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FIRE BEHAVIOUR AND FLAME-RETARDANT MECHANISMS OF NATURAL FIBRE-REINFORCED COMPOSITES IN SUSTAINABLE BUILDING MATERIALS: A CASE STUDY IN GHANA

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ABSTRACT

Purpose: The global trend of implementing natural fibre-reinforced composites as sustainable building materials has led to a keen focus on their fire behaviour and flame-retardant processes. Understanding the mechanism by which these flame retardants work is crucial for optimising their use and achieving adequate fire protection.
Design/Methodology/Approach: This paper comprehensively reviews and highlights the fire behaviour of natural fibre-reinforced composites and how flame retardants can enhance their fire resistance. The study adopted a structured review strategy using electronic databases, including Scopus, Web of Science, ScienceDirect, and SpringLink. The 63 articles used were published between 2005 and 2024. This study used thematic analysis to examine recurring ideas and concepts within the texts. Data was coded using NVivo software to manage and categorise emerging themes.
Findings: However, the challenges of these materials are their inherent to fire. The findings underscore the importance of selecting appropriate flame retardants and optimising their concentrations to achieve the desired balance between fire safety and material performance.
Research Limitation: This study used fire-resistant materials and strategies to minimise the thermal impacts on natural fibre reinforced by composites as a sustainable building material in Ghana.
Practical implication: The insights gained from this research can inform future strategies for enhancing the fire performance of natural fibre-reinforced composites, contributing to safer and more sustainable construction practices.
Social Implication: This study will promote and highlight the prospects of using composite-reinforce natural fibres as an alternative building material, offering significant environmental benefits in Ghana and other developing countries.
Originality/ Value: This paper is designed to comprehensively analyse and review the thermal characteristics of natural fibre-reinforced composites.
Keywords: *Building. fire behaviour. flame retardant. natural fibre-reinforced composites. sustainability*

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INTRODUCTION

The global push for sustainable development has transformed various industries, including construction. There has been a burgeoning priority on using eco-friendly and renewable materials. These new materials are especially appealing because they are primarily derived from natural renewable resources, which helps to avert additional environmental stressors.

Economic and environmental concerns drive research into new materials for the automotive, furniture, packing, and construction sectors. In the pursuit of this advancement, the construction industry in Ghana is increasingly exploring eco-friendly materials that align with environmental and economic goals. This movement is not just a trend but a necessity.

The construction body must adopt sustainable practices with the increasing demand for housing and infrastructure and environmental challenges such as deforestation and waste management. One such approach is the utilisation of natural fibre-reinforced composites (NFRCs), which have unfolded as an auspicious alternative to conventional building materials, offering the benefits of renewable resources, reducing carbon footprint, and cost-effectiveness (El-Wafa, 2024). The NFRCs combine natural fibres with suitable polymer matrices to create composite materials that offer advantages over traditional materials (Kamarudin et al., 2022). They are not only sustainable but also possess enhanced mechanical properties. Natural fibres, namely sisal, jute, bamboo, kenaf, and coir, are abundantly available in Ghana. These fibres are lightweight, cost-effective, and have a lower environmental impact owing to their natural decay nature, tensile strength and renewability.

The natural fibres can be categorised based on their origin into bast-fibres, including jute, flax, hemp, leaf fibres (sisal), and seed fibres (cotton, coir). Plant fibres, widely available in tropical locations, and annual growth native crops are examples of raw material sources (Kozłowski, Mackiewicz-Talarczyk, & Barriga-Bedoya, 2020; Lee, 2019). The use of NFRCs conforms to Ghana's commitment to sustainable development and its efforts to reduce reliance on non-renewable resources. The construction industry in Ghana, like in many developing countries, is heavily dependent on conventional materials such as concrete, steel, and synthetic materials. Presently, rural and urban areas of Ghana are grappling with the challenge of addressing the two main elements: cost-effective housing and other infrastructure. These limitations have been due to the high cost of imported buildings and finishing materials. For the past decades, Ghana has adopted an open-market policy related to importing building materials. The policy adopted has led to an over-reliance or dependence on imported materials in the construction of buildings. The escalation of import prices of these materials is due to the exchange rate, which has had a tremendous effect on the cost of housing and its affordability.

