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ENHANCING FIRE RESISTANCE OF *Gmelina arborea* USING SODA ASH AND BORIC ACID ADMIXTURE

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ABSTRACT

The timber used in construction is often susceptible to combustion during fire outbreaks, necessitating the enhancement of its flame-retardant properties. In this study, Gmelina arborea was impregnated with boric acid, soda ash, and their admixture to assess fire resistance properties. The treated wood was characterized using thermogravimetric analysis (TGA) and scanning electron microscopy (SEM), while key operational parameters – ignition time (IT), flame propagation rate (FPR), and after-glow time (AGT) – were evaluated. The percentage residue for boric acid was 68.8%, for soda ash 68.3%, and for the admixture 8.60%, indicating the highest ignition time for the admixture-treated sample. SEM analysis revealed that the micrographs of soda ash and boric acid treatments exhibited rough and undefined structures compared to the well-defined pores of the admixture-treated wood, highlighting structural modifications that enhance fire resistance. The results demonstrated that soda ash, boric acid, and their admixture effectively delayed ignition and reduced flame spread. The combined admixture exhibited the highest fire resistance, lowest flame propagation rate, and shortest after-glow time. Notably, while individual treatments improved fire resistance, their combination at varying concentrations displayed a synergistic effect, further enhancing the material's fire retardancy.

Keywords: *Boric acid, Fire resistance, Gmelina arborea, soda ash.*

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1. INTRODUCTION

Wood is widely used in construction and interior decoration due to its abundance, renewability, recyclability, biodegradability, and ease of processing (Dvorak, 2004). However, its combustibility poses a significant fire risk. Fire is a rapid oxidation reaction that releases heat, light, and various combustion byproducts (Nwajiobi et al., 2016). When exposed to sufficient heat and an oxidizing agent, such as oxygen, combustible materials can sustain rapid oxidation, leading to destructive fire incidents (Méndez-Mejías et al., 2018). To mitigate fire hazards, flame retardants are employed to reduce the ignition potential and limit fire spread. These compounds create protective barriers, insulating materials, and inhibit combustion (Demir & Ozturk, 2016).

Enhancing wood's fire resistance is critical to expanding its safe use in high-temperature environments (Khademibami and Bobadilha, 2022). Phosphorus-based flame retardants such as phosphoric acid and ammonium dihydrogen phosphate (ADP) effectively enhance wood’s fire resistance by forming a protective char layer upon thermal degradation (Ali et al., 2019). Additionally, these retardants create a shield that limits damage to the wood and inhibits the release of flammable volatiles (Olaniran et al., 2022). Other studies have explored the use of antimony trichloride and ammonium sulphanate as fire retardants for *Gmelina arborea*, demonstrating their efficacy in delaying combustion (Arinze et al., 2019). Furthermore, boron-based fire retardant systems have gained interest due to their halogen-free, colorless, odorless, low-toxicity, and cost-effective nature (Minkah et al., 2021).

Gmelina arborea is cultivated in tropical and subtropical regions due to its rapid growth, reaching a diameter at breast height (DBH) of 60–80 cm within 20 years of rotation (Ajike et al., 2022). The species' adaptability, ease of regeneration, and affordability make it a preferred raw material for various applications, including pulp and paper production (Emeka et al., 2021). This study focuses on enhancing the flame-retardant properties of *Gmelina arborea* and exploring methods to improve its durability and strength. The goal is to develop a sustainable, fire-resistant building material that aligns with the increasing demand for safer construction materials (Arinze et al., 2019; Owoyemi et al., 2016).

Despite the widespread use of *Gmelina arborea*, no prior research has investigated the fire-retardant potential of impregnation with soda ash and boric acid. Given the severe financial and structural consequences of fire outbreaks, improving the fire resistance of *Gmelina arborea* is imperative. The application of these flame retardants aligns with fire safety regulations, promotes sustainable practices, and mitigates economic losses associated with fire incidents (Nwajiobi et al., 2016). The incorporation of soda ash and boric acid as fire retardants presents a promising approach to improving the fire resistance properties of *Gmelina arborea*. Therefore, research in this area can contribute to the development of safer and more fire-resistant wooden structures, enhancing occupant safety and reducing fire-related economic losses.

