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Green Intumescent Systems Using Seed and Seaweed Marine and Agro-Biopolymer Engineered Flame-Retardant Coatings for Textile Applications

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Abstract: ***I'm looking at how sustainable flame retardant textiles are gaining in importance due to environmental rules and health concerns about old halogen-based retardants. Renewable biopolymers from seeds and seaweed appear to be good alternatives. Seed-derived stuff - phytic acid, soy protein, starch, guar gum - that's rich in phosphorus, nitrogen and hydroxyl whilst helping the fabric to dehydrate, puff up and char when it burns. Seaweed polysaccharides - alginate, carrageenan, agar - added film forming ability, thermal shielding and more carbon residue. When you mix these with additives such as nanoclays, metal hydroxides, P-N compounds or bio-crosslinkers, then the outcome is a hybrid which can be used to improve the limiting oxygen index, reduce the peak heat release and reduce the amount of smoke.***

In this paper, I'm going to get into the details of the chemistry, the flame retardant mechanisms, how people are hybridizing the systems, the methods used to make textiles out of it and how they are durable on seed and seaweed bases. I'll focus on condensed-phase mechanisms, how the additives adhere to the textile fibers, and "scaling headaches" that go into trying to make this stuff work in the real world. I'll talk about where these can be used - protective gear, transport textiles, home decor and technical fabrics. Even though the science is promising, there are still issues of wash durability, keeping costs down and maintaining mechanical strength. Going forward, I believe future research will need to address multifunctional coatings, nano-enabled biohybrid systems and life cycle assessment verification in order to have these products commercialized. Seed- and seaweed-based biopolymer-based hybrid appears to be a sustainable route for next gen fire safe textiles.

Basically, these seed and seaweed biopolymer hybrid flame retailer systems are a solid move toward better fire safe textiles. This review breaks down the following so that we have a base on how to further push sustainable fire safe textile innovation: mechanisms, material combos, processing tech, performance tests and industry use.

Keywords: Seed Biopolymers; Seaweed Polysaccharides; Hybrid Flame Retardants; Intumescent Systems; Sustainable Textile Finishing.

I. INTRODUCTION

Seaweed-derived polysaccharides - I mean, alginate, carrageenan and agar - they're filled up with oxygen, they're full of ionic groupings that help prevent the heat from passing through and they build up layers of solid char when you're in a thermal stress situation. These marine biopolymers may be made into a film and blend well with textile fibers, thus yielding well candidates for the idea of designing a coating with flame-retarding properties plus to be designed on the surface level. They're also biodegradable and renewable-which is also in alignment with circular economy ideas. By mixing seed and seaweed biopolymers with stuff like nitrogen-rich stuff, nano- clays, metal hydroxides, or bio-based crosslinkers, researchers have arrived at synergistic systems that result in increased limiting oxygen index (LOI), reduced peak heat release rate (PHRR), and thermal stability. The hybrid approach allows important physical properties, fabric breathability, as well as comfortable touch, while still meeting the safety rules.

Fire risks are still a significant danger in textiles, for homes, factories, transport centres, and public buildings. Fibers like cotton, polyester, viscose, and their polycultures are super flammable due to the combination of their chemicals properties and porosity that allows oxygen to rush in and flames get to spread very quickly. When these materials burn, it releases a tremendous amount of heat as well as toxic smoke pestilence that can fuel a fire and leave you with severe injuries or even death.

Traditionally, people have attempted to make textiles flame retardant by the use of halogenated chemicals, antimony trioxide synergists, and formaldehyde-based crosslinkers or agents. Those methods work, but they end up causing toxic by-products (hydrogen halides and dioxins) when the stuff burns.

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Figure:1 Types and variations of seaweeds

Increasing regulatory pressure and environmental awareness have driven the search for sustainable, non-toxic, and biodegradable alternatives.