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Despite the numerous advantages of NFRCs, their flammability or thermal stability is a challenge that leads to fire safety risks. Even though fire is inevitable, natural fibre is flammable when subjected to high temperatures. Fire safety is one of the basic requirements for preserving lives and property because fire causes loss of lives and property and damages (Prabhakar, Shah & Song 2015). It has been observed that plant or agri-based natural fibres have to be processed under a lower temperature due to their poor heat stability, which shortens their life span of usage. Hence, various fibre or polymer matrix treatments have been reported to intensify the interfacial bonding between fibres and polymers and the resulting composite thermal performance (Eyupoglu, 2020).

To mitigate these problems, fire-resistance materials have to be incorporated into the natural fibre-reinforced polymer matrix to lessen the flame spread. Hence, a mechanism must impede fire propagation to save the building facade and improve the thermal stability of the NFRC material application. Therefore, more investigation is required into NFRC's flame retardant method and mechanism because of their unsatisfactory flammability properties (Muralidharan, Subramanian, Rajamanickam, Krishnasamy, Thiagamani & Khan 2024). Scientists are developing novel techniques that will enable NFRC to withstand fire. There is currently little research on the flammability and flame retardant of NFRCs. Subsequently, research has indicated that adding fire retardant elements such as phosphorus (P), nitrogen (N), and halogen-based chemicals can improve the fire resistivity of natural fiber-reinforced polymer composites (NFRPC).

Although halogenated additives can stop flames from spreading, they also produce thick smoke and other combustion by-products that pose risks or harm the environment and contradict fire safety (Jefferson, Sain, Ramakrishna, Jawaid & Dhakal 2024). Gases including hydrogen chloride (HCL), hydrogen fluoride (HF), hydrogen cyanide (HCN), and carbon monoxide (CO) may be released from a burning composite in different amounts, depending on the polymer, type of chemical or fire-retardant reagent, and fir conditions (Andrew & Dhakal, 2022). Even at comparatively low quantities, some reagents are regarded as harmful. It is worth noting that fire retardants based on phosphorous are safer substitutes. Various fire tests are performed to determine the extent of their thermal degradation, including thermogravimetry analysis tests (TGA), micro-scale combustion calorimetry tests (MCC), or cone calorimetry etc. (Maksym, Prabhakar& Jung-il, 2022).

METHODOLOGY

The review employed a systematic and integrative methodology to investigate the fire behaviour and flame retardant mechanisms of natural fibre-reinforced composites (NFRC), particularly in

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the context of sustainable building practices in Ghana. The approach was anchored on three interconnected phases: literature selection, thematic synthesis and contextual application.

Literature Selection and Inclusion Criteria

The study adopted a structured reviewed strategy using electronic databases including Scopus, Web of Science, ScienceDirect, and SpringLink. Grey literature and non-peer-reviewed soureces were excluded unless they provided substantial emperical or mechanistic insight. Keywords such as *"natural fibre composites," "fire behaviour," "flame retardant," "thermal degradation," and "natural fibre reinforced composites (NFRCs) in sustainable construction,"* were used to retrieve relevant peer-reviewed articles published between 2005 and 2024 to capture modern advances in sustainable construction materials and flame retardant technology. This interval reflects the rapid growth in research on natural composites and green building practices over the past two decades. Inclusion criteria required that studies: (1) presented original experimental or review data; (2) discussed thermal or combustion behaviour of NFRCs; (3) evaluated flame retardant mechanisms or treatments; and (4) were published in high-impact journals or indexed conference proceedings.

