RECENT ADVANCEMENTS IN FLAME RETARDANT TEXTILES

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Abstract

This literature review explores recent advancements in flame retardancy for various textile materials, specifically focusing on cotton, polyester, nylon, and polypropylene. The investigation encompasses comprehensive studies and innovative techniques and formulations applied to enhance flame retardant properties in these textiles. The distinct combustion mechanisms and inherent characteristics of each material are considered, shedding light on tailored approaches for effective flame retardancy. The review examines the utilisation of novel flame retardant formulations, nanotechnology, and other emerging techniques to address the flammability challenges associated with each textile. The synthesis of research findings provides valuable insights into the evolving landscape of flame retardancy in cotton, polyester, nylon, and polypropylene, offering a foundation for future developments in textile engineering and fire safety of textiles across a multitude of industries

Key words:
Flame retardant textiles, Cotton, Polyester, Nylon, Inherent flame retardant materials

1.0 Introduction

The property of flame retardancy is a desired quality commonly attributed to polymeric substances. This characteristic pertains to the polymer's capacity to restrain, inhibit, or impede the propagation of fire upon contact. Thus, flame retardants (FRs) are a class of chemical compounds that exhibit one or all of the above described characteristics, and are usually employed in textiles via chemical treatments, which in turn modifies the mechanism of combustion to give the desired effect [1].

Flame-retardant fabric finds extensive application across

Fig 1. Contributing factors leading to inculcating flame retardant textiles in automotive and aircrafts.

diverse industries, primarily prioritising user safety. Its utilisation is prevalent in the manufacturing of protective equipment and gears across industries. Additionally, it plays a crucial role in the production of fabrics intended for use in transportation, such as interiors for locomotives, ensuring enhanced safety standards and reducing fire-related risks [2].

The versatile nature of flame-retardant fabric underscores its significance in safeguarding individuals in various operational environments. In these sectors, the incorporation of flame retardant textiles is not merely a precautionary measure but a critical necessity driven by several key factors, such as material longevity, emergency response facilitation, and compliance with industry standards amongst many more [2,3].

1.1 Combustion Mechanism Of Textiles:

Combustion is an exothermic chemical reaction involving a substance, often a hydrocarbon (fuel), and atmospheric oxygen (oxidant). This process yields energy in the form of heat and light, with carbon dioxide and water as the resultant byproducts. The combustion of textiles is a complex process involving the ignition and subsequent burning of fibrous materials. Textiles, which encompass a broad range of materials such as natural fibres (cotton, wool) and synthetic fibres (polyester, nylon), are susceptible to combustion when exposed to a sufficient heat source. The combustion of textiles is influenced by various factors, including the composition of the material, its structure, and the presence of any applied treatments such as flame retardants [3].

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The combustion mechanism of textiles typically consists of several stages [4]:

1. Ignition: This marks the initiation of the combustion process, where the textile material is exposed to heat, leading to thermal decomposition and the release of flammable gases.

2. Pyrolysis: During pyrolysis, the textile material undergoes chemical changes due to heat, producing volatile gases and leaving behind char or residue. The released gases contribute to the formation of a flammable atmosphere around the material.

3. Flame Spread: Once ignition occurs, flames may propagate across the textile surface. The rate of flame spread is influenced by factors like material composition, weave or knit structure, and the presence of any flame-retardant treatments.

4. Complete Combustion or Extinction: Depending on the conditions, combustion may either continue until the entire material is consumed, or it may be extinguished due to factors such as lack of oxygen, removal of the ignition source, or the presence of flame-retardant additives.
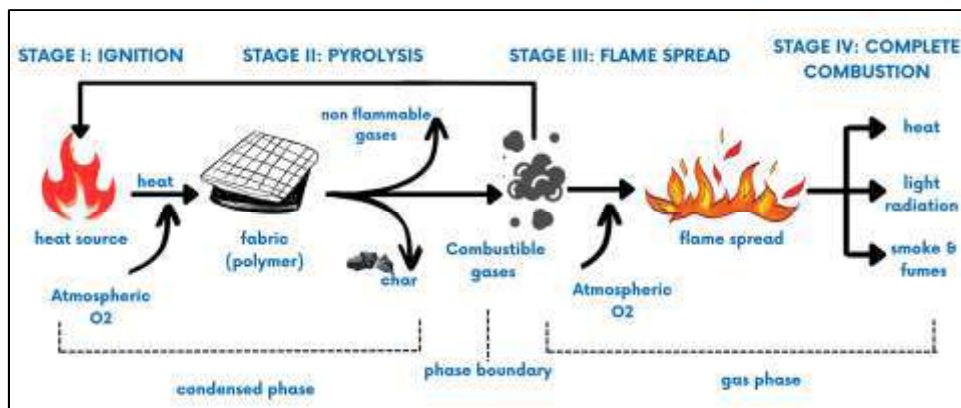

Fig 2. Combustion Mechanism of Textiles

Polymer flame-retardant mechanisms encompass gas-phase and condensed-phase strategies. The chemical composition and structure of the FRs play a key role in determining the way through which the FRs can be active in the condensed or gas phase. Gas-phase flame retardancy involves the generation of free radical inhibitors through material heating or combustion, disrupting the combustion chain reaction. Condensed-phase flame retardancy involves the creation of an isolation layer (char) on a material's surface during combustion, facilitating charcoal formation that serves as a shielding effect.

Conventionally, flame-retardant materials have encompassed organic polymeric, non polymeric, and polymeric/non polymeric hybrid compositions, incorporating elements such as N, S, P, Si, B, or Cl either individually or in combination) in their chemical structure, enabling potential synergistic effects. While halogen-based flame retardants (FRs) were acknowledged for their efficiency, their inherent toxicity led to a prohibition, prompting both academic and industrial research pursuits towards environmentally benign alternatives [4,5,6].

2. Inherently Flame Retardant Textiles:

Inherently flame-resistant (IFRs) fibres are materials that have the property of flame resistance built into their chemical structures. In the creation of Inherently Flame Retardant fabrics, fibres crafted from materials intrinsically resistant to flames are employed. These intrinsic fibres, engineered synthetics, are intentionally designed to possess inherent flame-resistant properties, displaying non-ignition when exposed to flames in environments with normal oxygen levels. Inherent fabrics generally exhibit higher Thermal Protective Performance (TPP) scores compared to treated fabrics, indicating their ability to shield wearers from elevated temperatures. Additionally, these fabrics tend to be lightweight.

A few of the most prevalent Inherent Flame Retardants (IFRs) are listed below:

a) **Kevlar:** The quest for a fibre combining the heat resistance of asbestos and the stiffness of glass led to the creation of synthetic, heat resistant, lightweight fibre, Kevlar, characterised by a molecular orientation parallel to the fibre axis [7]. Trademarked as Kevlar, poly-para-phenylene terephthalamide is a nylon-like polymer first introduced commercially by Du Pont in 1971 [8]. The synthesis of Kevlar involves utilising the monomers 1,4-phenylene-diamine (para-phenylenediamine) and terephthaloyl chloride in a condensation reaction, producing hydrochloric acid as a byproduct. Various grades of Kevlar cater to diverse applications, leveraging its numerous valuable properties, including a high tensile strength-to-weight ratio and exceptional thermal stability. These characteristics make it ideal for producing items such as bulletproof vests, cables, tires, protective and safety gear [9].

b) **Nomex:** Nomex, developed by scientists at DuPont, stands as an inherently flame-resistant and high-temperature resistant fibre. This fabric, derived from poly(meta-phenyleneisophthalamide), or Nomex, is crafted through a synthesis involving meta-phenylenediamine and isophthaloyl chloride in an amide solvent. It belongs to the aramid chemical class, akin to Kevlar. Nomex demonstrates exceptional resistance to flames, refraining from melting, dripping, or supporting combustion in air. Renowned for its proven performance, Nomex serves as a high-melting fibre

utilised in the fabrication of flame-proof protective clothing, paralleling the applications of Kevlar [10].

c) Zylon: Zylon is a trademarked name for a range of thermoset liquid-crystalline polyoxazole, a synthetic polymer invented and developed by SRI International in the 1980s. Synthesis of poly (p-phenylene-2, 6-benzobisoxazole), PBO, involves the condensation reaction of 4, 6-diamino -1,3-benzenedoldihydrochloride (DABCO) and terephthalic acid (TA). The resulting synthetic gold-coloured fibre, patented and commercialised by Toyobo as Zylon, was the strongest human-made polymer at the time, exhibiting a tensile strength 1.6 times that of Kevlar. PBO polymers were groundbreaking as the first artificially made organic fibres surpassing both steel and carbon fibre in cross-sectional strength. Zylon boasts a melting point above 1470° Fahrenheit (780°C) and exhibits exceptional flame resistance, requiring conditions above 68% oxygen for combustion. It finds applications in space exploration, body armours, and extreme weather situations [11].