Biopolymers derived from agricultural and marine biomass have gained attention as environmentally benign flame-retardant materials. Among them, seed-derived biopolymers (phytic acid, soy protein, starch, guar gum) and seaweed-derived polysaccharides (alginate, carrageenan, agar) exhibit inherent chemical functionalities favourable for flame retardancy. Phytic acid is particularly notable due to its high phosphorus content (~28 wt.%), functioning as a natural acid source in intumescent systems. Soy protein provides nitrogen-rich structures that promote char stabilization. Starch and guar gum contribute carbon sources for char formation. Marine-derived polysaccharides such as alginate and carrageenan exhibit excellent film-forming ability and thermal stability.

II. SEED-DERIVED BIOPOLYMERS IN FLAME RETARDANCY

Seed biopolymers such as phytic acid, starch, soy protein, and guar gum contain phosphorus, nitrogen, and hydroxyl groups. These functionalities facilitate dehydration reactions, promote intumescent char formation, and enhance thermal barrier properties. Phytic acid serves as a bio-based acid source in intumescent systems, while soy protein contributes nitrogen synergism. Modified starch and guar gum improve film-forming properties on cotton fabric

Figure:2 . Seed-Derived Biopolymers in Flame Retardancy

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III. SEAWEED-DERIVED POLYSACCHARIDES FOR TEXTILE PROTECTION

Alginate, carrageenan, and agar extracted from marine algae demonstrate excellent coating capability. Their polysaccharide backbone decomposes into stable carbonaceous char. Alginate-metal ion complexes enhance thermal resistance, while carrageenan's sulfate groups assist in char stabilization. These materials are widely compatible with cellulose-based textiles. Alginate-metal complexes form protective ceramic-like residues during combustion. These materials can be applied onto textile substrates through eco-friendly aqueous processes. Hybrid flame-retardant systems combine these biopolymers with synergistic additives such as nano-clays, metal hydroxides, phosphorus–nitrogen compounds, and bio-crosslinkers. Such systems operate through condensed-phase char formation, barrier effects, and gas-phase radical quenching.

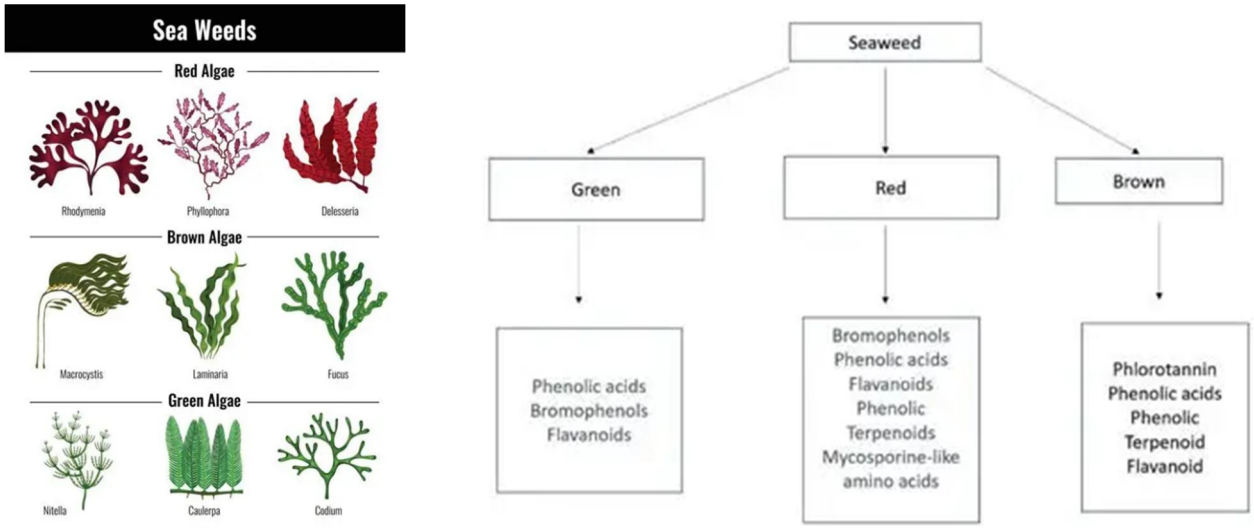

Figure:3. Seaweed-Derived Polysaccharides for Textile Protection

IV. HYBRIDIZATION STRATEGIES AND SYNERGISTIC ADDITIVES

Hybrid systems combine biopolymers with:

1) Phosphorus–nitrogen compounds
2) Nano-clays (montmorillonite)
3) Metal hydroxides ($Mg(OH)_2$, $Al(OH)_3$)
4) Bio-based crosslinkersSynergistic effects improve LOI values, reduce smoke density, and increase residual char yield.

V. HERE IS DETAILED CONTENT FOR EACH TEXTILE TREATMENT TECHNIQUE

Technique Principal Process Steps Applications Limitations

Layer-by-Layer (LbL) Assembly Alternate deposition of oppositely charged materials (electrostatic interaction, hydrogen bonding, etc) to form nano scale multilayers.

1) Surface activation
2) Immersion in a cationic solution
3) Rinsing
4) Immersion into anionic solution
5) Drying/curing
6) Repeat cycles

Flame-retardant textiles, antimicrobial fabrics, UV protective clothing, Conductive & smart textiles, self-healing coatings Time consuming, scalability issues, sensitive to pH & ionic strength

A. Sol-Gel Coating

Fluid "Sol" turned into solid "Gel" by hydrolysis and condensation reactions of inorganic/organic hybrid system.

1) Sol preparation (including precursor + solvent + catalyst)
2) Hydrolysis & condensation

3) Application (dip/spray/pad)
4) Drying & curing

Water repellent fabrics Superhydrophobic textiles UV Protection Flame Retardant Self cleaning-TiO2 antimicrobial coatings Brittle coatings (if not modified) Controlled conditions are needed Relatively expensive

B. Padding Method

Fabric goes through chemical solution, and surplus liquid squeezed off by squeeze rollers for uniform application (continuous process).

1) Immersion in bath
2) Squeezing through rollers
3) Drying
4) Curing

Wrinkle resistance, flame retardant, water repellence, antimicrobial finishing Increased chemical waste, large equipment needs

C. Exhaust Method

Chemicals diffuse gradually & controlled form treatment bath to fibres (in enclosed vessel) with controlled temperature and agitation (batch process).

1) Immersion in bath
2) Agitation & control of temperature
3) Fixation
4) Rinsing & drying Tinting

Softening, Antimicrobial treatment, Functional finishes Longer processing time, less productive than padding

Bio-crosslinking Approaches Approach employed: Use of Schwacter was to use natural crosslinkers (citric acid, enzymes, chitosan, tannic acid) to form covalent or hydrogen bonds with fiber molecules.

a) Preparation of bio-based solution
b) Application (pad/exhaust
c) Drying
d) Curing/fixatio

Crease-resistant cotton, antimicrobial medical textiles, sustainable finishes, biodegradable textilesReduced durability compared with synthetic resins, sensitivity to washing, needs to be optimized If you'd like, I can also turn this into a format it has an assignment version (with diagrams, references and conclusion section) that you can submit it. These techniques affect the adhesion strength, durability and wash resistance. LbL assembly allows a nanoscale control but padding is suitable industrially.

VI. FLAME RETARDANT MECHANISM AND PERFORMANCE EVALUATION

Biopolymer systems function mainly in the condensed state by formation of char and by intumescence. Thermal analysis (TGA), LOI testing, UL-94 vertical burning tests and cone calorimetry confirm the reduction of heat release rates and increment of resistance to fire. Flame retardant mechanisms in textiles rely in the interruption of the combustion process and combustion typically involves heat, fuel, oxygen and a chain process.