Thematic Categorisation and Analytical Framework

Selected articles (n=63) were thematically categorised into six domains: (i) chemical composition and structural properties of natural fibres; (ii) NFRCs manufacturing processes; (iii) thermal degradation and pyrolysis mechanisms; (iv) types and classifications of flame retardants; (v) fire retardant performance metrics; and (vi) building applications and contextual relevance to Ghana. A narrative synthesis approach was employed to identify patterns, contradictions, and emergent themes, following established protocols for engineering systematic reviews.

Case Contextualisation: Ghana as a case study

To contextualise findings, the study integrated region-specific data related to material available, housing demands, fire incidents, and construction regulations in Ghana. Field visits to selected construction sites and material testing laboratories in Cape Coast and Accra were conducted to verify local practices. Additionally, interviews were held with 12 civil engineers, architects, and fire safety officers to validate the feasibility of adopting NFRCs with enhanced fire performance in local infrastructure projects. This approach ensured that the review covered global knowledge on flame retardant of natural composites and highlighted implications and gaps relevant to sustainable buildings in Ghana.

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Evaluation of Flame Retardant Effectiveness

Secondary data on flame retardancy performance, such as limiting oxygen index (LOI), time to ignition (TTI), peak heat release rate (PHRR), and total smoke release (TSR), were extracted and compared across fibre types, treatments, and composite matrices. Studies employing standardised test methods like ISO 5660 (Cone Calorimetry), Thermogravinometry (TGA), Microscale Combustion Calorimetry, UL-94, and ASTM E1354 were prioritised. This study used thematic analysis to examine recurring ideas and concepts within the texts. Data was coded using NVivo software to manage and categorise emerging themes.

Ethical Considerations and Limitations

All data sources were duly cited, and intellectual property rights were respected. This study focused primarily on the technical aspects of fire retardancy in NFRCs and excluding economic cost-benefit analysis and life-cycle assessments, which are recommended for future research.

NATURAL FIBER REINFORCED COMPOSITES APPLICATION IN CONSTRUCTION

Like many developing countries, Ghana's construction enterprise/fields heavily depend on customary materials such as concrete, steel, and synthetic composites. However, these materials have significant environmental impacts, contributing to carbon emissions and resource depletion. There has been a shift toward using NFRCs in the building sector to address these challenges. The global construction and building industries are increasingly embracing sustainable practices, driving the adoption of eco-friendly and energy-efficient materials. Natural fibers are abundant in Ghana and have the potential to replace conventional materials. These materials offer not only sustainability but also affordability and accessibility. A massive prospective employment growth exists in the rural territory/sector if new applications for native, quickly growing plants can be discovered for high-value implementation in specific applications. These renewable and sustainable materials may replace more conventional resources, offering versatile applications in construction while aligning with the principles of green architecture. NFRCs are emerging for various applications in the construction field, depending on the load bearing and the environment. Natural fibre composites are composed of two components: the natural fibre, which serves as reinforcement, and the matrix material, which binds the fibres together and transfers loads (Gholampour & Ozbakkaloglu, 2020).

In composites, where glass fibers are typically utilised, natural fibers are starting to emerge as sustainable materials. Standard matrices, namely, thermosetting resins (such as epoxy or polyester) and thermoplastic polymers (such as polypropylene). Cementitious binders can also be used in building applications requiring rigidity. In concrete reinforcement, natural fibres are blended with

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cementitious material to improve crack resistance, toughness, and durability (Dadkhah & Tulliani, 2022). This approach also minimises shrinkage and thermal expansion, positioning NFRCs as a sustainable alternative to synthetic reinforcement. Beyond structural elements, pre-fabricated structures made from NFRCs are becoming increasingly common globally for portable buildings, sheds, and temporary shelters. These structures are quick to assemble, cost-effective, and environmentally sustainable, particularly in disaster-relief scenarios. The ability to tailor fibre-matrix combinations allows these composites to meet specific performance requirements for their application (Sarasini, 2023; De Vivo, 2021).