d) Panox: PANOX, an oxidised polyacrylonitrile (PAN) fibre, exhibits exceptional resistance to burning, melting, softening, and dripping. Recognized internationally as an industry standard for non-flammable textile fibres, PANOX finds versatile applications providing effective protection against fire and heat across various fields. The production process involves thermal stabilisation of polyacrylonitrile (PAN) at 300 °C, yielding an oxidised textile fibre with an approximate carbon content of 62%. The remarkable Limiting Oxygen Index (LOI) value of PANOX, exceeding 45% (dependent on fibre density). These inherently flame-resistant fibres from SGL Carbon boast high thermal stability, excellent fire resistance, and good thermal insulation properties. With superior handling and processing characteristics, PANOX fibres prove to be an optimal choice for crafting heat-resistant and flame-proof woven and non-woven fabrics. PANOX has established itself globally, proving its efficacy in various industries for flameproof applications. The industrial applications span across fire-resistant technology, chemical and heat-resistant technology, railway interiors, steel industry, and fabrics in the automotive industry [12].

e) Trevira CS: Trevira, a globally recognized entity, is renowned for its production of yarns tailored for flame-retardant textiles, utilising the inherently flame-retardant polyester known as Trevira CS. The chemical structure of the polyester fibre is modified to embed flame-retardant properties in the form of a comonomer—an organophosphorus compound—ensuring resilience to external influences. Products crafted from these fibres exhibit exceptionally high Limiting Oxygen Index (LOI) at 42%, showcasing outstanding flame retardancy without the need for additional environmentally damaging fire protection treatments. These versatile fibres can be blended with other materials to achieve desired effects, emitting minimal levels of toxic fumes in case of a fire, prioritising safety against smoke suffocation risks. Beyond flame retardancy, Trevira CS fibres boast attributes such as high colour brilliance, light fastness, abrasion resistance, and ease of care, making them applicable in diverse sectors [13,14].

f) Proban: Introduced in the 1950s, PROBAN provides a durable flame retardant treatment for cotton and other cellulosic fibres and blends. This durability stems from the formation of a cross-linked inert polymer within the fibre, ensuring that the physical properties of the base fabrics remain largely unaffected due to the absence of a chemical reaction with the fibre. PROBAN-treated fabrics undergo decomposition when exposed to a flame, resulting in the formation of a localised insulating char that acts as a barrier. Notably, PROBAN-treated fabrics do not smoulder, exhibit no afterglow, restrict flame spread outside the charred area, and do not melt away, preventing the creation of openings for flame penetration. Furthermore, they do not produce hot, sticky residues that could adhere to the wearer's skin. Currently, PROBAN-treated fabrics are widely used in various personal protective clothing applications across industrial, military, and civil sectors [15].

3. Commonly Employed Techniques For Integration Of FRs In Textiles:

Designing efficient and environmentally friendly flame retardants poses challenges. Malucelli et al. summarised three highly promising surface engineering approaches that emerged, particularly in the last decade and continue to remain a popular choice of the industries for employing the fabrics with flame retardant chemicals [16].

a) Nanoparticle Adsorption:

Nanoparticle adsorption represents the initial undertaking of deposition of nano-entities onto fabric surfaces. This methodology entails the immersion of the fabric within a stable suspension of nanoparticles, creating a nanometric distribution that functions as a physical barrier and thermal shield. This barrier is effective in safeguarding the fabric against flames or heat flux. Since this method relies solely on ionic interactions between the substrate and nanoparticles, it is characterised as a non-durable treatment, with exceptions noted for systems incorporating a cross-linker between cotton and nanoparticles. Different nanoparticles produce varying results in terms of LOI, flammability, and toxicity.
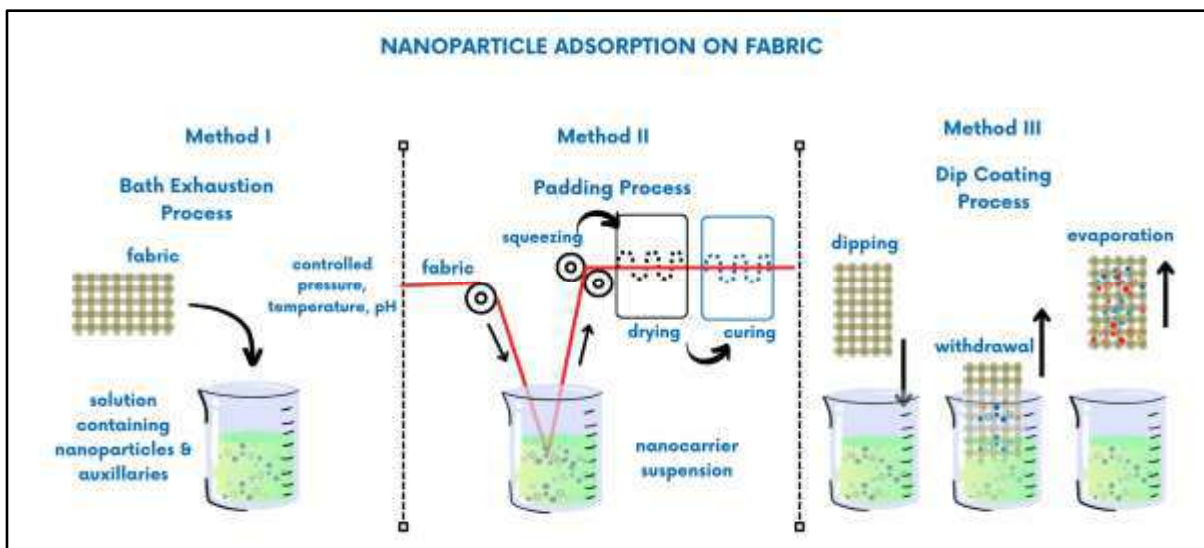
Fig 3. 3 widespread methods facilitating nanoparticle adsorption on fabrics.

b) Sol-gel Technique: The sol-gel technique has already remarkably proved its exceptional potential regarding the synthesis of new materials with a high degree of homogeneity at molecular level and with outstanding physical and chemical properties. The sol-gel is a versatile synthetic route based on a two-step reaction (hydrolysis and condensation), wherein monomers are transformed into a colloidal solution (sol) serving as a precursor for an integrated network (gel) of discrete particles or network polymers. This strategy utilises reactive precursors, like (semi)metal alkoxides, in hydrolysis and condensation reactions, resulting in fully inorganic or hybrid organic–inorganic 3D networks. Notable examples of (semi)metal alkoxides include tetramethoxysilane (TMOS), tetraethoxysilane (TEOS), aluminium isopropoxide, and titanium tetraisopropoxide. The sol-gel method stands out due to its applicability at or near ambient temperature, with thermal treatments employed in some cases to accelerate reaction kinetics. Besides the successful phosphorus-doped sol-gel method, a recent advancement in this technique combines photoinduced polymerization with subsequent thermal treatment (a dual-cure strategy) to create hybrid organic–inorganic flame retardant coatings so as to bring about a synergistic effect. This approach allows direct impregnation of textiles with a liquid mixture containing both organic monomers/oligomers and alkoxy precursors. Depending on the structure and composition of the sol-gel precursors, multifunctional coatings can be designed, exhibiting flame-retardant properties alongside other desirable features such as hydrophobicity, antibacterial activity, and electrical conductivity.

c) Layer by Layer Method: Layer-by-Layer (LbL) assembly, pioneered by Iler in 1966, involves a step-by-step film buildup based on electrostatic interactions. Reconsidered in 1991, LbL assembly has since been extended to incorporate inorganic nanoparticles (exploiting various interactions like covalent and hydrogen bonds). The electrostatic variant of LbL assembly involves the alternating immersion of the substrate into oppositely charged polyelectrolyte solutions, resulting in the accumulation of positively and negatively charged layers on the substrate surface, with total surface charge reversal after each immersion step. In conclusion, Layer by Layer assembly can be considered an evolution of the nanoparticle adsorption process. After a decade of significant advancements, this method remains highly utilised for its versatility in combining molecularly-sized components with different functionalities. It facilitates innumerable combinations of various molecular components having differing functionalities. This allows the design of tailored assemblies to confer peculiar properties to the underlying substrate without affecting its bulk characteristics, despite the very limited thickness. Over the last 10 years, there has been a transition from fully inorganic to hybrid organic–inorganic and then to intumescent assemblies. The resulting nanostructured assembly, often comprising around 10 layers. Industrial-scale applications often involve spraying, while dipping is common for lab-scale treatments. These coatings demonstrated a notable increase in Limiting Oxygen Index (LOI) and self-extinguishing features without compromising the mechanical properties of the textile material, highlighting the effectiveness of these deposited assemblies in reducing total heat release.

