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Eco-Friendly Flame Retardants For Sustainable Fire Safety: A Comparative Fire-Performance And Environmental Health Assessment Of Nano-Silica And Ammonium Polyphosphate

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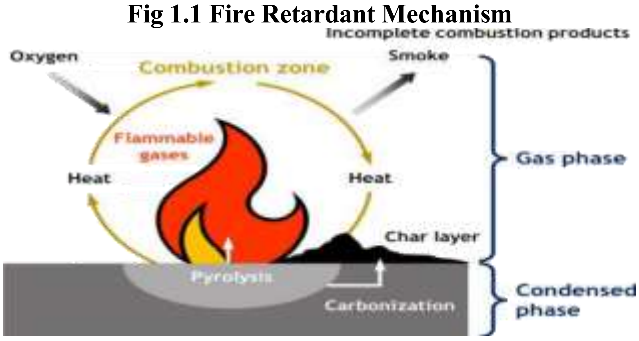
ABSTRACT
Fire Retardant are the effective passive controls which have the efficiency to control the spread of fire also it is an important control aspect in Fire Safety. But when they exposed to fire some of the Fire-retardant release smoke which may not be eco-friendly. So, eco-friendly fire-retardant additives have been studied and their fire resisting performance has been analyzed. The fire-retardant material has been mixed with Solvent based paint separately. This substrate has been applied on the Wood testing surface and the Do It Yourself (DIY) experiment has been carried out. The five performance criteria have been identified and the ecofriendly fire-retardant performance have been determined and the environmental assessment study has been done.

Keywords: Eco friendly, Solvent based paint, Fire retardant additive, DIY

1. INTRODUCTION

Fig 1.1 Fire Retardant Mechanism



A fire retardant is a substance that slows down or stops the spread of fire, or reduces its intensity. Fire retardants can be used in a variety of ways, including: (I) Applied to surfaces Fire retardants can be applied as a coating; (ii) Spray to prevent fires from starting. The Fire Retardant will work in three phases (1) like Decomposition, Gas Phase Mechanism and Condensed phase mechanism. While the Fire Retardant has be exposed to fire, it will go through the above-mentioned phases that it releases smokes which may cause environment impact. Currently, the following Fire Retardants have been used in the industry like Poly brominated Di phenyl Ethers (PBDEs), Hexabromocyclododecane (HBCD)* and Chlorinated Paraffin. Apart from Ammonium Poly phosphate most of the above-mentioned fire retardants have been banned in many countries because of their anticipated environmental impacts. These impacts includes Persistence in environment, Bio accumulation in wildlife and humans , Toxicity to aquatic / terrestrial life and adverse health effects.

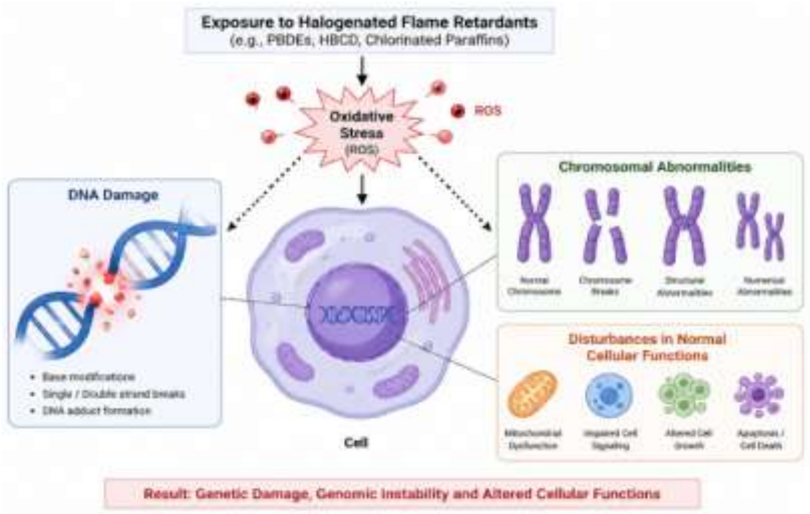


Fig 1.2 Genetic and Cellular Effects of Halogenated Flame Retardants.