2. REVIEW OF LITERATURE

2.1 Fire Retardants

Fire retardants are substances designed to reduce the flammability or combustion rate of materials, thereby enhancing fire resistance. These chemicals act primarily through physical or chemical means—such as promoting char formation, diluting flammable gases, or forming protective barriers to heat and oxygen. They are available in various forms (powder, gel, liquid, foam) to suit different material types (Rowell and Dietenberger, 2012).

Timber, widely used in construction and furniture, is inherently combustible. While it has relatively poor thermal conductivity, its structural properties and availability make it attractive for indoor and outdoor applications (Davidson and Freas, 1987). To improve its fire safety, timber is often treated with fire retardants. Historically, treatments date back to Roman times when ships were treated with alum and vinegar. The use of ammonium phosphates and borax by Gay-Lussac further established the role of chemical retardants (Rowell and Dietenberger, 2012).

Modern applications recognize that fire retardants must be selected carefully based on the wood species and the performance environment. For instance, Xie et al. (2016) reported that phenol-formaldehyde and melamine-formaldehyde treatments had distinct effects on Scots pine, influencing fire risk differently through smoke and heat hazards.

2.2 Formulation of Fire Retardants

Fire retardants are typically categorized by their dominant chemical components: brominated, phosphorus-based, nitrogen-based, chlorinated, and inorganic salts (Davidson and Freas, 1987). Among these, inorganic salts such as boric acid, sodium silicates, and ammonium sulfate are extensively used in timber due to their effectiveness, affordability, and compatibility with common timber applications.

Though boric acid has a relatively low water solubility (0.056 g/ml), it remains widely used because of its flame-retardant and insecticidal properties. Soda ash, on the other hand, offers higher solubility and improved flame inhibition but may increase hygroscopicity (Cavdar et al., 2015). These two chemicals, when combined, can create a synergistic effect in reducing ignition time and heat release rates without introducing harmful by-products.

2.3 Effects of Fire Retardants on Timber Properties

2.3.1 Durability

Durability, particularly under humid conditions, is a concern for fire-retardant-treated (FRT) timber. While boric acid and soda ash can improve resistance to microbial degradation, their hygroscopic nature may cause increased moisture uptake, leading to decay or structural weakening over time (Östman et al., 2001; Chu et al., 2017).

2.3.2 Mechanical Strength

Fire retardants can alter the physical integrity of wood, sometimes decreasing mechanical properties like modulus of rupture (MOR) and modulus of elasticity (MOE) due to chemical reactions or thermal degradation (LeVan & Winandy, 2007; Wen et al., 2014). This impact varies based on chemical composition and treatment conditions and thus must be evaluated specifically for *Gmelina arborea* in your study.

2.3.3 Hygroscopicity and Corrosion Risk

FRT timber tends to absorb more moisture than untreated wood, particularly when treated with hygroscopic salts like sodium borate or ammonium phosphate. This can lead to higher humidity sensitivity, increasing the risk of fungal decay and corrosion of metal connectors (Ayrilmis et al., 2007; Laranjeira et al., 2015). However, careful formulation and post-treatment drying can mitigate these effects.

2.3.4 Other Considerations

While fire retardants can also affect machinability, gluability, and paint adhesion, these are generally not primary concerns unless the treated wood is to be processed post-treatment. In many practical cases, machining is done before impregnation (Davidson and Freas, 1987).

3. RESEARCH METHODOLOGY

3.1 Materials

Gmelina arborea wood was obtained from the local plank market in Nigeria. Analytical-grade boric acid (H_3BO_3) and soda ash (sodium carbonate, Na_2CO_3) were purchased, while distilled water was sourced from the Pathology Department of the Federal College of Forestry, Ibadan.