Understanding combustion behaviour, surface morphology and the techniques of application is paramount for application of various FR textiles from an industry point of view. Following a comprehensive grasp of the mechanisms, flame retardants are commonly administered to textiles to diminish flammability and impede the combustion process. Compliance with established standards safety and regulatory ensures textiles meet safety criteria, reducing fire-related risks in diverse settings. Ongoing research in this domain seeks to formulate effective flame-retardant synthesises and strategies, taking into account environmental sustainability,
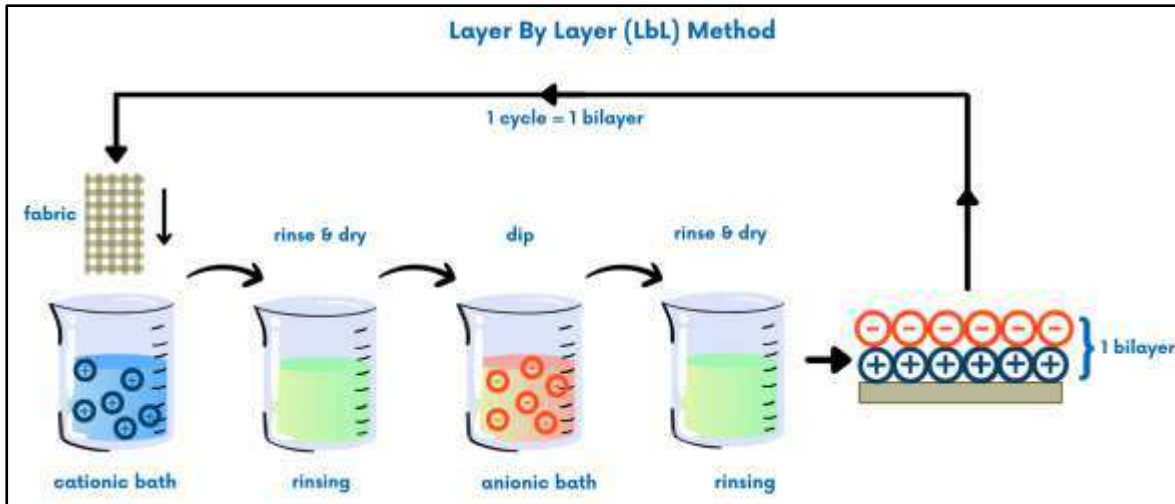
Fig 4. Schematic diagram of Layer by Layer (LbL) Assembly Method

toxicity, cost and other distinctive properties of various textile materials. Subsequent sections will delve into the recent advancements in this field.

4.Cotton:

Cotton, a natural fibre, holds paramount commercial significance owing to its versatile applications in textiles, apparel, and other consumer goods globally. Cotton fibres consist largely of a naturally occurring polymer called cellulose (88-96.5%) and is highly flammable.

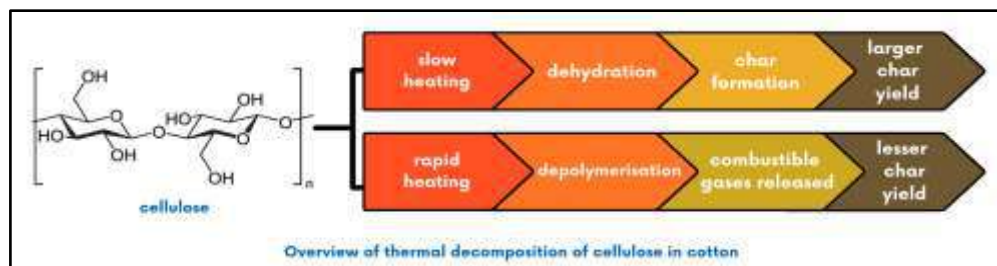*4.1 Thermal degradation of cotton & mechanism of FRs employed:*

Fig 5. Overview of thermal degradation of cellulosic structure of cotton

Heating cotton leads to depolymerization, i.e, it undergoes dehydration and consequently cellulose decomposition. This thermal decomposition of the polymer occurs at different temperatures, influencing its flammability. Slow heating promotes dehydration, leading to the formation of a carbonaceous multi-lamellar structure, or char. In contrast, rapid heating causes depolymerization, resulting in the release of combustible gases. Cotton heated slowly in air produces a larger char yield compared to fast heating, indicating its natural tendency to form a protective char layer that inhibits combustion. Scientists often prefer condensed-phase flame retardancy for cotton due to the material's cellulose-rich composition. The goal is to create an insulating layer on the surface of cotton during combustion.

This layer facilitates the formation of a protective char, acting as a physical barrier that reduces heat and mass transfer. Consequently, condensed-phase flame retardancy helps to impede the propagation of flames and contributes to the overall reduction of cotton's flammability [16].

4.2 Cotton Fabrics Treated with Polymeric Flame-Retardant:

In a departure from halogen-based flame retardants, novel formulations have been synthesised to prioritise sustainability and environmental friendliness. The introduction of polymers containing nitrogen (N), sulphur (S), and phosphorus (P) atoms enables cotton to acquire fire-resistant properties. These organic polymers derive their flame-retardant characteristics from the presence of one or a combination of these three elements. These elements may be inherently present in the original polymers, or they can be introduced through a chemical modification process. This shift towards non-halogenated formulations reflects a commitment to more sustainable and eco-friendly fire-retardant solutions [17].

a) P based organic polymer:

I. Ling et al. conducted the synthesis of a hyperbranched polymer (HBP) incorporating phosphoric acid (H3PO4), resulting in the formation of the phosphate esterification product of HBP. Subsequent reactions with urea (H2N–CO–NH2) yielded an ammonium salt. Introducing this formulation to cotton fabric facilitated a reaction wherein the cationic NH4+ ions interacted with the –OH groups of cellulose, imparting flame-retardant properties. The reaction was catalysed by dicyandiamide [18].

The addition of a phosphorus-containing high-branched polymer-ammonium salt significantly improved the flame retardancy of cotton. Ling and Guo (2020) demonstrated that incorporating 28.1% of this polymer-ammonium salt increased the Limiting Oxygen Index (LOI) to 42%, enhanced char formation (approximately 35%, tested by Thermogravimetric Analysis at 600°C), reduced the $[CO_2]/[CO]$ ratio, and achieved a maximum char length of 5.6 cm for the cotton fabric. In comparison, the untreated cotton fabric exhibited a lower LOI (17.2%), lower TGA char formation (2.5% at 600 °C), a higher $[CO_2]/[CO]$ ratio (56.5), and burned completely in the vertical flame test.

ii. An identical experiment was carried out by Guo et al. in 2022, wherein an attempt was made to synthesise a novel glycerol based flame retardant. The paper discussed synthesising an ester with starting materials glycerol, phosphoric acid and urea. This was further catalysed by dicyandiamide. This chemical was grafted through dipping, padding and curing onto the cellulosic fibres [19].

The paper claimed a successful esterification of glycerol and the triphosphoric acid. It boasted a higher LOI (37.3%) for the treated cotton after the addition of urea to the solution made. However, on mimicking the experiment, addition of urea led to excessive foaming, which further turned into a viscous liquid with a glue-like consistency. This sticky adduct could be made runny on adding water but went back to its original consistency on further stirring. This behaviour aligned perfectly with the statements made in a patent on making phosphate esters by Tai et al. (1978). Further specifications on the appropriate concentrations of glycerol and other starting materials along with experimental procedures to be followed to procure optimum results were clarified in the same patent [20].

b) N based organic polymer:

Manfredi et al. conducted a reaction involving N,N′-methylenebis(acrylamide) (MBA) and (4-aminobutyl) guanidine, resulting in the formation of Poly(amidoamine). Subsequently, an aqueous solution of this polymer was meticulously added dropwise onto cotton fabric, ensuring uniform coverage. The treated fabric was then subjected to a drying period of 5 minutes at 100 °C.

Manfredi et al. (2018a) observed that when testing pure cotton fabric using TGA at 600 °C, the remaining char and $[CO_2]/[CO]$ ratio were approximately 12% and 39, respectively and it burned completely in a short time during a vertical flame test, leaving no visible residue. However, cotton fabrics treated with the mentioned solution (add-on 19%) exhibited enhanced characteristics, including higher char production (approximately 30%, tested by TGA), a

lower $[CO_2]/[CO]$ ratio (approximately 9, tested by cone calorimetry) than that of pure cotton fabric. Additionally, the vertical flame test of the treated fabric resulted in a maximum damaged length (char length) of 2.3 cm [21].

