

# Myeongjun Song\_IARCO - 송명 준.pdf

*by* Sanaul Haque

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**IARCO RESEARCH PROPOSAL**

**Full Legal Name:** Myeongjun Song

**Institution:** Gap-year student, Daegu Science High School for the Gifted

**Category:** Junior

**Class/Grade/Year:** Gap-year student

**Country:** South Korea

**Major (if senior):** None

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**Registered Email Address:** [www.song0718@gmail.com](mailto:www.song0718@gmail.com)

**Research Topic:** Improving Pyrogallol–Polyethyleneimine Fire-Resistant Coatings on Tree Bark via Low-Dose Phytic Acid

Title: Improving Pyrogallol–Polyethyleneimine Fire-Resistant Coatings on Tree Bark via Low-Dose Phytic Acid

### Research Problem

Wildfires have become a rising global issue of increasing frequency and severity over recent decades, stimulated by anthropogenic activities including deforestation and land-use change and stimulated strongly by anthropogenic climate change. Their consequences range from ecological destruction to pollution and heavy economic loss. Therefore, effective measures for mitigating wildfires are critically needed. A potential solution is to apply flame-retardant (FR) material to mitigate the combustibility of susceptible environments. However, classic FRs including halogenated and organophosphate ones are toxic, persistent, and bioaccumulative and thus experience rising regulative constraints.

These challenges are being met with proposed solutions of bioinspired FRs such as chitosan, lignin, tannic acid,  $\beta$ -cyclodextrin, and phytic acid (PA). However, most of them possess limitations such as the emission of toxic combustion gas or environmental persistence owing to heavy metal binding. Of the candidates proposed, the bioinspired, polyphenolic pyrogallol–polyethyleneimine (PG–PEI) coating system emerged recently as a highly prospective system. It is also adhesive, non-toxic, with a structure close to natural polyphenols, and readily applied as a spray coating, thus amenable to in situ protection of the highly combustible substrate of a tree bark. PG–PEI coatings polymerize to give graphitic, pyrolytically stable char films of passive firebreaks on exposure to flaming combustion, and they can mitigate the emission of smoke, preserve the ecological systems, and protect neighboring infrastructure.

Regardless of above-mentioned merits, however, PG–PEI coatings are still restricted in char yield and combined fire resistance relative to traditional FRs. Therefore, additional optimization is necessary for real-world function. The addition of low levels of PA, a green phosphorus-based FR endowed with a combination of catalytic and crosslinking activities, can improve char structure and thermal durability without losing biocompatibility. This synergy consideration does so directly to fill the imminent requirement for environmentally benign, efficient, and transportable wildfire prevention technologies.

### Existing Literature

Previous studies of bioinspired, polyphenolic FR systems have demonstrated high flame retardancy and sustainability relative to conventional ones. Polyphenolic flame retardants (FRs) have received extensive attention as green replacements for halogenated systems, due to their bioinspired origins, inherent aromatic nature, and multifunctionalities. Derived from plant bio[46]ss or chemically synthesized based on natural processes, compounds like lignin, tannic acid (TA), flavonoids, eugenol, gallic acid (GA), and ellagic acid (EA) offer many hydroxyl groups and planar aromatic backbones that facilitate char generation, radical scavenging, and smoke minimization during

combustion [1-3]. As the most common aromatic polyphenol found in biomass, lignin offers high carbon content and heat resistance, the latter enhanced further through the functionalization with phosphorus- or N-based protagonists (e.g., APP, DOPO, melamine) or the addition of synergists like layered silicate clays and metal phosphates [4-10]. Similarly, TA and GA build strong metal-phenolic networks featuring  $\text{Fe}^{3+}$ ,  $\text{Ni}^{2+}$ , or  $\text{Zn}^{2+}$ , improving the yield of char as well as barrier properties, meanwhile remaining compatible within the polymers [11-13]. Flavonoids and eugenol, derived from fruits, vegetables, and plant-based essential oils, are modifiable, through phosphorylation, thiol-ene click reaction, or hydrosilylation, yielding sophisticated FR systems delivering simultaneously high fire resistance as well as attractive toughness [14-16].