3.2 *Gmelina arborea* Wood Preparation and Pre-Treatment

The Gmelina wood samples were cut into uniform splints measuring 45 cm in length, 0.6 cm in width, and 0.4 cm in thickness. These splints were oven-dried at 105°C until a constant weight was obtained. Various concentrations of soda ash, boric acid, and their admixture were prepared using stock solutions and dilution series. Impregnation followed the procedure outlined by Gazizov et al. (2020), where three splints per concentration were soaked for 48 hours. Untreated splints served as the control. After impregnation, the samples were dried to a constant weight in an electric oven at 105°C. The weight of the flame retardant absorbed by the samples was calculated using Equation [1]:

Weight gain (%) = $\frac{W_2 - W_1}{W_1} x100$ .... (1)

Where;

W_2 = weight of the specimen after treatment.

W_1 = weight of the specimen before treatment.

3.3 Characterization of Treated and Untreated Wood Splints

Thermogravimetric analysis (TGA) and Scanning Electron Microscopy (SEM) were employed to analyze surface morphology, thermal stability, and volatile component fractions of wood samples after impregnation.

3.3.1 Determination of Ignition Time (IT)

In a draft-free room, each splint was clamped vertically and ignited at the base using a Bunsen burner or cigarette lighter. Ignition time was recorded as the interval between initial contact with the flame and the appearance of a visible flame. The procedure was repeated for each sample, and the average ignition time was calculated, as suggested by Eboatu and Garba (1990).

3.3.2 Determination of Flame Propagation Rate (FPR)

$$\text{FPR (cm/sec)} = \frac{Distance\ traveled\ by\ char\ front\ (cm)}{Time\ taken(\text{sec})} \quad \ldots\ldots\ldots\ldots\ldots\ (2)$$

Samples were clamped vertically and ignited at the base, and the charred front was measured at specific time intervals. Each test was performed three times, and the average readings were recorded.

3.3.3 Determination of After-Glow Time (AGT)

After-glow time was measured as the time (seconds) between flame extinction and the last visible glow. Each test was repeated three times, and the average after-glow time was recorded (Eboatu & Garba, 1990).

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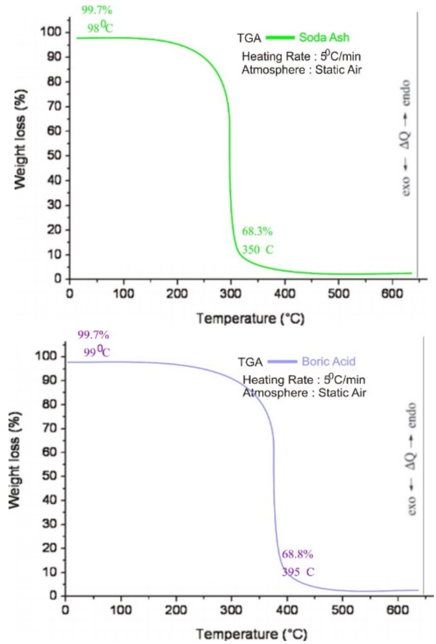
4. RESULTS AND DISCUSSION

4.1 Characterization of Treated and Untreated *Gmelina arborea* Wood Splints

Thermogravimetric Analysis (TGA)

TGA results for surface morphology, thermal stability, and volatile component fractions after impregnation with various concentrations of flame retardants are presented in Figure 1(a-c). *Gmelina arborea* wood, being a diffuse porous hardwood, contains vessels, fibers, and ray parenchyma cells that facilitate liquid flow into its microstructure. The optimum temperature range was between 160°C and 240°C.