Based on published literature, eco-friendly alternatives such as nano-silica and APP are associated with a lower potential for genotoxic and molecular toxicity compared with conventional halogenated flame retardants. Halogenated flame retardants have been widely used for decades to improve fire safety in a variety of materials. However, concerns have grown regarding their potential effects on both environmental and human health. Research has shown that exposure to some brominated and chlorinated flame retardants can increase oxidative stress within cells, leading to DNA damage, chromosomal abnormalities, and disturbances in normal cellular functions. At the molecular level, these compounds may influence the activity of genes involved in detoxification, inflammation, and cell survival. There is also evidence suggesting that long-term exposure may contribute to epigenetic changes, such as alterations in DNA methylation, which can affect gene regulation without modifying the DNA sequence itself. In addition, the combustion of halogenated flame retardants can generate toxic by-products that may further contribute to biological and environmental risks.

As a result, there is growing interest in the development of safer and more sustainable flame-retardant technologies. Among the promising alternatives are nano-silica and Ammonium Polyphosphate (APP), both of which are halogen-free and function through different mechanisms than traditional halogenated systems. Nano-silica acts as a thermal barrier, reducing heat transfer and slowing material degradation, while APP promotes the formation of a protective char layer that limits flame spread. Although some organophosphate flame retardants have been reported to exhibit toxicological effects, APP is an inorganic polymeric phosphate commonly used in intumescent formulations and is generally considered to have a more favorable safety profile. Because these materials do not depend on halogen chemistry, they produce fewer hazardous combustion products and are less likely to interfere with cellular and molecular processes associated with genetic damage.

From a molecular and genetic perspective, the use of nano-silica and APP offers a practical pathway toward reducing the potential health impacts associated with conventional flame retardants. By minimizing oxidative stress and limiting exposure to toxic combustion products, these materials may help reduce the risk of DNA damage and disruptions in normal gene regulation. Consequently, the shift toward halogen-free flame-retardant systems represents an important step toward achieving both effective fire protection and improved environmental sustainability.

Consequently, the transition toward halogen-free flame-retardant systems represents an important step toward improving fire safety while reducing environmental and potential health impacts. Therefore, this research aims to identify an effective eco-friendly fire-retardant coating and compatible solvent-based paint for use in and around LPG storage areas, including LPG bullets. The study evaluates selected halogen-free, inorganic, bio-based, and nano-material-based flame retardants with consideration for fire performance, environmental sustainability, and potential genetic and molecular health effects.

1.1 Do It Yourself (DIY) Experiment

The ultimate idea of research is to identify solution either for the existing technical issues or to enhance the existing controls/solutions to improve the process. In Process Safety, researches are going to find the solutions for the unexpected process incidents or to improve the controls so that the process-oriented incidents can be controlled effectively. The Do It Yourself (DIY)[2] experiments are the type of methods where the pilot laboratory or experimental set up conducted by individuals or like-minded people based on self-built equipment/methods in the optimal cost with innovative ideas. The primary advantages are the creativity and methodology can be developed on own which is an important aspect required for a researcher. It will improve the practical skill and the rapid prototyping so that the experiments can be carried out fastly. If the researcher is unable to access the lab facilities or if the equipment is not available or unable to procure in the research institution, DIY experiment will be the best option. The disadvantages of DIY experiments are lack of precision, limited equipment, likelihood of more errors. The above-mentioned Eco-friendly fire-retardant experiment has been carried out as DIY category. Based on the going fire retardant studies relevant equipment and lab set up has been done. This DIY experimental results should be considered as suggestive input and further elaborative formal experiments are recommended