4.3 Cotton Fabrics Treated with Non-Polymeric Flame-Retardants [17]:

a) P based organic non-polymer:

Ammonium phytate (APA) is synthesised by combining phytic acid (PA) with urea. In the context of cotton, when mixed with APA, the cationic NH_4+ ions within APA react with the –OH groups of cellulose, resulting in the production of flame-retardant cotton fabric. This reaction is catalysed by dicyandiamide, as elucidated by Feng et al. in 2017. The flame-retardant attributes of the cotton fabric come from the covalent linkages between cellulose chains and phosphorus-containing non-polymeric compounds [22].

Feng et al. studied textile treated with APA and observed differences in fire-related properties. For the control fabric, which burned entirely with no residue, the LOI, remaining char at 600 °C (TGA test), $[CO_2]/[CO]$ ratio, and residue (cone calorimetry test) were approximately 17.8%, 0.8%, 86.18, and 1.31%, respectively. In contrast, the fabric treated with APA (add-on 14.49%) showed higher values for LOI (36.1%), remaining char at 600 °C (about 40%), and $[CO_2]/[CO]$ ratio (3.05), along with a residue of 36.24%. [22]

b) N, P-based non-polymeric organic compounds:

An example of a nitrogen-containing compound is the ammonium salt of ethylenediamine tetramethylene phosphonic acid (AEDTMPA). The AEDTMPA is produced by reacting ethylenediamine tetramethylene phosphonic acid (EDTMPA), prepared from the reaction that occurs among the reactants ethylenediamine, formaldehyde, and phosphorous acid (H_3PO_4), with urea. After adding a cotton fabric, the –OH groups of the cellulose molecules reacted with the phosphonic groups in the AEDTMPA to form P–O–C covalent bonds.[23]

Zheng et al. (2016) showed that adding N, P-based AEDTMPA to cotton significantly enhanced its flame resistance. The LOI, TGA char formation, and cone calorimeter residue increased from about 20% to 43.6%, approximately 8% to around 43.4% (at 600° C), and 1.3% to 42.5%, respectively. Pure cellulosic textiles burned completely, while AEDTMPA-treated textiles had a damaged length of only 3.5 cm in the vertical flame test. The $[CO_2]/[CO]$ ratio decreased from 78 to 2.1 after treatment [23].

2.4 Cotton Fabrics Treated with Hybrid Flame Retardants:

Hybrid compounds, incorporating nitrogen, phosphorus, and sulphur, establish a cohesive network that synergistically

enhances flame-retardant properties in both gas phase and condensed phase of combustion mechanism. This collaborative effect results in an advanced flame-retardant capability, surpassing the individual contributions of solely polymeric or non-polymeric compounds and augments flame-retardant characteristics [17].

a) Hybrid non-polymeric-polymeric Flame Retardant:

Zhang et al. (2019b) demonstrated a flame-retardant treatment for cotton through layer-by-layer deposition. The process involved alternating cationic polyelectrolytes and anionic compounds. Specifically, cotton was treated with bilayers of cationic polyethylenimine (PEI) and anionic phytic acid (PA). The procedure consisted of immersing the cotton in a PEI solution, followed by rinsing and drying at 80 °C. Subsequently, the fabric coated with cationic PEI underwent immersion in a PA solution, followed by rinsing and drying. This cycle was repeated eight times, resulting in the application of eight PEI/PA bilayers on the cotton fabric.

The cotton fabric treated with PEI/PA bilayers, as studied by Zhang et al. (2019b), showed improved flame-retardant characteristics. The untreated cotton fabric had an LOI of 18.5% and a TGA residue (at 600 °C) of about 16.3%, while the treated cotton fabric exhibited an LOI of 37% and a TGA residue of approximately 35%. In a vertical flame test, the treated sample had a damaged length of around 7 cm, whereas the non-treated cotton fabric burned completely [24].

b) Hybrid Organic-Inorganic Flame Retardant:

An effective flame-resistant coating for cotton involves a dual-component solution of phytic acid (PA) and silica. This coating solution was prepared by combining tetraethyl orthosilicate (TEOS), ethanol, and PA. A cotton fabric was immersed in this PA/silica solution for a specific duration. Following immersion, the impregnated cotton fabric was extracted, dried at 80° C, and subsequently cured at 160 °C for 3 minutes. The treated cotton fabric underwent washing and air-drying processes thereafter.

Research on dual and multicomponent coatings applied to cotton, demonstrated their efficacy in imparting flame retardancy. In the study conducted by Cheng et al., it was observed that untreated cotton fabric burned entirely in a brief period without leaving any residue. Conversely, fabrics treated with these coatings exhibited rapid self-extinguishing behaviour after ignition, resulting in a significant reduction in the maximum damage length in each instance. Additionally, the TGA char formation increased for the treated fabrics [25].

4.5 Green Flame Retardant Systems For Cotton- Bio-Macromolecular Coating Of Cotton [16]:

When it comes to cellulosic substrates, flame retardants (FRs) incorporating phosphorus and nitrogen stand out as the most effective systems, as evident from the discussed data. Ongoing and extensive research is being conducted in this field, with a growing focus on biomaterials amid the gradual depletion of oil resources. In the ongoing quest for novel, cost-effective, and environmentally sustainable FRs, the utilisation of biomacromolecules including phytic acid, amino acids, and proteins, have garnered attention as flame retardants for cotton fabrics. Similar to polyols, the numerous -OH groups on starch macromolecules can undergo esterification with a substantial amount of phosphoric acid, avoiding the use of formaldehyde, and make a flame retardant coating in theory. The notable advancements in this direction have been outlined in Fig. 6.
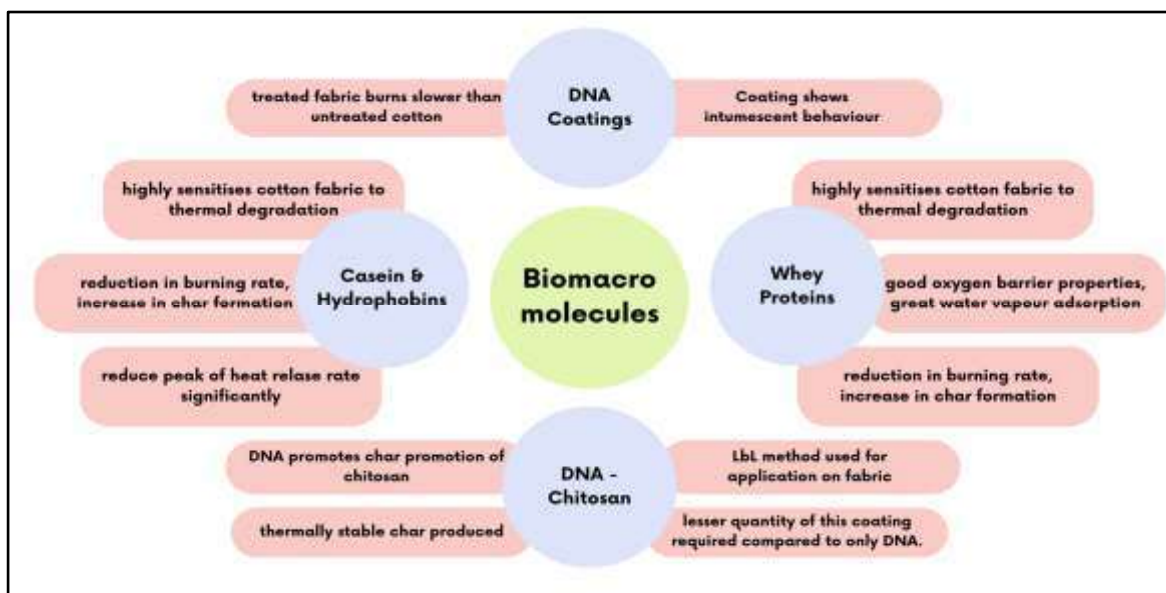

Fig 6. Outline of notable advancements in biomacromolecular coatings for cotton

Significant strides in enhancing flame retardancy for textiles are primarily focused on cotton, given its inherent high flammability and widespread commercial use. The concurrent presence of phosphorus, along with other elements like nitrogen, sulphur, boron, chlorine, barium, and nanomaterials (CNT, silica, and TiO2), holds substantial potential for achieving synergistic effects when treated cotton is exposed to flames or heat sources.

Textiles treated with P-based non polymeric flame retardants, specifically AHEDPA and APA [22], exhibited superior performance compared to various other flame-retardant types, as evidenced by higher LOI values, a favourable CO2/CO ratio, and reduced char length. The versatility of phosphorus-based flame retardants, coupled with their synergistic effects with other elements, leads to modifications in both the condensed and gas phases, significantly enhancing the efficiency of the flame retardant. In contrast, biomacromolecular-based flame retardants did not yield consistent results and proved to be slightly more expensive than the aforementioned alternatives.