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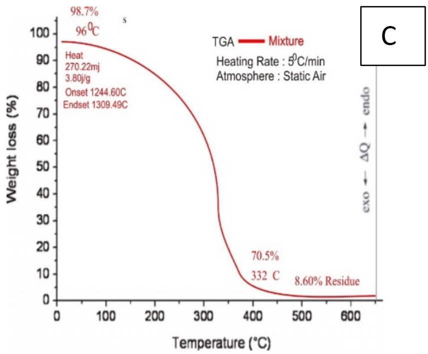
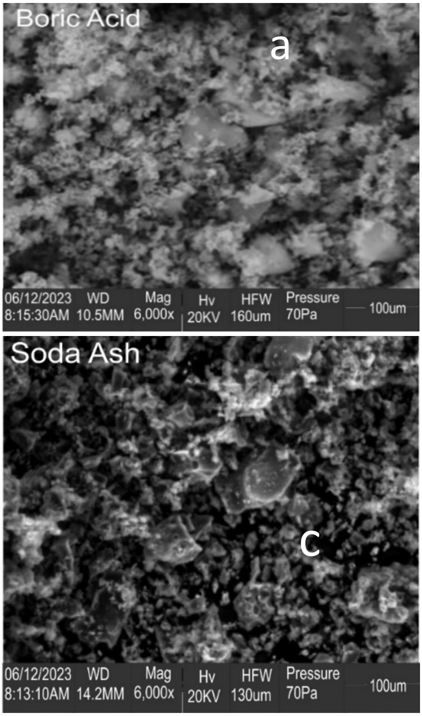


Figure 1. TGA curves of Gmelina arborea wood impregnated with different fire retardants. (A) Boric acid (B) Soda Ash (C) Admixture

As shown in Figure 1, the percentage residue for boric acid was 68.8%, for soda ash was 68.3%, and for the admixture was 8.6%, indicating minimal char residue from the admixture. This explains the increased ignition time in admixture-treated samples, as reported by Kadir et al., (2015) and Kultermann & Spence (2016). The SEM micrograph of soda ash and boric acid showed rough, undefined structures, while the admixture-treated wood exhibited well-defined pores, indicating structural modifications that enhance fire resistance, as corroborated by Khademibami & Bobadilha (2022).

4.2 Scanning Electron Microscopy (SEM) Analysis

SEM images of *Gmelina arborea* wood samples impregnated with soda ash and boric acid, and their admixture are shown in Figure 2 (A-C). These images confirm that impregnation increased with concentration, enhancing flame retardancy. This observation aligns with Sharma & Diwan (2016), who found increased flame resistance in Eucalyptus wood samples treated with flame retardants.



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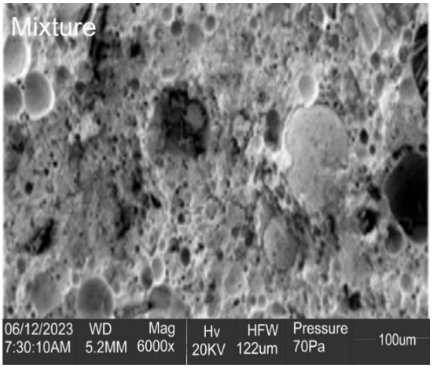

Figure 2. SEM micrograph of Gmelina arborea impregnated with (a) Soda ash, (b) Boric acid (c) Admixture

4.3 Percentage Efficiency of Flame Retardants in Wood Splints

Percentage efficiency represents the amount of flame retardant absorbed by each wood splint. Efficiency increased with concentration, with the admixture exhibiting the highest absorption, followed by soda ash and boric acid. Table 1 and Figure 3 present the percentage efficiency at various concentrations.

Table 1. Quantity of flame retardant absorbed by each Gmelina arborea wood splint at different concentration levels

Concentration (g/cm)	Percentage efficiency of Na_2CO_3 absorbed (%)	Percentage efficiency of H_3BO_3 absorbed (%)	Percentage efficiency of $Na_2B_4O_7$ absorbed (%)
0	0	0	0
4	12.35	18.52	16.67
8	25.53	19.75	24.65

12	27.16	22.22	30.25
16	32.06	26.54	33.33
20	43.62	37.03	37.04
24	50.62	41.36	41.36

Source: Author(s) own work.