1.2 Eco friendly Fire Retardants

The following Fire retardants have been used in the industry like., Polybrominated Diphenyl Ethers (PBDEs), Hexabromocyclododecane (HBCD), Chlorinated Paraffins. Most of these fire retardants have the following environmental concern like Persistence in environment, Accumulation in wildlife and humans, Toxicity to aquatic and terrestrial life and Endocrine disruption. To overcome these environmental impacts, eco-friendly fire-retardant research is in progress. In this research the following fire-retardant additive like Tartaric Acid, Ammonium Phosphate and Nano Silica have been considered. Tartaric Acid ($C_4H_6O_6$) [3] can be derived from natural sources like grapes also from other citrus fruits like orange, lemon with the process of fermentation, extraction and purification. Tartaric Acid is biodegradable, non-toxic and they cause low environmental impact. It is slightly skin and eye irritant. As a Fire Retardant it is a moderate flame inhibition and thermal stability in nature. Ammonium Phosphate $(NH_4)_3PO_4$ can be synthesized through the reaction of ammonia (NH_3) and phosporic acid (H_3PO_4) also It can be derived either from organic waste or from bio-based phosphorus sources like fish bone etc. The ammonium phosphate is a non-toxic bio degradable fire retardant [4] having excellent flame inhibition and thermal stability which potential release of ammonia. Nano Silica (SiO_2) can be derived naturally from silica sand or by the chemical synthesis like Sol-gel process or Precipitation method. The rice husk ash, fly ash and bio-based silica sources are the alternate sources for Nano Silica. It is a biodegradable, non-toxic, low environmental impact fire retardant [5] with excellent thermal insulation and flame inhibition properties. The paint based used in this experiment is solvent based paint which is environmentally friendly and Low odor in nature.

2. MATERIALS AND METHODS

The following materials and DIY laboratory set up have been arranged to carry out the fire retardant performance analysis experiment.

Fig 1.3 DIY Experiment Resources

2.1 Materials

(I) Jenson & Nicholson Universal Primer (Composition) : Epoxy Resin (40-60%), Poly amide Resin (20-40%), Solvents (10-30%):, Additives (5-10%), UV stabilizers, anti-settling agents, and wetting agents; Pigments (5-10%): Titanium dioxide (white),Film Thickness 40 micron thickness/coat,
Drying time 30 mins- 01 Hour
(ii) Apcolite Solvent based paint (Composition): Alkyd resin (binder) 30–40%, solvent (mineral turpentine/white spirit) 25–35%, pigments 15–25%, extenders/fillers 5–15%, additives 1–3%. Film
Thickness 40 micron thickness/coat,
Drying time 24 hrs
(iii) Flame Torch: Maximum Temperature: 60 deg Centigrade; Torch distance between the testing surface & flame torch: 6.5 cm; Flame length from the torch towards testing surface : 4.5 cm; Volume of Torch (propane container volume) 215 cubic centimeter.
(iv) (IR) thermometer – Max Range 110 degree centigrade
(v) Pine Wood substrate Dimension: 7.5 cm x 7.5 cm x 1 cm and to measure the smoke spread vertical traveling time, vertical measurement of 3.75 cm has been marked from the center point.

2.2 Methods

The DIY experiment setup and the research execution methods are based on the following standards: [9,10,11]

Based on the literature study, the following procedure has been followed and the experiment has been carried out:

a) In the wood specimen, from the center vertical distance (Vertical Traveling -VT) has been marked so as to determine the smoke spread for a specific distance in a given time

b) The proposed eco-friendly fire retardants (10%) have been mixed with Solvent paint to form a Fire-Retardant Coating blend

c) Wood specimen has been double coated with the above blend

d) The wood specimen has been allowed to dry for 24 hours

e) The Wood specimen has been aligned on the heat-resistant stand

f) Flame torch has been exposed on the specimen for 5 minutes

3 Theory/Calculation

The following performance criteria have been considered to determine the effectiveness of the fire-retardant coating that has been applied on the wood specimen

Performance Criteria I: Smoke Spread (Vertical Traveling Time – VT in min: secs)

Time taken for the Smoke to Spread from center point to vertical distance of 3.75 cm. Longer time for the smoke spread is preferable which shows the effectiveness of the Smoke suppression property.