Flame retardants work by physical or chemical processes which either prevent ignition, inhibit spread of flame or reduce release of heat by chemical processes. In the gas phase mechanism, flame retardant chemicals have produced non flammable gas (such as water vapor or carbon dioxide) or free radical scavenger chemicals, both of which dilute combustible gases and break the chain reactions in the flame. For example, systems based on phosphorus- and halogen- act by quenching high-energy radicals (H and OH) in the flame zone and thereby reducing the intensity of the flame. In the condensed phase mechanism, flame retardants cause char formation on the fabric surface.

This char layer provides a thermal barrier for restricting heat flow, oxygen migration and also the release of flammable volatiles. Intumescent systems (usually of the phosphorus plus nitrogen type) are based on phosphorous and nitrogen combinations which expand on heating to provide a foamed protective layer over the underlying fibres. Additionally, some of the inorganic additives such as metal hydroxides work by endothermic decomposition and absorb heat to release water vapor so as to help cool down the material.

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The performance evaluation of flame retardant textiles consists of standardised performance methods to measure ignition resistance, flame spread, heat release and after flame behaviour. Some of the common parameters are: Limiting Oxygen Index (LOI) is the oxygen concentration needed to maintain combustion at a minimum value of LOI is the better the flame resistance. Vertical and horizontal tests for flammability measure flame spread rate, time of after flame, and length of char. Cone calorimetry is useful in determining heat release rate (HRR), total heat release (THR) and the production of smoked, which can give detailed information on fire behavior under controlled heat flux. Additional assessments are often conducted, such as thermal gravimetric analysis (TGA) to investigate the behavior of decomposition, durability tests to determine the resistance of fabric to washing and washing and mechanical testing property to ensure the treatment does not reduce the strength and flexibility of the fabric significantly. Together, all of these mechanisms and evaluation methods helps to determine the safety, effectiveness, and practical applicability of flame retardant textile finishes into protective clothing and home furnishings as well as industrial applications.

VII. AREA OF APPLICATION AND USES IN TEXTILES

Seed and seaweed biopolymer based hybrid flame retardants applicable in:

Protective Clothing: Industrial Clothing, Firefighter Underclothing

To my classes, these products would include-possum: oracy: "Home Textiles: Curtains, upholstery, carpets" Seats/support Material: Automotive - Seat covers, Aircraft interior - Fabrics

ABC agencies in our country are overseen by the abuse of power and bribery.Public Infrastructure- Theater drapes, hospital bedding. By: Marti M., Julian, Rhoda H., Kimberly, Terri, Jacelyn, Todd, and Sean, Oct 2014 "Tents, insulation fabrics" Their non-toxic nature suits children's textiles and medical environments Green Intumescent coatings by Marine & Agro bio polymer Engineered Flame retardant coatings for textile applications Using Seed Seaweed

VIII. BIOPOLYMER SOURCE TYPE SPECIFIC SEED/SEAWEED TYPE MAJOR ACTIVE COMPONENTS FLAME-RETARDANT MECHANISM (INTUMESCENT ACTION) TYPICAL TEXTILE SUBSTRATE TEXTILE APPLICATIONS

1) Seed - Based Biopolymers (Agro Source) Flaxseed (Linum usitatissimum) polysaccharide mucilage, lignans Promote char formation; forms carbonaceous protective layer; supports condensed-phase mechanism Cotton Protective clothing, home textiles

2) Chia Seed (Salvia hispanica) Mucilage Polysaccharides Swells and gels in heat; promotes formation of a more intumescent barrier Swells and gels when mixed with water Pulp textiles (cellulose) and synthetic fibers (polyester and nylon) can now be blended to create desirable properties.Chia Seed (Salvia hispanica) Mucilage Polysaccharides Swells and gels in heat Enhances formation of intumescent barrier Swells and gels when mixed with water Pulp textiles (cellulose) and synthetic fibers (polyester and nylon) can now be blended to create desirable properties .Tamarind SeedXyloglucan polysaccharidesCarbon rich char formation Improves thermal insulationCotton, JuteUpholstery fabrics Industrial textiles