Adsorbed flame-retardants may be washed out during laundering, and even cotton treated with covalently linked flame-retardants experiences a slight reduction in flame-retardancy after washing, leading to a minimal release of cotton into wastewater. Flame retardants synthesised by Zhang et al. and Cheng et al. [24, 25], are predominantly situated on the fibre's surface, resulting in lower washing fastness when compared to other mentioned flame retardants designed for cellulosic fibres. Durability of FRs continues to remain a major area that requires further research.

5. Polyester:

Polyester, classified as a synthetic textile, stands as one of the preeminent fabrics globally, renowned for its exceptional tensile strength and durability. This prominence is particularly notable in applications requiring resilience against rigorous abrasion and fading of colour, exemplified by its prevalent use in transport modes, sportswear, and uniforms. Polyester is not highly flammable and thus, upon exposure to flames, polyester exhibits a resistance to ignition. Polyester is naturally flame-retardant, however, once ignited, the fabric melts with severe dripping. Polyester polyester undergoes melting and burning simultaneously. Notably, polyester has a higher flammability temperature compared to type 6 nylon, making it less prone to catching fire easily.

5.1 Thermal Degradation of polyester, & mechanism of FRs employed:

Polyester, a synthetic polymer derived from polyethylene terephthalate (PET), inherently possesses flame-retardant properties due to the composition of its monomers, ethylene glycol, and terephthalic acid. The tightly woven molecular structure of polyester contributes to its heat resistance,
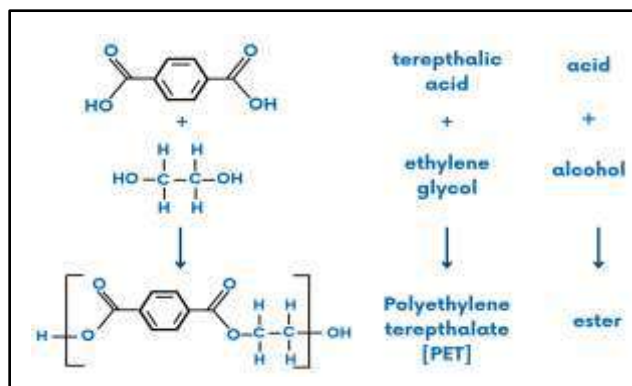

Fig 7. Formation of the polymer, Polyester (PET) from terephthalic acid and ethylene glycol through esterification.

making it a common choice for protection against heat and fire hazards.

The thermal degradation of polyester involves transesterification, hydrolysis, ester bond cleavage, and alkyl chain cleavage at high temperatures, diminishing its thermal stability. Polyester, being a synthetic fabric composed of long-chain polymers, undergoes pyrolysis when exposed to high temperatures, resulting in the release of volatile byproducts, altering the fabric's physical and chemical properties. Slow pyrolysis of PET has been studied widely as breakdown of PET leads to the formation of numerous species which can broadly be grouped into light(gas) species, waxy products, and solid residues [26]. Waxy products consist mostly of organic acids such as benzoic acids and terephthalic acid. Gaseous by-products including acetaldehyde, CO2, CO, CH4 benzene and toluene were erected using mass spectroscopy. Degradation of aromatic compounds would either allow condensation which would lead to carbonaceous residue; or chain scission which would further give rise to volatile species [27].

Efficient flame retardant systems, relying on both gaseous and condensed-phase mechanisms, are vital for enhancing polyester's resistance to combustion. Understanding polyester's thermal degradation behaviour is essential for evaluating its performance and safety in applications exposed to elevated temperatures.

Polyester is flame retardant in comparison to other fabrics. However, its treatment with fire retardants before and after fabrication, boosts this property. Techniques of application of FRs in polyester during fabrication entails the addition of the chemical to the spinning solution, thus inculcating the flame retardant deep within the material during the manufacturing process. Aerosol or spray methods are used for injection of FRs within polyester fibres after its fabrication. Regarding synthetic fabrics such as polyester, a primary objective remains the development of novel halogen-free flame retardants that can promote char formation and prevent unwanted dripping.
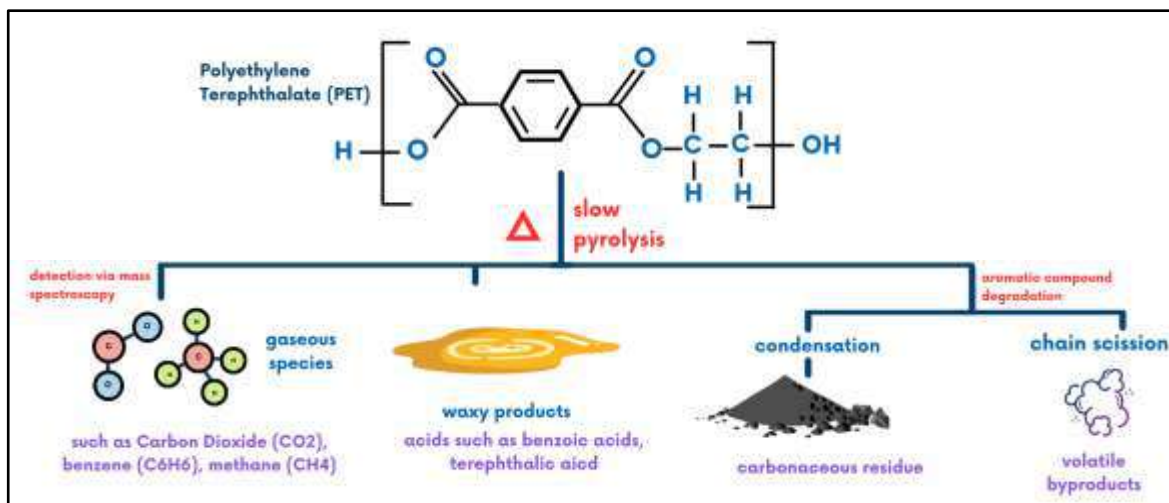
Fig 8. Slow pyrolysis of Polyethylene Terephthalate (PET) into smaller by-products

5.2 Casein Protein Treatment:

In the pursuit of environmentally friendly solutions to impart flame retardancy and reduce dripping in polyester, Carosio et al. employed a macromolecule, casein. A novel approach involved treating polyester and polyester−cotton fabrics with an aqueous casein suspension to enhance their thermal stability and flame retardant properties. The casein powder, comprising 12−15 αs1 casein, 3−4 αs2 casein, 9−11 β casein, and 2−4 κ casein in grams per litre, was synthesised. This powder (5 wt %) was dispersed in distilled water under mechanical stirring (300 rpm). The suspension was then heated to 80 °C in a thermostatic bath, and the pH was adjusted to 10 using a 1 M NaOH solution. Cotton fabrics were immersed in the casein suspension for 5 minutes, squeezed with a lab padder, and subsequently dried to a constant weight in an oven at 80 °C. The resulting total dry solid add-on on polyester reached 20 wt %. Subsequent comprehensive tests were conducted on the polyester fabric treated with casein, and the ensuing results are elaborated upon in the following discussions.

Caseins extracted from bovine milk, applied to polyester through an impregnation method, emerged as an effective flame retardant. This biomacromolecule played a crucial role as a char-former, promoting polyester dehydration and cyclization to form char. This inhibited the generation of volatile species, significantly enhancing polyester resistance against a methane flame and considerably reducing the burning rate (−67%), although not completely suppressing the melt-drip phenomenon. The casein treated polyester could limit the flame propagation within 30 mm and had increased residue. The LOI of polyester was improved from 21% to 26%. Since this was cost effective too, such biomacromolecules have the potential to replace phosphorus based FRs [28].

5.3 Nanoclays:

Polymer nanocomposites (PNCs) have garnered significant interest over the last decade due to their resistance to flammability, cost-effectiveness and easy accessibility. These materials exhibit considerable enhancements in mechanical, physical, and thermal properties, even with a minimal silicate content (3–6 wt%). The synthesis of clay nanocomposites, or 'nanoclays,' involves methods such as melt blending, in situ polymerization, and solvent techniques. The incorporation of nanoclays into polymers, such as polyester, has demonstrated a substantial reduction in flammability, reported Ayesha Kausar. At ICT Mumbai, Teli and Kale produced a master batch of nanoclays made by compounding linear low density polyethylene (LLDPE) with 30% nanoclay in a twin screw extruder. Polyester chips were dried in a vacuum dryer for 16 hours at 150 C to remove traces of moisture. The previously made masterbatch was also dried in an oven at 60 C for 4 hours. The melt spinning of the PET chips blended with nanoclay masterbatch was carried out with temperatures of the extruder zones being distinctly above the melting point of the PET chips. In the extruder zone, there was a provision for supply of nitrogen gas to prevent oxidation of PET. PET chips melted down to a molten mass. This mass was moved to the metering pump followed by the Die head zone. The filaments extruded were cooled down by blowing cool air in a quench duct. The filaments were guided to the roller via metered spin finish passage and then subsequently were taken over to the draw rollers. The filaments were finally fed to the take up winder machine over the condenser arm wheel, which applies tension to the yarn and controls the speed of the spindle, ensuring that a consistent package could be produced. The final speed of melt spinning was 107 m/min and denier per filament was 8. Various tests were carried out on this polyester filament which have been delved into Fig 9. Schematic diagram of inculcating nanoclays into polyester filamentsfurther ahead [29, 30].