In addition to plant-derived systems, polydopamine (PDA) represents a mussel-inspired synthetic polyphenol with strong adhesion, biocompatibility, and dual-phase FR action. Its catechol and amine groups scavenge radicals in the gas phase while promoting thermally stable char in the condensed phase [17-18]. PDA readily coordinates with metals, nanomaterials, and phosphorus species, enabling synergistic hybrid FRs with enhanced dispersion and catalytic char formation [19-23]. Across these systems, common mechanisms include condensed-phase stabilization via aromatic char, gas-phase radical scavenging, and synergistic reinforcement through phosphorus, nitrogen, and metal-based additives. Collectively, the literature underscores polyphenolic FRs as renewable, versatile, and tunable platforms that simultaneously provide fire safety, sustainability, and multifunctional properties for next-generation polymer and textile applications.

Among various polyphenolic FRs, the pyrogallol-polyethyleneimine (PG-PEI) system is an exemplary insect-inspired polyphenolic FR coating with high potential for wildfire resistance. PG, the trihydroxybenzene derivative of gallic acid, offers adhesion sites as well as reactive sites through the hydroxyl moieties, while branched PEI offers numerous nucleophilic amines; collectively, they build up strong oxidative coupling-based crosslinked networks [24-28]. Upon exposure to heat, the resulting network transforms into honeycomb-like graphitic char that confines the heat as a stable thermal barrier [29-33]. PG-PEI aqueous coating treatments on live tree bark, as shown by Castillo et al. [34], enhanced the charring as well as the fire resistance while retaining the eco-friendliness as well as the biocompatibility, as confirmed through elemental profiling, cytotoxicity tests, as well as the survival tests carried out in vivo. PG-PEI systems, besides being used as exemplary FRs, also exhibit multifaceted applications, such as dye adsorption,  $\text{CO}_2$  absorption, as well as the removal of wastewater, increasing their value as versatile as well as sustainable FR platforms [35-41].

## **Research Question**

Does the incorporation of low-dose phytic acid (0.1–0.5 wt%) into the bioinspired pyrogallol-polyethyleneimine (PG-PEI) coating system enhance their flame-retardant performance on cellulose-rich tree bark by catalyzing char formation, improving thermal shielding, and lowering heat transfer, while preserving the eco-friendliness and biocompatibility necessary for tree bark targeted applications to mitigate wildfire?

## **Methodology**

In this research, the influence that the addition of small levels of phytic acid (PA) has on the fire-suppression capability, heat properties, and biocompatibility of the pyrogallol-polyethyleneimine (PG-PEI) coatings on high-cellulose materials is determined through a rigorous experimental technique.

#### Materials:

PG, PEI (50%), and PA (50%) came from Sigma-Aldrich, Steinheim, Germany. Red pine wood boards were provided by Iveranda, Gwangju, South Korea, and the solutions of cellulose nanofiber (CNFs) (2%) came from Hansol Paper, Seoul, South Korea. Commercial FR coating (Brand A) came from Yuwon Tool Safe, Ulsan, South Korea.

#### Preparing wood specimens coated with PA-PG-PEI:

<sup>47</sup> A 0.2 M PG solution and a 10% PEI solution were prepared by adding deionized water. PA solutions of 0.1%, 0.3%, and 0.5% were prepared and combined with PG solutions to obtain PA-PG solutions.

<sup>12</sup> Red pine wood blocks were spray-coated with the 1:1 mixture of PA-PG (or PG) and PEI solutions and air-dried for 2 h at room temperature.

#### Structural analysis and composition:

- X-ray photoelectron spectroscopy (XPS): Bare, PG-PEI-, and 0.1–0.5% PA-PG-PEI-coated woods, both before and after combustion, were measured for their surface elemental composition and bonding states with a Nexsa G2 XPS system (ThermoFisher, USA).