Performance Criteria II: Rear Surface Temperature in Deg Centigrade

Wood Specimen Rear side temperature has been measured for every 1 min to till 5 min to know the heat-resistant ability of the fire retardant. Low back temperature is preferable which indicates higher thermal insulation property.

Performance Criteria III : Exposed Surface (front) in Deg Centigrade

Temperature will be measured @ 5th minute to know the heat-resistant ability of the fire retardant. Low front temperature is preferable.

Performance Criteria IV: Time for Initial Ignition in Minutes/Seconds

Time at which the first ignition starts. Longer time is preferable which shows the fire-resistant nature.

Performance Criteria V: Visual Observation of Char on the sample. The more char formation is highly preferable which indicates the Fire-Retardant effectiveness.

4 RESULTS

The experiment has been carried out as per the above-mentioned procedure and the results have been tabulated as below with the required performance criteria to determine the effectiveness of Eco-friendly fire retardant with the Solvent-based paint.

Eco Friendly Fire Retardant & Solvent paint blend Performance Data									
Paint: Solvent based	Time for initial ignition (TTI)	Rear Surface Temperature					Exposed Surface Temp @ 5 min	Smoke spread @3.5 cm	Visual Observation (Char Formation)
Fire Retardant (10% concentration)		1 min	2 min	3 min	4 min	5 min			
Tartaric acid $C_4H_6O_6$	15 secs	29.3°C	32°C	42°C	49.7°C	52.6°C	55 deg C	42 seconds	Low - Moderate
Ammonium Phosphate $(NH_4)_3PO_4$	15 secs	43°C	48.5°C	51.4°C	52.3°C	58°C	50.9 deg C	30 seconds	Moderate
Nano Silica SiO_2	3 mins	30°C	36.7°C	41.7°C	42.9°C	43.8°C	51.1 deg C	39 seconds	High

Table 1.1 Eco friendly Fire Retardant Performance Data (Temp in Deg C)

To determine the level of char formation on the wood specimen, visual observation has been done.

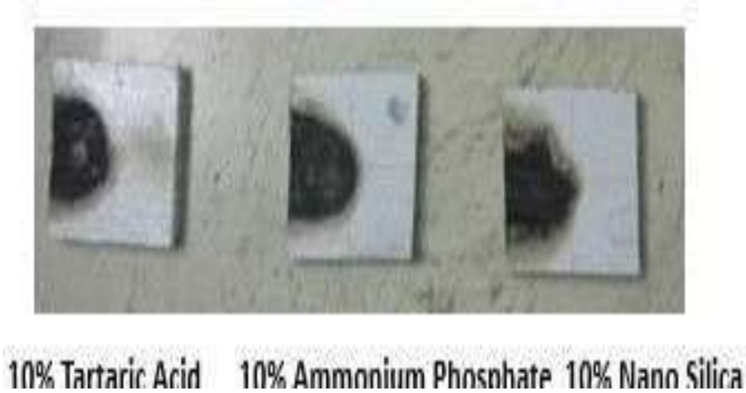


Fig 1.4 Char Formation

5 (Qualitative Structure–Activity Relationship) QSAR-BASED MOLECULAR TOXICOLOGY ASSESSMENT

Quantitative Structure–Activity Relationship (QSAR) is a computational method used to predict the biological, toxicological, or environmental effects of a chemical based on its molecular structure.