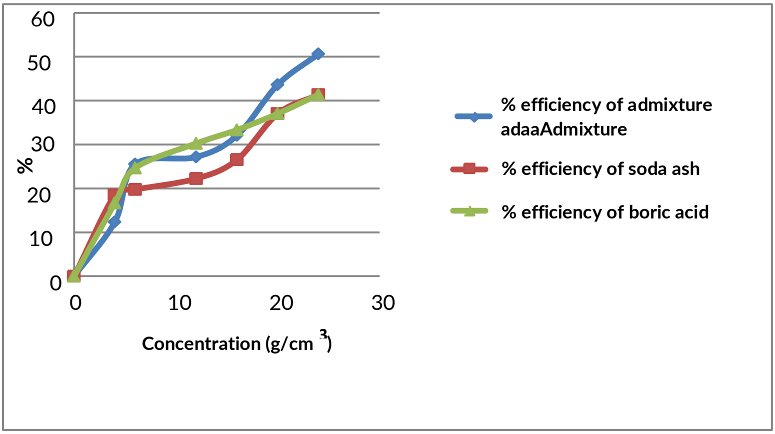

Figure 3. Percentage efficiency of different flame retardants on Gmelina arborea wood splints

4.4 Effect of Flame Retardants on Ignition Time

Figure 4 shows that ignition time increased with concentration. The presence of soda ash and boric acid in the admixture raised the ignition temperature of the wood splints. Untreated wood splints had the shortest ignition time. Table 2 and Figure 4 detail ignition times at different concentrations.

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Table 2. Ignition time of Flame Retardants on Gmelina arborea wood splint at different concentration levels

Concentration (g/cm)	Average ignition time of Na_2CO_3(s)	Average ignition time of H_3BO_3 (s)	Average ignition time of $Na_2B_4O_7$(s)
0	10	10	10
4	14	21	22.5
8	18	24	26
12	21	26.5	31
16	32.5	31	35
20	34.5	32.5	37
24	42	33.5	41.5

Source: Author(s) own work.

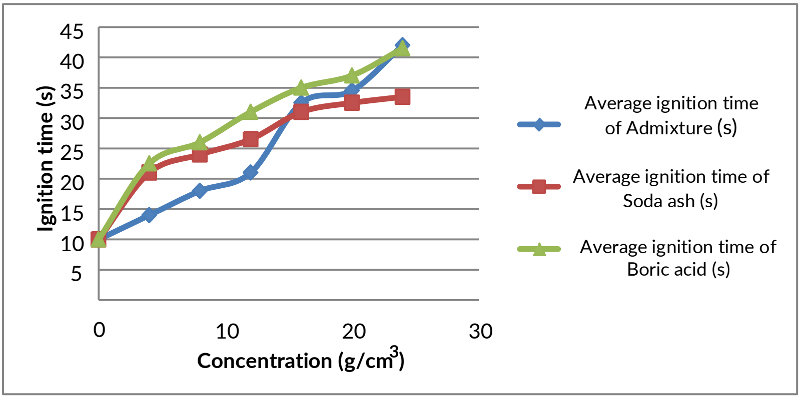

Figure 4. Effect of different flame retardants on ignition time of Gmelina arborea wood splints

From consideration of the three retardants used, it is observed that even at lower concentrations, there is an enhancement in the ignition time. Wood splints treated with the flame-retardant admixture gave the highest ignition time. This is because soda ash and boric acid had a flame retarding effect on the wood. The effect of soda ash was steady concerning the increase in concentration. On the other hand, the effect of boric acid was gradual at lower concentrations but increased rapidly at higher concentrations. Thus, it can be deduced from this work that ignition time increased much as the concentration of soda ash and boric acid increased.

4.5 Effect of Flame Retardants on Flame Propagation Rate (FPR)

As shown in Table 3 and Figure 5, FPR decreased with increasing concentrations of soda ash, boric acid, and their admixture, indicating effective flame retardancy. The admixture had the lowest FPR, providing the best retardant effect. This aligns with Erike et al. (1995), who reported similar trends. Soda ash decomposes upon heating to release CO_2, forming a protective coating that inhibits combustion. Boric acid acts as a free radical trap and promotes char formation, further reducing flammability.

Table 3. Propagation Rate (FPR) of Flame Retardants on Gmelina arborea wood splints

Concentration (g/cm)	Average FPR of Na_2CO_3 (cm/s)	Average FPR of H_3BO_3 (cm/s)	Average FPR of $Na_2B_4O_7$ (cm/s)
0	0.17	0.17	0.17
4	0.13	0.13	0.1
8	0.13	0.1	0.09
12	0.1	0.07	0.08
16	0.08	0.06	0.05
20	0.06	0.05	0.05

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24	0.06	0.05	0.04

Source: Author(s) own work.