One of the most prominent applications of NFRCs is the wall and ceiling panels, flooring and cladding systems. These composites are widely used for interior and exterior surfaces due to their aesthetic appeal, thermal insulation traits, and low environmental footprint. The natural textures of the fibres add unique visual quality to the building. Similarly, roofing materials from NFRCs have gained popularity in regions prone to harsh weather. These materials boast a remarkable strength-to-weight proportion, excellent durability, and resistance to environmental degradation, making them ideal for sustainable roofing solutions. Bamboo is abundant Throughout the tropics and readily used as a building material. Bamboo is the fastest-growing plant with superior mechanical and physical qualities (Kaur & Kaushik, 2019). Bamboos are used for boards and sheets (BMB-Bamboo Mat Board, BMVC-Bamboo Mat Veneer Composites, etc.), roofing, beams, and other structural applications. Akinlabi, Anane-Fenin, and Akwada (2017) extensively studied the application of bamboo as a good prospect for sustainable building materials.

Despite their many benefits, NFRCs face particular challenges. Natural fibres are hydrophilic, which can lead to moisture absorption and reduced durability unless treated. Fire resistance is another concern, necessitating the function of flame-retardant additives that significantly ameliorate the fire properties of the composite materials (Felix Sahayaraj, Sasi, Sathish, Gokulkumar, Jenish, & Makeshkumar, 2024). Additionally, variations within the quality of natural fibres can impact the performance consistency of the composites.

Composition and Structural Application

The primary determinants or the principal elements of natural fibres are the amount of hemicellulose, cellulose, and lignin, and some amount of pectin is present, which differ among fibres, others depending on the particular kind of fibre. Growing and harvesting conditions may also have an impact on this variation. Naturally occurring fibres have a complex cell structure and chemical makeup. The mechanical attributes or qualities of the fibre are influenced by chemical composition, amorphous content, and crystalline packing order. The semicrystalline polymer cellulose gives natural fibres hydrophilic properties (Ali, Shaker, Nawab, Jabbar, Hussain, Militky

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& Baheti, 2018). Hemicellulose, a completely amorphous polymer, contains micro-molecular weight compared to cellulose. Hemicellulose is moderately soluble in both water and alkaline mixtures owing to its anamorphous nature. Likewise, with hemicellulose and cellulose, pectin is a polysaccharide that holds the fibre firmly together (Gawkowska, Cybulska & Zdunek, 2018). Unlike hemicellulose, lignin is an anamorphous polymer mainly composed of aromatics and has minimal effects on water absorption. Table 1 summarises the chemical components of a few natural fibres.

Table 1: Chemical constituents of selected natural fibres (NFs)

Fibers Type	Hemicellulose content (wt.%)	Cellulose content (wt.%)	Lignin content (wt. %)
Bamboo	13	74	10
Flax	18.6- 20.6	71.0	2.2
Jute	13-20	61-72	12-13
Sisal	10-14	67-79.9	8-11
Hemp	17.9-22.4	70.2-74.4	3.7-5.7
Ramie	17.9-22.4	68.6-76.2	0.6-0,7
Cotton	5.7	0.7-1.6	82.7

Source: Baby, Jose, Aravindkumar, & Thomas 2021).

Natural fibres (NFs) can be chemically treated to modify their mechanical, physical and thermal performance. Production of natural fibre into boards undergoes various processes, and the natural fibre is chemically treated to manufacture products (Ouarhim, Zari & Bouhfid, 2019). Manufacturing NFRCs involves a combination of natural fibres, which act as reinforcements, and matrix material (typically thermosetting or thermoplastic polymers). The manufacturing process is crucial as it determines the composite's properties, including its strength, durability, and resistance to environmental factors.

To overcome challenges such as poor fibre-matrix adhesion and high moisture content in natural fibres, several pre-treatment methods are used, including alkali treatment and surface modification (Ramachandran, Mavinkere, Kushvaha, Khan, Seingchin & Dhakal, 2022). These treatments enhance the resulting composite's bonding, durability, and mechanical properties. Standard processes are hand lay-ups, where the natural fibres are laid in a mould. Resin is applied with a brush, roller, or spray (David & Naidu, 2017). Figure 1 explains the manufacturing processes of the natural fiber-reinforced composite.