Teli and Kale's (2012) nanoclay masterbatch, when melted together with PET chips, produced enhanced stability of the fibres against head and gave a flame retardant effect to spun PET nanocomposite fibres. At just 2% add-on of nanoclay in
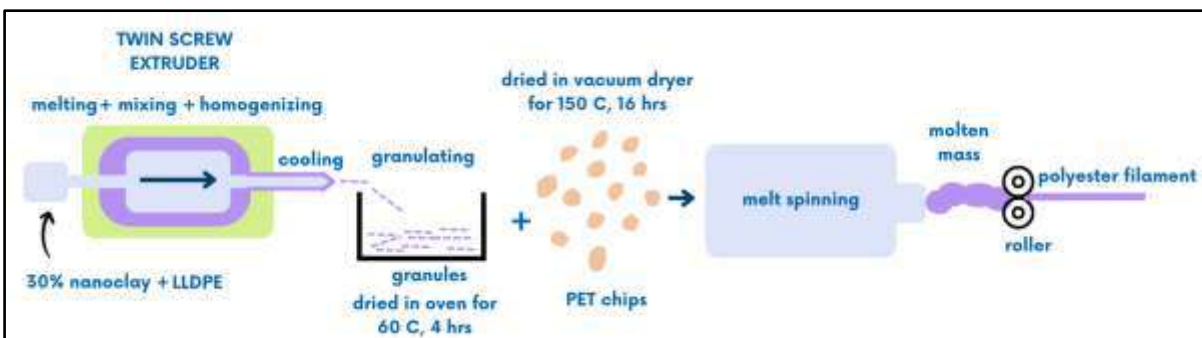
Fig 9. Schematic diagram of inculcating nanoclays into polyester filaments

PET composite fibre, the LOI of the polyester filament increased to 27%. This suggests that the nanocoating modified the PET combustion mechanism. Washing and light fastness of treated polyester remained unaffected too, in comparison to virgin polyester. However, there was a decrease in tensile strength and elongation (%) with increase in nanoclay content. Acting as an insulating ceramic barrier, just a miniscule amount of nanocoating protected polyester from heat, oxygen, and mass transfer during combustion, delaying ignition and reducing effective heat release as a lower amount of polymer burned [30].

5.4 Copolymerization Of Phosphorus Based Compounds In Polyester Fabric Matrix :

Flame retardant polyester fibre refers to the copolymerization, blending or finishing to make polyester fibre with non-flammable properties. Modern flame retardants (FRs) for polyester are primarily produced through copolymerization with a bifunctional organophosphorus compound derived from phosphinic acid. A noteworthy example involves the use of comonomers of sulphone–phosphonate for copolymerisation, produced by Toyobo GH, as to impart flame retardancy to polyester. The copolymerization of these FR compounds with polyester molecules significantly enhances the Limiting Oxygen Index (LOI) of the treated fabric. Importantly, the combustion of the treated fabric does not result in the generation of burning molten droplets, addressing a major concern associated with burning polyester. Furthermore, the application of this flame retardant is considered environmentally friendly compared to alternative flame retardant application methods. Additionally, under increasing temperatures, studies indicate that FR-treated polyesters exhibit lower toxicity than their FR-treated cotton counterparts [31].

Introduction of HPP: Zhao et al. successfully synthesised a high-phosphorus content polyester by polymerizing polyethylene terephthalate (PET) with a phosphorus containing flame retardant 3-(Hydroxyphenyl phosphinyl) propanoic acid (HPP) using a three-reactor system on a commercial scale. Subsequently, the thermal degradation of the synthesised polyester was investigated.
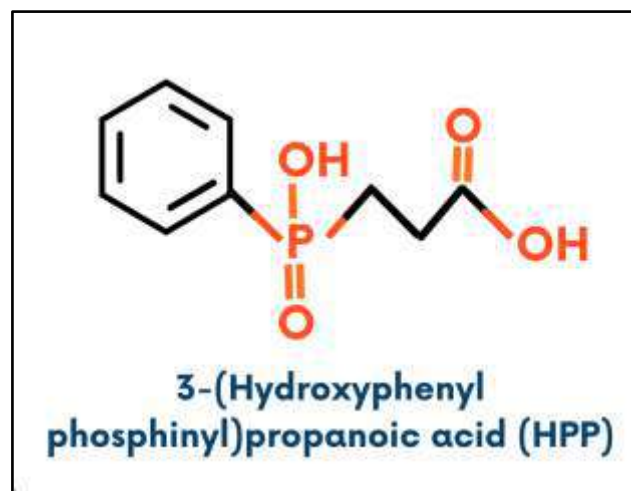

Fig 10. Molecular structure of 3HPP

This treated polyester was more flexible, and could degrade thermally at temperatures lower than virgin. This is concluded as advantageous as phosphorus containing polymers degrade into phosphoric acid, and other phosphorus derivatives, which promote char formation by interfering in the condensed phase of textile combustion. The HPP treated polyester was more labile and hence contributed to the flame retardancy of the polyester [32].

While copolymerization of phosphorus retardants is a common method to render polyester flame retardant, a notable challenge is the hydrolysis susceptibility of phosphorus-containing polymers, despite their efficacy in preventing dripping. Inorganic architectures, combining monolayer deposition through nanoparticle adsorption and intumescent assemblies enriched with inorganic nanoparticles like silica and clay, have proven effective as thermal insulator barriers. These structures reduce heat, oxygen, and mass transfer, steering polyester towards pyrolysis and char formation instead of releasing volatile gases that sustain combustion. Single-step adsorption of lamellar nanoparticles increases the time to ignite polyester samples, and multi-step deposition of silica nanoparticles imparts self-extinguishing properties while suppressing melt dripping in treated polyester fabrics [31, 32].

6. Nylon:

Nylon is a synthetic polymer fabric known for its exceptional strength, durability, and versatility. It is commonly used in various applications, including clothing, carpets, and industrial materials. This synthetic textile is characterised by amide bonds in its molecular structure, and is commonly referred to as polyamide. Widely utilised in commercial applications, nylon 6 and nylon 66 constitute the predominant forms of this textile. While nylon itself is not inherently flame-resistant, unlike polyester, its flammability depends on the specific type of nylon and its manufacturing process. Generally, untreated nylon can be flammable and may melt or burn, but flame-resistant treatments can be applied to enhance its fire resistance.

6.1 Thermal Degradation Of Nylon And Mechanisms & Mechanism Of Frs Employed :

The molecular configuration of Nylon is characterised by elongated chains composed of recurring amide groups. Thermal degradation of nylon 6 and nylon 6,6 is a singular progression, culminating in crosslinking and the generation of non-volatile char. This char formation induces a deviation from the first-order kinetics of thermal degradation, exhibiting a decrease in char yield with escalating temperatures. The reduction in achievable crystallinity upon cooling from the melt is attributed to crosslinking, accompanied by an elevation in molecular weight and the emergence of coloration.

The decomposition of nylon mirrors that of polyester, resulting in molten droplets at higher temperatures during combustion, contributing to flame propagation. Nylon and polyester, both flammable, exhibit distinct reactions to fire. Nylon melts before burning, while polyester undergoes melting and burning simultaneously. Notably, polyester has a higher flammability temperature compared to type 6 nylon, making it less prone to catching fire easily.

Recent research endeavours focusing on enhancing the flame retardancy of nylon 6 fibres encompass strategies such as intrinsic flame retardancy through the incorporation of flame-retardant functional groups within the nylon 6 molecule structure via chemical reactions. Additionally, flame-retarded composites are achieved through physical blending, in situ polymerization, or electrostatic spinning. Surface strategies, inclusive of multi-layer design, fibre coating, and surface blending with other fabrics, further contribute to augmenting the flame retardancy of nylon 6 fibres [33].