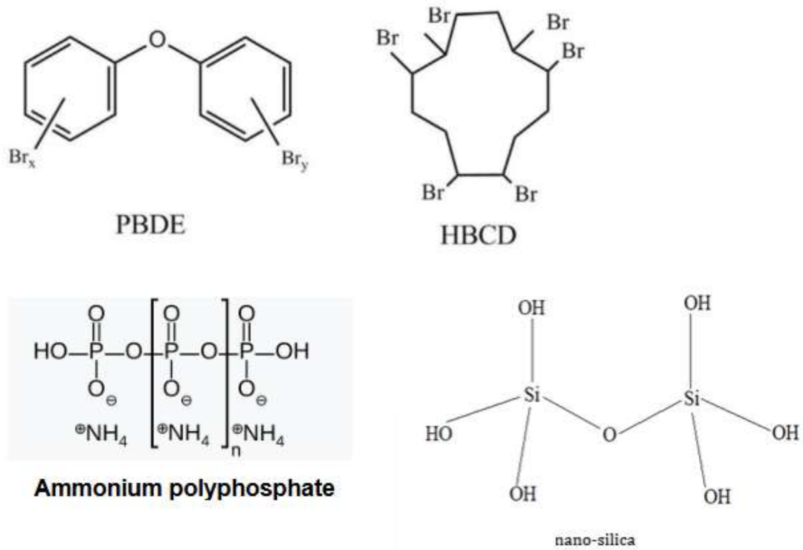


Fig 1.5 Molecular Structure

Polybrominated Diphenyl Ethers (PBDEs): $C_{12}H(10-n)Br_nO$ PBDEs are bromine-containing flame retardants that can remain in the environment for long periods and accumulate in living organisms. Previous studies have linked PBDE exposure to oxidative stress, DNA damage, endocrine disruption, and changes in gene expression, making them a concern from both environmental and molecular toxicology perspectives. Hexabromocyclododecane (HBCD): $C_{12}H_{18}Br_6$ HBCD is another brominated flame retardant that has attracted attention due to its persistence in the environment and tendency to accumulate in biological systems. Research has reported associations between HBCD exposure and oxidative stress, cellular damage, and potential genotoxic effects, raising concerns regarding its long-term environmental and health impacts. Ammonium Polyphosphate (APP): $(NH_4PO_3)_n$ APP is a halogen-free phosphorus-based flame retardant widely used in intumescent coatings. Unlike brominated flame retardants, APP does not possess structural characteristics commonly associated with environmental persistence and bioaccumulation. Based on its chemical structure and mode of action, APP is generally considered to present a lower potential for molecular toxicity while providing effective fire protection through char formation. Nano Silica (SiO_2): Nano Silica is an inorganic material that functions primarily as a thermal barrier in fire-retardant systems. Its simple chemical composition lacks the halogenated structures often associated with toxicological concerns. As a result, Nano Silica is generally regarded as having a lower theoretical potential for genotoxic and molecular toxicity compared with conventional halogenated flame retardants, although its effects may vary depending on particle size and exposure conditions.

6 RESULTS AND DISCUSSIONS

The following points can be inferred from the Table 1.1 & Fig 1.3. The data shows that Nano Silica (SiO_2) performs best, with a significantly higher time to initial ignition of 3 minutes compared to 15 seconds for both tartaric acid and ammonium phosphate. Its rear surface temperature increases gradually from 30°C (1 min) to 43.8°C (5 min), which is lower than tartaric acid (29.3°C to 52.6°C) and ammonium phosphate (43°C to 58°C). The exposed surface temperature at 5 minutes is 51.1°C for nano silica, close to ammonium phosphate (50.9°C) but lower than tartaric acid (55°C). Smoke spread time is 39 seconds, better than tartaric acid (42 seconds) but slightly higher than ammonium phosphate (30 seconds). Importantly, nano silica shows high char formation, while tartaric acid shows low–moderate and ammonium phosphate moderate, indicating that nano silica provides superior fire resistance overall. The experimental results indicate that Nano Silica (SiO_2) is the most effective fire-retardant additive among the materials evaluated. Its longer ignition delay, lower heat transfer, and higher char formation demonstrate improved fire resistance and thermal protection. APP also showed satisfactory fire-retardant behavior, while tartaric acid provided comparatively lower protection. From an environmental and human health perspective, Nano Silica and APP offer advantages over conventional halogenated flame retardants such as PBDEs and HBCD. Published studies have linked halogenated flame retardants with environmental persistence, bioaccumulation, and adverse biological effects. In contrast, Nano Silica and APP are halogen-free materials and are generally considered to have a lower potential for environmental and toxicological impacts. Therefore, the findings suggest that Nano Silica and APP can provide effective fire protection while supporting environmental sustainability and human health safety. Among the tested additives, Nano Silica demonstrated the best balance between fire performance and eco-friendly characteristics.