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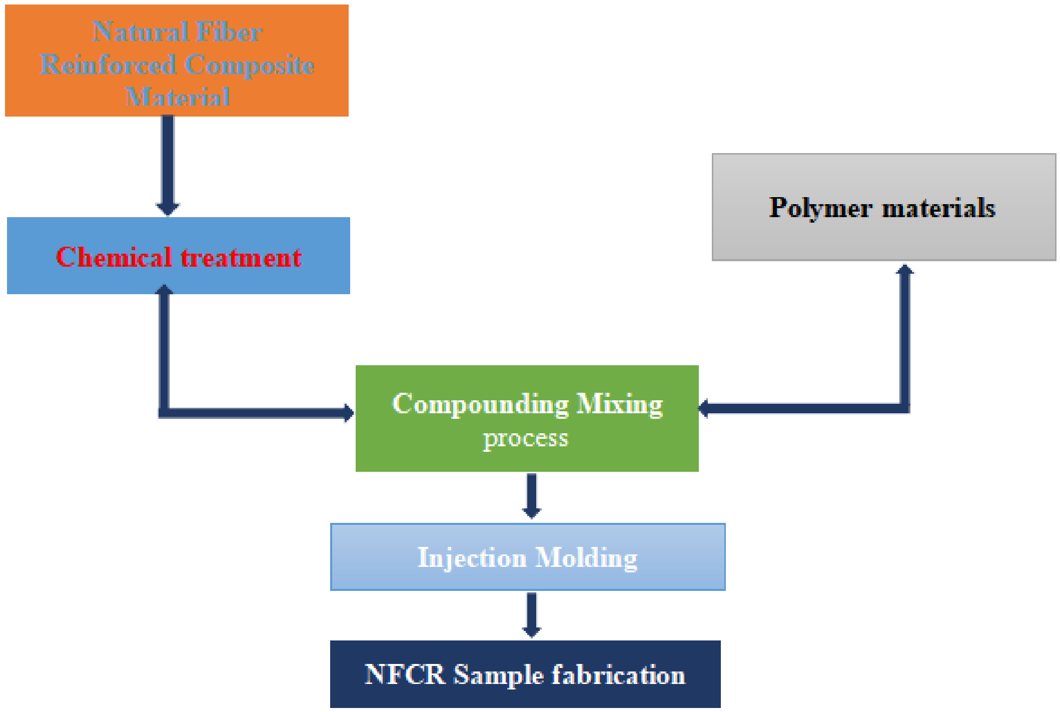

Figure 1: Manufacturing process of NFRC

Layers are stacked and compacted to remove air bubbles, and the composite is cured at room temperature or with the required heat. Another method is compression moulding involves a pre-impregnated natural fibre (with resin) or a dry fibre mat with liquid resin placed in a heated mould. High pressure and heat are applied to shape and cure the composite. With the vacuum bagging process, natural fibre and resin are layered and sealed with a vacuum bag. Air is removed to ensure distribution and minimise voids. Curing can occur at room temperature or with controlled heat. In Injection moulding, a thermosetting resin is mixed with the natural fibre, melted and injected into a mould to form the composite. In the extrusion process, the resin is fed into an extruder, and the composite is heated, mixed, and extruded through a die (Karaduman& Karaduman, 2021; Batra & Bali, 2024).

Mechanical Properties

Natural fibres possess unique mechanical properties that make them suitable for reinforcement in composite structures. However, depending on the fibre's chemical morphology, the age, tensile strength and modulus of elasticity are the key parameters for construction applications. Although generally weaker than synthetic fibres like glass or carbon, natural fibres are significantly lighter

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and offer adequate strength for non-load bearing and light structure applications. Studies show that natural fibre composites exhibit good specific strength (strength-to-weight ratio), which makes them competitive with traditional materials (Suriani, Ilyas, Zuhri, Khalina, Sultan, Sapuan & Sharma, 2021). Flax fibres, for instance, are known for their stiffness and are used in applications requiring high strength and dimensional stability. Jute and sisal fibres are commonly used in composite materials for construction elements such as panels, partitions, and roofing.