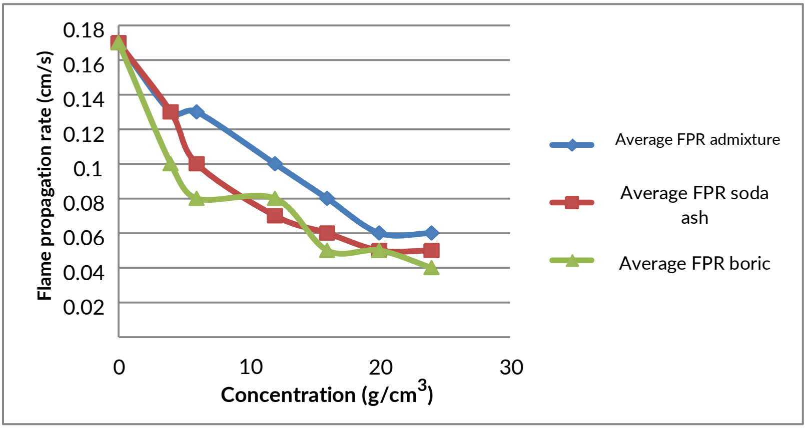

Figure 5. Effect of flame retardants on flame propagation rate of wood splints

4.6 Effect of Flame Retardants on After-Glow Time (AGT)

Figure 6 demonstrates that AGT decreased as retardant concentration increased, with the admixture extinguishing first, followed by soda ash and boric acid. Glow duration depends on the quality of residual carbonaceous char and oxygen availability. Increased concentrations of soda ash and boric acid reduced char formation, thus minimizing AGT, similar to findings by Onuegbu et al. (2011).

Table 4. After-Glow Time (AGT) of Flame Retardants on Gmelina arborea wood splints

Concentration (g/cm)	Average AGT of Na_2CO_3 (s)	Average AGT of H_3BO_3(s)	Average AGT of $Na_2B_4O_7$ (s)
0	203	203	203
4	185	118	55
8	174.5	105	52.5
12	124	99.5	49.5
16	113	90	36
20	102.5	77	26
24	86	55	19

Source: Author(s) own work.

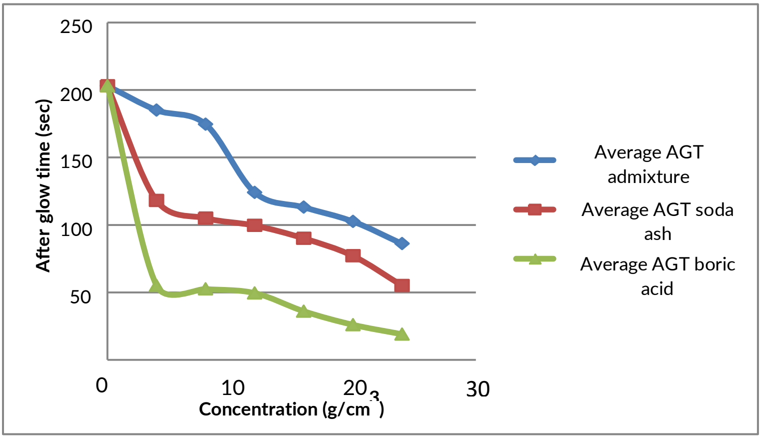

Figure 6. Effect of flame retardants on after-glow time of Gmelina wood splints

5. CONCLUSION

Soda ash, boric acid and their admixture are good fire retardants in delaying and resisting ignition. The admixture of the two retardants gave the resistant ignition, lowest flame propagation rate and after-glow time. There also was remarkable improvement when the wood splints were treated individually with each of the flame retardants but it was more pronounced when the two flame retardants were combined at different concentrations depicting the effect of synergy. The DTG curve of the admixture shows a remarkably low char residue of 8.60% and the well-defined pores of the admixture SEM micrograph highlighted the admixture impregnation unto the Gmelina wood. Timbers treated with these flame retardants, especially with the mixture of the retardants will resist the onset of fire. Hence, the impregnation treatment method can effectively impart flame resistance to wood.