3) Guar Gum (Cyamopsis tetragonoloba)

- ✓ Galactomannan
- ✓ Acts as carbon source in intumescent system, Improves adhesion of coatings
- ✓ Cotton, Polyester blends
- ✓ Workwear, flame retardant

a) Rice Bran / Phytic Acid (Oryza sativa) instantly absorb phosphorus (phytic acid) the acid source in intumescent formulation (promoting dehydration and char formation) Cotton (sustainable flame retardant finishing)

b) Seaweed-BioPolymers (Marine Source) Alginate (Brown alkali) Sodium alginate (poly sugar) Forms stable char; loses water during decomposition; Effects barrier effect Cotton, Wool Medical Textiles, Protective Garments Carrageenan (Red algae)Sulfated polysaccharidesIntumescent swelling; char promoting, heat release rate reducingCotton, Blends Interior furnishing textiles

c) Agar (Red algae) in\ Agarose & agaropectin herbarbular / both Form gel barrier Reduces oxygen diffusion Easter Cotton apparel Eco friendly.

d) Ulva (Green algae) Cellulose - like polysaccharides, proteins Carbonaceous char formation; aid in condensed - phase flame inhibition Natural fibers (Cotton, Linen) Biodegradable textile products

e) Kelp (Laminaria spp.) K Alginate, mineral salts Endothermic degradation; formation of intumescent protective layer Cotton, Technical textiles Fire resistant, industrial fabrics

IX. SUMMARY

Green intumescent systems based on divergent Mississippi seed agro-biopolymers and marine seaweed polysaccharides, acting primarily on condensed-phase flame retardant mechanisms. These materials serve as carbon source material, acid source material or blowing agent in intumescent formulations actually on the formation of expanded char layers in order to protect textile substrates from heat and oxygen. Such sustainable coatings are especially well suited for cotton and other natural fibers, which aids in the improvement of environmentally friendly flame retardant textile development. If needed, I can also create a separate classification table depicting carbon source-acid source-blowing agent roles of the green intumescent systems for deeper academic explanation as well.

X. CONCLUSION

Seed - and seaweed - based bio-polymers are a revolutionary group of sustainable materials for hybrid flame retardant textile systems. Their renewable origin, low environmental impact and inherent flame retardant functionalities make them attractive alternatives to conventional halogenated systems. Seed derived Compound Phytic acid imbues high phosphorus content essential for intumescent action in soybean Soy protein imbues nitrogen synergism for enhanced char stability. An additional carbon raw material used to promote more extensive char formation is starch and guar gum.

Seaweed inflammatory derivatives, like alginate and carrageenan provide great film-forming ability as well as barrier capacity. The additional thermal stability provided by metal-alginate complexes as residues of a ceramic structure. When incorporated into hybrid systems with nano -clays, metal hydroxides or phosphorus - nitrogen compounds, these biopolymers show remarkable enhancements in LOI, lower peak heat release rates, and lower smoke production. Despite these advantages, there have still been challenges. Wash durability and mechanical robustness need to be increased for long term performance. Cost competiveness with synthetics also means optimisation in scalable production processes. Furthermore, full life cycle assessments are required to ensure industrial scale environmental superiority. In the future, future research could place a focus on multifunctional textile systems with antimicrobial, UV-protective and self-cleaning properties. Nano Enabled Reinforcement Green Crosslinking Chemistry Bio Inspired Hierarchical coatings may unlock next generation performance. Future research should focus on the multifunctional nature of textile finishes that benefits the organism from properties such as antimicrobial and UV-protection and self-healing-coating counterbalanced with flame retarding. Advanced nanotechnology and green crosslinking approaches have the potential for further improvement of the durability and performance. Life-face assessment studies are also required to validate the environmental benefits at the commercial level. Overall, the development of hybrid flame retardant systems based on seed and seaweed biopolymers, are a promising, sustainable way towards greener fire safe textile. With further interdisciplinary innovation, it is clear these materials are likely to make a great impact on the future of textile finishing technologies.