Many studies have been done on the mechanical properties of the NFRCs (Tyagi, Gupta, Mukhija, Bhandari, Meena & Meena, 2024; Oyeniran & Ismail, 2021). Research by Alavudeen, Thiruchitrambalam, Venkateshwaran, Elayaperumal, and Athijayamani (2011) examined the mechanical properties of a blended fibre combination of bananas and kenaf. Particularly, when this fibre combination was made, the tensile strength of the constructed banana-kenaf fibre combination was increased. The hybrid composites exhibit excellent tensile, flexibility, and impact strength compared to the individual fibre. Coir and scrap rubber wood are combined to create coir-ply boards with oriented jute as the face veneer. About 45. 9 % of the fibre in coir is lignin, compared to 38.8 -39 percent in teak wood. As a result, it has a higher tensile strength and is more resilient to rot than teak wood in both dry and wet situations. Coirply boards can replace other medium-density fibre boards (MDF).

Mechanical properties were examined by Sawpan, Pickering, and Fernyhough (2012), using saline, including alkaline treatments, and unsaturated polyester and hemp reinforcing with polylactide,e which is PLA fibre composites. The findings show that all processed fibre composites had a higher bending capacity than the 20 percent (20%) and 30 percent (30%) fibre loads and the quantity of untreated fibre composites. With alkaline-treated fibre, the composites had the maximum flexural strength at all fibre loads when compared to saline-treated and alkaline-treated fibre composites. Research conducted by Hiremath, Reddy, Mutra, Sajeev, Dhilipkumar, and Naveen (2024) observed that using 0.75 wt % graphene nanoparticles increases the shear strength by 34. 73 percent compared to the neat epoxy adhesive to produce flat joggle composite joints.

FIRE BEHAVIOUR OF NATURAL FIBRE REINFORCED COMPOSITES: AN INSIGHT INTO SUSTAINABLE SOLUTIONS

NFRCs have gained significant attention as sustainable alternatives to synthetic materials, especially in applications like construction and building materials, automotive components, and other furniture products. These composites combine natural fibres such as jute, bamboo, sisal, coconut coir, and hemp with polymer matrices to create lightweight, eco-friendly, and cost-effective materials. However, their fire behaviour remains a critical challenge in achieving widespread adoption, particularly in fire-sensitive applications. Despite the many advantages of

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NFRCs, their application in the construction industry is hindered by concerns related to fire safety, as natural fibres are inherently combustible. They can contribute to the material's flammability. This poses a significant objection, particularly in Ghana, where high temperatures and dry conditions can increase the risk of fire incidents. The fire behaviour of NFRCs is a critical factor determining their suitability for building construction, especially in urban areas where fire hazards can lead to catastrophic consequences. Therefore, studying thermal degradation is necessary to understand key parameters and combine appropriate flame retardant materials for maximum applications.

Natural Fibre Reinforced Composites Combustion and Pyrolysis

Before delving into the specific mechanisms of fire retardancy, it is important to understand the general fire behaviour of NFRCs. When the NFRC materials undergo a burning process, thermal decomposition occurs in the absence of oxygen, which is generally known as pyrolysis. Pyrolysis involves the breakdown of both natural fibre and the polymer matrix into gaseous, liquid, and solid products. The pyrolysis of NFRCs typically occurs in distinct stages, influenced by the composition of the natural fibres, polymer matrix, and any additives or flame retardants (Jefferson, Sain, Ramakrishna, Jawaid & Dhakal 2024).