REFERENCES

Ajike, C., Enibe, S. O., Okonkwo, U. C., & Amoo-Onidundun, O. (2022). Modelling of the drying characteristics of Gmelina arborea wood: kinetics and thermodynamics studies. *Unizik Journal of Technology, Production and Mechanical Systems*, *1*(1), 11–21.

Ali, S., Hussain, S. A., Zahirasri, M., & Tohir, M. (2019). Fire Test and Effects of Fire Retardant on the Natural Ability of Timber: A Review. *Science and Technology*, *27*(2), 867–895.

Arinze, R., Chris-okafor, P., Okoye, N., and Iziga, C. (2019). Reducing the Flammability of Gmelina arborea Wood Using Flame Retardants. *American Scientific Research Journal for Engineering, Technology, and Sciences*, *37*(1), 53–61.

Ayrilmis, N., Candan, Z., & White, R. (2007). Physical, mechanical, and fire properties of oriented strand board with fire retardant treated veneers. *Holz Als Roh- Und Werkstoff*, *65*(6), 449–458. https://doi.org/10.1007/s00107-007-0195-3

Cavdar, A. D., Mengeloğlu, F., & Karakus, K. (2015). Effect of boric acid and borax on mechanical, fire and thermal properties of wood flour filled high-density polyethene composites. *Measurement: Journal of the International Measurement Confederation*, *60*, 6–12. https://doi.org/10.1016/j.measurement.2014.09.078

Chu, D., Mu, J., Zhang, L., & Li, Y. (2017). Promotion effect of NP fire retardant pre-treatment on heat-treated poplar wood. Part 1: Color generation, dimensional stability, and fire retardancy. *Holzforschung, 71*(3), 207–215. https://doi.org/10.1515/hf-2016-008

Davidson, M. A., & Freas, A. D. (1987). *The Encyclopedia of Wood* (Revised ed.). New York: Sterling Publishing Company Incorporated.

Demir, A., Aydin, I., & Ozturk Hasan. (2016, November). Effect of Fire Retardant Chemicals on Formaldehyde Emission of Plywood. *25th International Scientific Conference: New Materials and Technologies in the Function of Wooden Products*, (pp. 63–66).

Dvorak, W. S. (2004). World view of Gmelina arborea: opportunities and challenges. *New Forest*, *28*, 111–126.

Eboatu A. N, Garba B & Akpabio I. O., (1993): "Flame Retardant Treatment of some Tropical Timbers." *Fire and Materials*, 17, 39-42, 1993

Emeka, S., Seim, W., & Onyekwelu, J. C. (2021). Mechanical properties of Gmelina arborea for engineering design. *Construction and Building Materials*, *288*, 123123. https://doi.org/10.1016/j.conbuildmat.2021.123123

Gazizov A. M., Kuznetsova O., Sharafutdinov A. A. & Shaimuhametova K. M. (2020). Improvement of fire retardant properties of wood materials. IOP *Conf. Ser. Mater. Sci. Eng.* 919 062014 DOI 10.1088/1757-899X/919/6/062014

Harada, T., Nakashima, Y., & Anazawa, Y. (2007). The effect of ceramic coating of fire-retardant wood on combustibility and weatherability. *Journal of Wood Science*, *53*(3), 249–254. https://doi.org/10.1007/s10086-006-0846-8

He, X., Li, X. J., Zhong, Z., Mou, Q., Yan, Y., Chen, H., & Liu, L. (2015). Effectiveness of impregnation of ammonium polyphosphate fire retardant in poplar wood using microwave heating. *Fire and Materials*, *40*(6), 818–825. https://doi.org/10.1002/fam.2344

Kadir, A., Marsono, B., & Balasbaneh, A. T. (2015). Combinations of building construction material for residential building for the global warming mitigation for M alaysia. Construction and Building Materials, 85, 100-108. doi: https://doi.org/10.1016/j.conbuildmat.2015.03.083