6.2 Intrinsic Flame-Retarded Nylon 6 Molecules:

The challenge of achieving uniform dispersion of flame retardants in the nylon 6 matrix, attributed to compatibility issues with small-molecule flame retardants, has prompted researchers to incorporate flame-retardant effects through co-polymerization of reactive monomers. In designing and selecting reactive flame retardants, it is crucial to ensure their ability to participate in the polymerization reaction of caprolactam, facilitating homogeneous dispersion. Reactive flame retardants for nylon 6 fibres often involve organic phosphonic acid or phosphonic acid derivatives due to their efficacy in achieving flame retardancy at low loading levels. Through copolymerization with caprolactam, the carboxyl groups of these compounds introduce phosphorus-containing functionalities into nylon 6 molecules, thereby imparting flame-retardant properties [34].

Lu et al. synthesised an intrinsically flame-retarded nylon 6, termed Thermoplastic Polyamide Elastomer (TPAE). They introduced phosphorus-containing groups, specifically 9,10-dihydro-10-[2,3-di(hydroxyl carbonyl) propyl]-10-phosphaphenanthrene-10-oxide (DDP), into the macromolecular chains through P-C covalent bonds. For copolymerization, DDP was first combined with decamethylene diamine to form a DDP salt solution, and the molecular structure was terminated with amino and carboxyl groups. On polymerization with nylon monomer, caprolactam, which is ring-opening, DPP was successfully introduced into nylon 6 molecular chains. The TPAE molecule comprises three segments: a hard polyamide (PA6) segment, a soft polyethylene glycol (PEG) segment, and DDP as the flame-retardant component. By precisely controlling the contents and distribution of these segments during synthesis, the properties of TPAEs could be effectively regulated [35].

Thus by introducing DDP, a phosphorus-containing group, into the P-C covalent bonds, an inherently flame retardant nylon 6 fibre was synthesised with the Limiting Oxygen Index above 35% The elements of C, O, P, and N were evenly distributed in the synthesised fibres, and no obvious structural defects were observed. With an add-on of 5% weight of DDP, the LOI value of fibres was raised to 28.4%. However, these results are not deemed as satisfactory, as copolymerisation with the monomer caprolactam possesses process challenges. Hence, for the quality of results this produces, this technique is extremely expensive.

6.3 Surface Strategy:

Inorganic flame retardants like red phosphorus, MCA, and montmorillonite are commonly employed in flame-retarded nylon 6. However, their limited compatibility with nylon 6 results in poor dispersion during physical blending and long-term migration during use. This migration negatively impacts the overall performance of nylon 6 composite fibres. Notably, the substantial specific surface area of nylon 6 fibres/fabrics exacerbates flame retardant migration, leading to a gradual loss of flame retardancy. Consequently, various surface strategies have been implemented to safeguard the fibres/fabrics [34].

a) Core-shell `Structure: The figure shows the preparation process of nylon 6 fibres with a two-phase core–shell structure. The uniqueness of this design lies in the core–shell structure which is a nanofiber, with polar polymer nylon 6 as
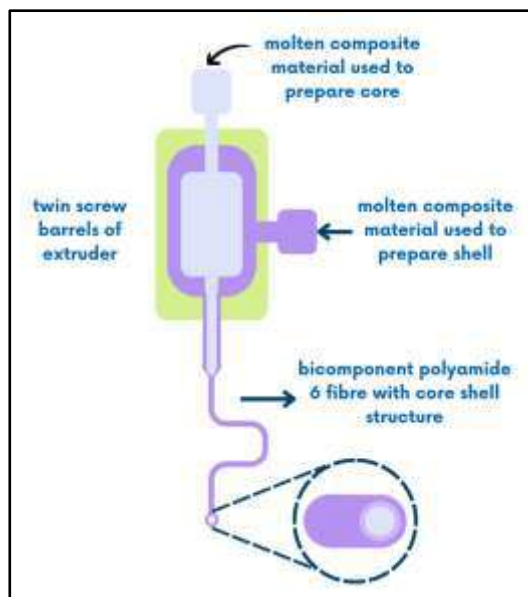
Fig 11. Production of bi-component core-shell structure

the outer shell and components like flame-retardant triphenyl phosphate (TPP) as the core. The core–shell structure design of flame-retarded nylon 6 fibres provides an innovative idea for low cost, excellent performance, and wide application. Horrocks et al. crafted bicomponent nylon 6 fibres containing aluminium diethylphosphonate (AlPi) and montmorillonite nanoclay (25A) at specific positions. These substances were dispersed individually or together within the core–shell structure. The study examined their impact on the mechanical properties, thermal degradation behaviour, and flame-retardant properties of the materials.

Upon combustion, a network of insulated silicates emerged on the polymer's montmorillonite surface. Enhanced flame-retardant effectiveness is observed when AlPi is positioned within the shell. Moreover, the migration of clay flakes to the fibre surface substantially restrains droplet behaviour. Optimal flame-retardancy performance is achieved when the material contains 10 weight% AlPi and 2 weight% clay as along with a high LOI (30%), it also is self extinguishing after ignition [36].

b) Surface coating or infiltration: To enhance flame retardancy and preserve mechanical properties in nylon 6 fibres, applying coatings with good water resistance is effective as it promotes charring and forms a stable insulation char layer. Alisa Šehić et al. applied a coating of vinyl trialkoxy silane modified with 9,10-dihydro-9-oxa-10-phosphaphenanthrene-10-oxide (DOPO-VTS) onto nylon 6 fibres using a sol–gel method. Through wetting, drying, and curing processes, the DOPO-VTS's silanol groups formed a nanostructured composite network on the fibres' surface, enhancing coating durability. Even at a high concentration (16%), the coating didn't significantly alter the surface of nylon 6 fibres and remained intact during washing. The DOPO-VTS molecular structure integrates organic phosphorus-containing flame-retardant groups and inorganic silicon-containing groups. Its flame-retardancy involves both condensed-phase and gas-phase processes. Phosphorus-containing groups accelerate nylon 6 decomposition, producing small caprolactam molecules. These groups synergize with silicon-containing groups. In another work by Aleksandra et al., DOPO derivatives were blended into nylon 6 instead. The sol–gel coating prepared in this study exhibited a greater reduction in heat release with a lower phosphorus content [37].

7. Polypropylene:

Polypropylene fabric is a nonwoven textile, i.e. it is made without use of techniques such as spinning or weaving. Polypropylene fabric is a textile made from propylene, which is a thermoplastic polymer commonly used in food packaging, plastic furniture, films, automotive parts, and medical devices. This plastic is a linear hydrocarbon polymer, and it is one of the most popular plastics due to its low cost and easy manufacturability.Due to the chemical constitution of the polymer it is easily flammable and so flame retardancy becomes an important requirement for polypropylene.Synthetic polypropylene (PP) in particular are sometimes more flammable than their natural counterparts and unlike them, shrink and melt (often yielding flaming melt drips). They are known to be difficult to fire retard.

7.1 Thermal Degradation Of Polypropylene & Mechanism Of Frs Employed:

Polypropylene exhibits high flammability, undergoing rapid combustion in air, characterised by a notably intense and clean flame. Due to its entirely aliphatic hydrocarbon structure, polypropylene lacks char residue during combustion. The degradation process in air is a single-step mechanism, predominantly involving random main-chain scission, leading to macromolecular main-chain fractures generating diverse free radicals. These free radicals subsequently undergo intramolecular or intermolecular hydrogen transfer reactions, contributing to the formation of various decomposition products.

Experimental findings from polypropylene thermal decomposition highlight the release of major gaseous products such as propylene, methane, ethylene, propane, and butane. With a self-ignition temperature of approximately 570° C, polypropylene exhibits a rapid decomposition rate in comparison to wood and other cellulosic materials. Notably, key chemical reactions influencing the combustion process occur in both the condensed and gas phases, imparting flame retardancy to the substrate [38].

7.2 Self-Reinforced Polypropylene Composites:

Self-reinforced composites (SRCs) represent a novel composite material category, featuring a polymer matrix reinforced with highly oriented polymer fibres or tapes

derived from the same polymer type. This self-reinforcement concept involves creating highly aligned molecular or supramolecular structures, enhancing mechanical properties compared to isotropic polymer matrices. The resulting high-performance polymer fibres, achieved through molecular orientation during spinning and drawing, offer advantages such as low density, cost-effectiveness, recyclability, and good interfacial bonding without surface treatment. Despite being entirely composed of highly flammable polymeric components, SRCs have found applications in fire-retardant priority fields. In the initial stages of burning, SRCs of polypropylene with reinforcing structures form a thick but loose heat-insulating foam, providing protection against combustion. The foam's heat protective efficiency is maintained until the degradation of the protective shield begins, indicated by a sharp increase in heat release rate when a significant amount of polypropylene (PP) enters the burning zone abruptly. Contrarily, plain-woven PP fabrics hinder the development of a highly expanded foam structure, leading to simultaneous shrinkage of interweaving fibres and intumescence of the flame-retarded matrix layers. This results in a more compact charred layer on the surface. The reduced peak heat release rates in multilayer plain-woven fabric-reinforced SRCs are attributed to factors such as reduced oxygen permeability, enhanced heat barrier capability, and increased strength of the compact char layer. The observed synergism between expanding and interlinked domains depends on optimising the ratio of expanding domains (flame retardant content) and the shrinking ability (degree of molecular orientation) [39].