7 CONCLUSION

This study evaluated eco-friendly flame retardants based on both fire performance and environmental and human health considerations. The results showed that Nano Silica (SiO_2) provided the best overall fire-retardant performance, followed by Ammonium Polyphosphate (APP). Nano Silica exhibited superior ignition resistance, thermal insulation, and char-forming ability. The QSAR-based assessment suggests that Nano Silica and APP have a lower potential for environmental and toxicological concerns than conventional halogenated flame retardants. Therefore, Nano Silica can be considered the most promising eco-friendly flame retardant among the materials evaluated, offering effective fire protection together with improved environmental sustainability and human health safety. Future studies may investigate hybrid Nano Silica–APP formulations to further enhance performance and sustainability.

BIBLIOGRAPHY

1. 1.G. Camino et al., (1991), Overview of fire retardant mechanisms, Polymer Degradation and Stability Volume 33, Issue 2, 1991, Pages 131-154, https://www.sciencedirect.com/science/article/abs/pii/014139109190014I
2. 2.David Sarpong et al., Do-it-yourself (DiY) science: The proliferation, relevance and concerns, Technological Forecasting and Social Change Volume 158, September 2020, 120-127, https://www.sciencedirect.com/science/article/abs/pii/S0040162520309537
3. Tartaric acid as a fire retardant for cellulose-based materials" (2017) - Journal of Thermal Analysis and Calorimetry, Vol. 127.5
4. Ammonium phosphate-based fire retardants for wood" (2016) - Journal of Fire Sciences, Vol. 34. 5.Nano-silica as a fire retardant for polymers" (2018) - Materials Today Communications, Vol. 15.4
5. Eco-friendly fire retardants for textiles" by the European Commission's JRC (2020)2. "Fire Retardancy of Wood Treated with Ammonium Phosphate" by the USDA Forest Products Laboratory (2019)
6. Nano-silica based fire retardant coatings for wood" by the University of California, Los Angeles (UCLA) (2018)
7. Tartaric Acid as a Fire Retardant for Paper" by the University of Toronto (2017)5. "Green Fire Retardants for Polymers" by the National University of Singapore (2016)
8. ASTM E119-22 Standard Test Methods for Fire Tests of Building Construction and Materials https://www.astm.org/e0119-22.html UL 723： Standard test method for surface burning characteristics of building materials
9. https://www.scribd.com/document/553165051/UL-723-2003-08-29
10. ASTM E84-21a Standard Test Method for Surface Burning Characteristics of Building Materials
11. https://www.astm.org/e0084-21a.html
12. 12.Conventional halogenated flame retardants have been associated with oxidative stress, DNA damage, chromosomal abnormalities, and alterations in gene expression at the cellular level (Costa & Giordano, 2007; Josephy, 1997).
13. 13.Costa, L. G., & Giordano, G. (2007). Developmental neurotoxicity of polybrominated diphenyl ether (PBDE) flame retardants. NeuroToxicology, 28(6), 1047–1067. https://doi.org/10.1016/j.neuro.2007.08.007
14. 14.Darnerud, P. O. (2003). Toxic effects of brominated flame retardants in man and in wildlife. Environment International, 29(6), 841–853. https://doi.org/10.1016/S0160-4120(03)00107-7
15. 15.Horrocks, A. R., & Price, D. (Eds.). (2008). Fire retardant materials. Woodhead Publishing.
16. Alongi, J., Han, Z., & Bourbigot, S. (2015). Intumescence: Tradition versus novelty. Progress in Polymer Science, 51, 28–73. https://doi.org/10.1016/j.progpolymsci.2015.04.002