Kadir, A., Marsono, B., & Balasbaneh, A. T. (2015). Combinations of building construction materials for residential buildings for the global warming mitigation for Malaysia. Construction and Building Materials, 85, 100-108. doi: https://doi.org/10.1016/j.conbuildmat.2015.03.083

Khademibami, L., & Bobadilha, G. (2022). Recent developments studies on wood protection research in academia: A review. Frontiers in Forests and Global Change. *Front. For. Glob. Change* 5:793177. doi: 10.3389/ffgc.2022.793177

Kultermann, E., & Spence, W. P. (2016). Construction Materials, Methods, And Techniques (4th Ed.). Boston: Cengage Learning.

Méndez-mejías, L. D., Moya, R., Forestales, C., Tecnológico, I., Rica, D. C., Rica, P. O. B. C., … Rica, P. O. B. C. (2018). Effect of Thermo-Treatment on the Physical and Mechanical, Color, and Fungal Durability of Wood of Tectona grandis and Gmelina arborea from Forest Plantations. *Material Science*, *24*(1), 59–68.

Minkah, M. A., Afrifah, K. A., Antwi-boasiako, C., Wentzel, M., & Batista, D. C. (2021). Pro ligno. *Journal of Wood Engineering*, *17*(1), 3–12.

Nwajiobi, C. C., Eboatu, A. N., Odinma, S. C., & Ezigbo, V. O. (2016). Effectiveness of Ammonium Chloride and Borax in Improving the Fire Retarding Property of Timber Effectiveness of Ammonium Chloride and Borax in Improving the Fire Retarding Property of Timber. *International Journal of Science and Technology*, *5*(2), 77–80.

Olaniran, S. O., Löning, S., Buschalsky, A., & Militz, H. (2022). Impregnation Properties of Nigerian-Grown Gmelina arborea. *MDPI: Forests*, *13*(1), 8–13. https://doi.org/10.3390/f13122036

Owoyemi, J. M., Adebayo, H. H., & Aladejana, J. T. (2016). Physico-Mechanical Properties of Thermally Modified Gmelina arborea (Roxb .) Wood. *Modern Environmental Science and Engineering*, *2*(10), 691–700. https://doi.org/10.15341/mese(23332581)/10.02.2016/007

Rowell, R., & Dietenberger, M. (2012). Thermal properties, combustion, and fire retardancy of wood. In R. M. Rowell

(Ed.), *Handbook of Wood Chemistry and Wood Composites* (2nd ed., pp. 127–150). CRC Press. https://doi.org/10.1201/b12487-9

Sharma P. & Diwan P. K. (2016) Investigation of thermal decomposition parameters of flame retardant impregnated eucalyptus wood, International Wood Products Journal, 7:3, 144-148, DOI: 10.1080/20426445.2016.1183067

Sogutlu, C., Demirci, Z., Dongel, N., Imirzi, H. O., Doruk, S., & Yalinkilic, A. C. (2011). The determination of the resistance to burning of some wood types impregnated with sodium borate solution. *Wood Research*, *56*(2), 233–244.

Torgovnikov, G., & Vinden, P. (2010). Microwave wood modification technology and its applications. *Forest Products Journal*, *60*(2), 173–182. https://doi.org/10.13073/0015-7473-60.2.173

Wen, M. Y., Kang, C. W., & Park, H. J. (2014). Impregnation and mechanical properties of three softwoods treated with a new fire retardant chemical. *Journal of Wood Science*, *60*(5), 367–375. https://doi.org/10.1007/s10086-014-1408-0

Xie, Y., Xu, J., Militz, H., Wang, F., Wang, Q., Mai, C., & Xiao, Z. (2016). Thermo-oxidative decomposition and combustion behaviour of Scots pine (Pinus sylvestris L.) sapwood modified with phenol- and melamine-formaldehyde resins. *Wood Science and Technology*, *50*(6), 1125–1143. https://doi.org/10.1007/s00226-016-0857-6