7.3 Other Advancements In Flame Retardancy Of Polypropylene:

In addition to the aforementioned advancements, the field of flame retardancy in polypropylene has seen limited progress. A noteworthy development involves novel fire retardant formulations incorporating nanodispersed clays. Nanoclays are under scrutiny for their flame retardant properties when applied to polypropylene. Polypropylene incorporating nanoclays along with both halogenated and non-halogenated FRs, was evaluated for flammability through LOI and thermogravimetric analysis. Research indicates that a singular flame retardant is insufficient in effectively reducing polypropylene flammability while maintaining acceptable fibre properties. However, the study highlights the effectiveness of synergistic flame retardant chemical species at levels below 5wt %,. This emphasises the importance of maximising the dispersion of both clay and flame retardant.

Although providing a more fundamental exploration of the challenges in flame retarding polypropylene, this research contributes to a deeper understanding of the underlying scientific principles. Additionally, the utilisation of carbon nanotubes and halogen-based flame retardants has been explored but with limited success, warranting further investigation [40].

8. Conclusion:

Here is a summarised overview of the recent advancements in the field of flame retardancy of textiles discussed in Table 1.

In conclusion, the literature review underscores notable progress and the ongoing challenges in the realm of flame retardancy for textiles. While significant strides have been made, particularly in addressing the high flammability of cotton, which has garnered substantial attention due to its widespread commercial use, the advancement in this field for other textiles remains somewhat constrained.

The most optimum choice of synthesising flame retardant for cotton depends on factors such as the desired level of flame resistance, environmental considerations, and application requirements. Each formulation and advancement discussed offers unique advantages, and the choice should align with specific needs and priorities. While P based FRs offer the least toxicity and are easy to handle and are cost effective as well, FRs having multiple elements such as N, Si, B bring about synergistic effects which increase the overall FR performance. The nascent use of biological macromolecules for imparting flame retardancy, although a green solution, can only be produced in small quantities and face problems scaling up to industrial levels. Surprisingly enough, it is an economically viable option which introduces a promising dimension to the field, though further research and investigation are warranted to fully comprehend its potential applications in the textile industry. However a major challenge faced by all the mentioned FRs is durability with respect to washing fastness.

The shared combustion mechanisms of nylon and polyester have led to commonalities in flame retardant application techniques, showcasing a convergence in strategies for these widely used textile materials. Due to their cost-effectiveness, ready availability, environmental friendliness, and enhanced physical properties, nanoclays have supplanted traditional halogen-containing flame retardants. Nanoclay combinations hold great promise for advancing applications in aerospace, automotive, electronics, barriers, construction, and the environment. The production of intrinsic flame retardants for nylon 6 fibres traditionally involves copolymerization of flame retardants and caprolactam, leading to process challenges and increased costs. Presently, alternative processing techniques such as physical blending and melt spinning are employed, though they often result in subpar flame retardancy. A notable breakthrough comes in the form of a novel synthesis involving a core-shell structure, showcasing outstanding performance and even enhancing the fabric's mechanical properties. This dual-functional coating facilitates early decomposition of nylon 6, producing small caprolactam molecules, and forms a compact, adiabatic, and protective char layer during combustion. Consequently, it reduces molten drop formation, mitigates

:Table 1: Summarised overview of the discussed recent advancements in the field of flame retardancy of textiles

Sr. No.	Textile	Cotton	Polyester	Nylon	Polypropylene
1.	**Structural Composition**	Made up mostly (90%) of a macromolecule, cellulose, a natural fibre.	A synthetic polymer made up of at least 85% by weight of an ester of a dihydric alcohol & terephthalic acid	synthetic polymer with amide backbone arranged in a linear structure.	Polypropylene is a polymer whose monomer is propylene (C_3H_6)
2.	**Flammability With LOI**	Extremely flammable (LOI:18- 21%)	flammable (LOI:20-23%) Inherently flame retardant, difficult to ignite	more flammable than polyester (LOI:20-23%)	Extremely flammable (LOI:17-18%)
3.	**Discussed Recent Advances**	1. P & N based organic polymer FR [18,19] 2. P based & N,P based non polymer FR[22,23] 3. Hybrid FRs [24,25] 4. Biomacromolecular coating [16]	1. Casein Protein Treatment [28] 2. Nanoclays[29,30] 3. Copolymerization of P based compounds [31,32]	1. Intrinsic Flame-Retarded Nylon 6 Molecules [34,35] 2. Core-shell structure [34,36] 3. Surface coating or infiltration [37]	1. Self-Reinforced Polypropylene Composites [39] 2. Nanodispersed clays [40]
4.	**Other Notable Mentions**	Introducing Carbon Nanotubes, Graphene, Metal based nanoparticles	Addition of inorganic, metal based additives and composites.	1. Blending of fabrics for better FR performance 2. Approaching various nanocomposites	-
5.	**Problems Yet To Overcome**	1.Difficulty in scaling up biomolecular based FRs 2.Implementing sustainable FRs that have durability to several washing cycles	1. Melt drip phenomena not tackled 2. Neglected slightly due to it having inherent FR tendencies	Trying to achieve intrinsic flame retardancy with excellent drip resistance, processing performance, and mechanical properties through the design of new reactive FRs.	1.Best efficiency given by halogen based FRs. which are banned. 2.Mechanical properties of the polymer alter on adding FRs 3.Extensive investigation required as FRs in markets for this fibre is not sufficient.
6.	**Scope of Further Advancement**	Extremely high	High	High	Moderate

flammability, and prevents fire spread and secondary ignition.

Polypropylene continues to remain the most under-researched textile in the field of flame retardancy. The distinct combustion mechanism of polypyrene fabric introduces unique challenges, emphasising the need for careful consideration in balancing flame retardancy with mechanical properties. The only FRs imparting desirable flame retardancy properties are halogen-based FRs which are highly toxic in nature and have been rendered problematic due to their extreme toxicity and subsequent bans in many countries.The development of self-reinforced composites, initially aimed at enhancing mechanical strength, emerged as a byproduct with improved flame retardancy. The synthesis of a flame retardant complying entirely with regulations while maintaining low toxicity levels has proven challenging. Ongoing efforts focus on

designing scalable, environmentally friendly, and durable flame retardants for textiles. Nanoclays are being instigated for this fabric as well.

The global shift towards green chemistry principles has influenced the synthesis of flame retardant chemicals, with a focus on nanotechnology and nanochemistry. This innovative approach opens new avenues for creating effective and environmentally friendly flame retardants. The elemental composition, incorporating inorganic elements and compounds like phosphorus, nitrogen, halogens, and

silica, plays a crucial role in determining the flame retardancy of textiles. Conversely, the exploration of organic compounds for flame retardancy remains a comparatively underexplored avenue.

In essence, this literature review provides a comprehensive overview of recent advancements in flame retardancy for cotton, polyester, nylon, and polypropylene textiles, offering valuable insights for researchers, practitioners, and stakeholders in the continuous pursuit of enhancing fire safety in textiles across a multitude of industries.
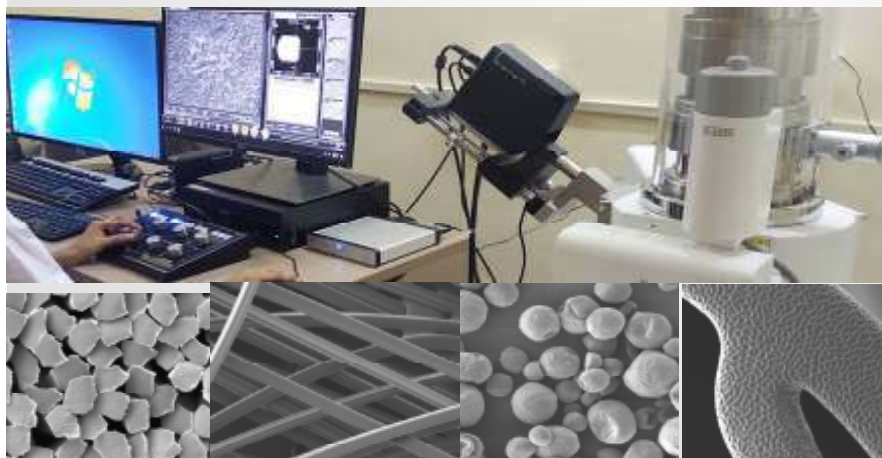
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