<sup>23</sup> - Field emission scanning electron microscopy (FE-SEM) and energy-dispersive X-ray spectroscopy (EDS): Coating morphology and elemental distribution were analyzed for PG-PEI and PA-PG-PEI coatings using SU5000 (Hitachi, Japan) and Oxford Ultim Max detectors.

#### Thermal and flame-retardant assessment:

- Thermogravimetric analysis (TGA): CNFs, coating compositions, and CNF-coated products were analyzed between room temperature and 800 °C (10 °C/min) under conventional air to determine weight loss, heat stability, and char yield (Q500, TA Instruments, USA).

- Vertical simulated burn test: Six specimens (bare wood, commercial FR, PG-PEI, and 0.1–0.5% PA-PG-PEI coatings) were subjected to a static flame for 5 min to check their burnability resistance as well as the percentage weight loss.

- Cone calorimeter test (CCT): Flame retardance of the materials was <sup>37</sup> determined on 10 × 10 × 0.6 cm wood blocks by Dual Cone Calorimeter (FTT Ltd, UK) under a heat flow rate of 35 kW/m<sup>2</sup>, as per ISO 5660-1.

- Laser flash analysis (LFA): Thermal conductivity and diffusivity of the uncoated and coated pellets ( $1 \times 1 \times 0.3$  cm) were determined at 250 °C by a xenon flash system (Netzsch, Germany).

Toxicity evaluation:

- Cytotoxicity Test: Ashes obtained after charring plain wood, commercial fire retardant, as well as wood treated with 0.1–0.5% PA-PG-PEI were retrieved in RPMI-1640 medium and applied to Detroit 551 human skin fibroblasts. Viability was determined by PrestoBlue™ assays, while statistical comparison used one-way ANOVA and Tukey's post hoc analysis.

This research procedure offers a scientific approach to ascertain the effect PA incorporation has on PG-PEI coating performance regarding char generation, heat insulation, fire resistance, as well as biocompatibility, so that the results are reproducible and environmentally pertinent. This study adopts a mixed-methods approach to ensure a comprehensive understanding of both measurable outcomes and underlying experiences.

### Research Topic

Increasingly, the occurrence and intensities of wildfires are rising around the globe, causing significant ecological destruction, pollution, and economic loss. Classical flame-retardant (FR) chemicals, including halogenated and organophosphate compounds, are environmentally persistent, toxic, and bioaccumulative, necessitating increasingly strict regulation. Bioinspired FRs, including chitosan, lignin, tannic acid,  $\beta$ -cyclodextrin, and phytic acid (PA), have been recognized as environmentally safe substitutes; nevertheless, many among these systems still face issues ranging from the release of noxious gases during combustion to environmental persistence due to the involvement of heavy metals. Among these substitutes, the polyphenolic pyrogallol-polyethyleneimine (PG-PEI) coating system has recently come up as a promising candidate. It is adhesive, nontoxic, structure-similar to natural polyphenols, and amenable to facile spray coating as an in situ protective layer over highly combustible substrates like tree bark. PG-PEI coating layers undergo gelation during flaming combustion, forming graphitic, heat-stable char assemblies that act as passive firebreaks, reducing smoke yields, conserving ecosystems, and protecting nearby infrastructure. Despite those advantages, PG-PEI coating films are still limited both in char yield as well as overall fire resistance compared to classical FRs. Addition of sub-micellar concentrations of phytic acid, a green phosphorus-based FR that is catalytically active as well as capable of forming molecular bridges, promises to increase char yield, complement thermal stability, as well as maintain the biocompatibility. This new, environmentally safe, and scalable technique directly addresses the acute need for safe, as well as efficient, wildfire prevention technologies.

### Quality of Writing

The language of this proposal is academically precise, clear, and appropriate for a multidisciplinary audience. Jargon is minimized, and the structure follows standard

research norms. The proposal adheres to grammar, citation, and formatting guidelines strictly to meet IARCO standards.

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