retardants was determined to be insignificant after using One-way ANOVA, $F(4)= 0.580$, $p= 0.680$.

A number of limitations may have led to the insignificant difference. Consultations with professionals regarding the data gathering procedures were restricted due to the COVID-19 pandemic. Furthermore, the ripeness of the fruit may have played a big factor in the precision and validity of the results since some of the mangoes were not completely ripe when they were opened.

A confounding variable that affected all the plant-based fire retardants was the solvent used during the maceration. The plant/fruits may have lost some of its phenolic content during the maceration process (López et al., 2013; Masibo & Qian, 2018). In an experiment performed by Jovanović et al. (2017), the results showed that the least amount of phenolic content was acquired during maceration. The ideal solvent would be methanol, but due to its high flammability water was used instead (Methanol: systematic Agent NIOSH CDC, n.d.; Safdar et al., 2017). This may have led to the insignificant difference in the dependent variables.

Polyphenols have traits which promote the creation of char during burning (Xia et al., 2018). When the polyphenols are lost during creation of the fire retardant, it decreases its efficacy. A decrease in char yield and charring rate will lead to less protection from the fire, affecting the dependent variables -- this is confirmed by the increased char theory. The confounding variables that affect the char yield and charring rate will also change the results of the smoke density.

As for mass loss, the confounding variable was stated when addressing research question one. The air flow and oxygen concentration are directly related to mass loss which created the insignificant difference between the three groups.

Examination of significant difference in the mass loss, char yield, charring rate, and smoke density of the experimental group compared to the control group

Table 6

Dwass-Steel-Critchlow-Fligner Pairwise Comparison on Mass Loss

	K-W	p-value
Positive Negative	1.03397	0.949
Positive Aloe vera	1.03397	0.949
Positive Avocado	2.21565	0.519
Positive Mango	0.44313	0.998
Negative Aloe vera	-0.14771	1.000
Negative Avocado	1.62481	0.780
Negative Mango	-1.32939	0.882
Aloe vera Avocado	0.73855	0.985
Aloe vera Mango	-0.44313	0.998
Avocado Mango	-1.92023	0.655

Table 6 shows the difference in the Mass Loss among the experimental and control groups (Aloe Vera, Mango, Avocado, Positive, and Negative). According to pairwise comparisons, *Positive and Aloe vera* had a p-value of 0.949, *Positive and Mango* had a p-value of 0.998, *Positive and Avocado* had a p-value of 0.519, *Negative and Aloe vera* had a p-value of 1.000, *Negative and Mango* had a p-value of 0.780, and *Negative and Avocado* had a p-value of 0.882. There was no significant difference between the groups as determined by One-way ANOVA, df = 4, p = 0.521.

Table 7

Dwass-Steel-Critchlow-Fligner Pairwise Comparison on Char Yield

	K-W	p-value
Positive Negative	1.03397	0.949
Positive Aloe vera	1.92023	0.655
Positive Avocado	0.73855	0.985
Positive Mango	1.62481	0.780
Negative Aloe vera	0.14771	1.000
Negative Avocado	-0.73855	0.985
Negative Mango	-0.14771	1.000
Aloe vera Avocado	-1.32939	0.882
Aloe vera Mango	-1.32939	0.882
Avocado Mango	0.73855	0.985

Table 7 shows the difference in the Char Yield among the experimental and control groups (Aloe Vera, Mango, Avocado, Positive, and Negative). According to Pairwise comparisons, *Positive and Aloe Vera* had a p-value of 0.655, *Positive and Mango* had a p-value of 0.780, *Positive and Avocado* had a p-value of 0.985, *Negative and Aloe Vera* had a p-value of 1.000, *Negative and Mango* had a p-value of 1.000, and *Negative and Avocado* had a p-value of 0.985. There was no significant difference between the groups as determined by One-way ANOVA, df = 4, p = 0.647.

Table 8

Dwass-Steel-Critchlow-Fligner Pairwise Comparison on Charring Rate

	K-W	p-value
Positive Negative	-1.64487	0.773
Positive Aloe vera	-0.44448	0.998

Positive Avocado	-1.03712	0.949
Positive Mango	1.95000	0.642
Negative Aloe vera	0.44313	0.998
Negative Avocado	-0.44313	0.998
Negative Mango	2.37781	0.446
Aloe vera Avocado	-1.03397	0.949
Aloe vera Mango	1.33343	0.880
Avocado Mango	2.08059	0.581

Table 8 shows the difference in the Charring Rate among the experimental and control groups (Aloe Vera, Mango, Avocado, Positive, and Negative). According to Pairwise comparisons, *Positive and Aloe vera* had a p-value of 0.998, *Positive and Mango* had a p-value of 0.642, *Positive and Avocado* had a p-value of 0.949, *Negative and Aloe vera* had a p-value of 0.998, *Negative and Mango* had a p-value of 0.446, and *Negative and Avocado* had a p-value of 0.998. Results revealed no significant difference between the groups as determined by One-way ANOVA, df = 4, p = 0.388.