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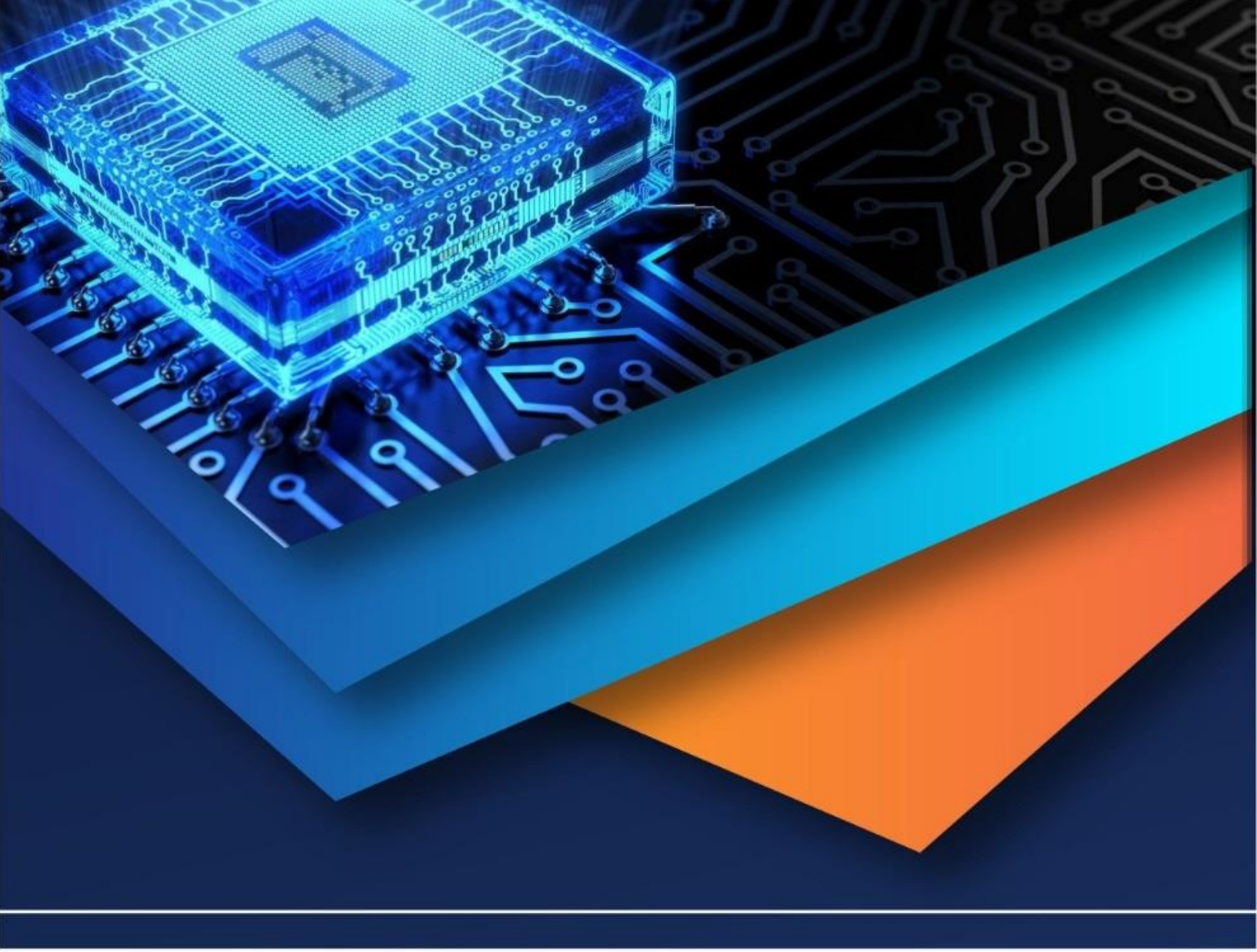

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