Table 9

Dwass-Steel-Critchlow-Fligner Pairwise Comparison on Smoke Density

	K-W	**p-value**
Positive Negative	-1.62481	0.780
Positive Aloe vera	-1.62481	0.780
Positive Avocado	-1.62481	0.780
Positive Mango	-1.03397	0.949
Negative Aloe vera	-0.44313	0.998

Negative Avocado	-0.73855	0.985
Negative Mango	0.14771	1.000
Aloe vera Avocado	0.14771	1.000
Aloe vera Mango	0.44313	0.998
Avocado Mango	-0.44313	0.998

Table 9 shows the difference in the Smoke Density among the experimental and control groups (Aloe Vera, Mango, Avocado, Positive, and Negative). According to Pairwise comparisons, *Positive and Aloe Vera* had a p-value of 0.780, *Positive and Mango* had a p-value of 0.949, *Positive and Avocado* had a p-value of 0.780, *Negative and Aloe Vera* had a p-value of 0.998, *Negative and Mango* had a p-value of 1.000, and *Negative and Avocado* had a p-value of 0.985. There was no significant difference between the groups as determined by One-way ANOVA, df = 4, p = 0.744.

Table 10

MANOVA Results on the Overall Significant Difference between the Sample Groups

	value	**F**	**df1**	**df2**	**p**
Pillai's Trace	0.32717	0.44540	16	80	0.965
Wilks' Lambda	0.70059	0.40589	16	53	0.975
Hotelling's Trace	0.38858	0.37644	16	62	0.983
Roy's Largest Root	0.24941	1.2471	4	20	0.323

Lastly, MANOVA was performed to determine the correlation between the independent and dependent variables (Table 10). There was no statistically significant difference between the fire retardant on the combined dependent variables, $F(16, 53) = 0.40589$, $p = .975$, Wilks' $\Lambda = .70$.

After running the data analysis, the researchers found no significant difference in the comparisons, making the null hypothesis true. This does not mean, however, that the bio-based fire retardants are not as good as the commercial ones (Gibbs, 2013). There are many factors to consider as to why the p-value was so high. Due to the inability to use machines or equipment to collect accurate data, the possibility of human error is likely no matter how meticulous the researchers may be.

Just like the two previous research questions, weather and humidity could have played a role in the reason for the insignificant difference. These may have affected the chemical reactions during the experiment because heat is an important part of fire (Song et al., 2014). Furthermore, in a study done by Bahrani et al. (2018) it was concluded that the weathering exposure reduced the effectiveness of fire protection in their coatings.

The tests were carried out in an uncontrolled environment so there are variables that affected the results. Controlled environments where humidity and temperature could be manipulated to the needs of the researchers is plausible as seen in the research of Forney and Brandi (1992) where they used glycerol water solution to control the humidity. Though there were many factors that need to be modified to get more accurate results, the finding still stands with the methodology. The ideal fire retardant coatings for wood should show minimal spread of flame, little to no release of smoke, be easily applied, and provide low cost of production and application (Mariappan, 2016).

CONCLUSION AND RECOMMENDATIONS

This research was focused on exploring the efficiency of plant and fruit-based fire retardants as opposed to a commercial fire retardant and boric acid-boron fire retardant. According to the results of this research, it was concluded that the plant and fruit-based fire retardants had beneficial effects on the smoke density and char yield of the material. The mango-based fire retardant decreased the mass loss of the material and the avocado-based fire retardant inhibited smoke density as a result of high char yield. However, the results were significantly affected by confounding variables, such as humidity, temperature, and airflow, which caused the data to be insignificant. Therefore, future researchers may use the standard flammability tests when performing the experiments to see better results. Furthermore, future research should also analyze the commercial fire retardant's poor smoke density and reduced char yield compared to the bio-based fire retardants. The smoke suppression property of commercial fire retardants may then be improved. Lastly, future research may control the ripeness of the fruit before extraction and refine the plant extracts and boron additive solution to yield results similar to the results of other studies. Using proper extraction methods to remove flammable compounds such as cellulose, they may isolate the fire-retarding organic compounds in mango and avocado.

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