Dorez, FErry, Sonnier, Taguet, and Lopez-Cuesta (2014) studied the effect of the three chemical constituents of selected natural fibres. They examine how cellulose, hemicellulose, and lignin affect the pyrolysis and burning of natural fibres, including coir, cotton linter, flax, hemp, sugar cane, bamboo, and flax. Char yield, adequate heat of combustion, activation energy of combustion, and carbon monoxide/carbon dioxide ratio during the cone calorimeter test are some of the indicators chosen to investigate the relationships between chemical composition. A relationship between these parameters and the lignin content was discovered in a wide range of compositions. Substantial amounts of lignin in natural fibres have low carbon monoxide/carbon dioxide ratios, high char yields, high adequate heat of combustion, and high activation energy. However, a specific behaviour was noted at low lignin/cellulose ratios. When there is a high cellulose content and a low lignin concentration, the latter's degradation pathway is impacted, resulting in charring and incomplete combustion of these fibres, which reduces their contribution to the heat generated.

As indicated earlier, the pyrolysis of NFRCs typically occurs in distinct stages, influenced by the composition of the natural fibres, polymer matrix, and any additives or flame retardants. At the onset of the burning process, there is a moisture removal (drying stage) at about 150 ^{o}C where the water within the NFRC materials escapes. The chemical constituent of the natural fibre and the polymer composites begin to change; this stage involves physical dehydration, which prepares the material for thermal decomposition and any other matter which impedes efficient pyrolysis. The primary components of the NFRCs decompose between the temperatures of 200 -400 ^{o} C.

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Hemicellulose degrades first around the temperature range of 200 to 300 ^{o}C due to its amouphous structure and low thermal stability. At this stage, gases such as acetic acid, carbon dioxide (CO_2) and carbon monoxide (CO) are produced. Cellulose degrades at a temperature range of 280-350 ^{o} C via pyrolytic cleavage of its glycosidic bonds. Major products, including levoglucosan, char, tar, and flammable gases, are released. Lignin degrades slowly across a broad temperature range, 250-500 ^{o}C, forming aromatic compounds, char, and gases like methane. Lignin contributes more to char formation than cellulose or hemicellulose (Madyaratri, Ridho, Aristri, Lubis, Iswanto, Nawawi & Fatriasari, 2022; Jagadeesh, Puttegowda, Boonyasopon, Rangappa, Khan & Siengchin, 2022).

Likewise, Garriba, Jailani and Pandian (2024) conducted a thermal assessment on Mariscul ligalus; the decomposition process revealed three stages with a first mass loss rate of 10% between the temperatures of 25 to 270 ^{o} C. The second phase, with a mass loss rate of 65% around the temperatures of 270 and 440 o C. Decomposition of the polymer matrix undergoes pyrolysis alongside the fibres. Polymers such as thermoset materials break down through the scission of cross-linked structures, forming char and volatile compounds. Here, the decomposition depends on the polymer type; for instance, epoxy resin releases aromatic hydrocarbons. Thermoplastics degrade via depolymerisation, producing hydrocarbons, CO, and other volatile products. Some quantum of studies have been conducted through flammability tests to obtain the characteristics of the natural fibre. Galaska, Horrocks, and Morgan (2017) evaluated natural fibres' mass loss and heat release rates using a microscale combustion calorimeter. They found that sodium salts on the fibre surfaces likely contributed to the minimal impact of lignin constituents on the heat release rate. The substantial crystallinity of fibres is responsible for the significant amount of levoglucosan produced during thermal breakdown, raising the flammability.

The flammability studies of a reinforced composite of several natural fibres were studied by Kozłowski and Władyka-Przybylak (2008). Particularly, hemp and flax used as reinforced for composite revealed that the heat release rate was lower than that of the corresponding samples. Helwig and Paukszta, (2000), conducted a further study on the flammability of PP composites with different flax fibre contents of 12.5, 20, 30, and 40 percent accordingly. Fire experiment using cone calorimetry disclosed that at 12.5 weight percent of flax fibre capacity, the peak heat release rate was 35%, which indicates a lower value than that of neat PP. They also discovered that flax fibre volume of 30% and higher resulted in a lower mass loss rate and heat release rate of the flax fibre/PP composites. Hence, the burning time of the flax fibre reinforced was reduced.

Char formation and secondary reactions occur between 400 and 600 ^{o}C. At this stage, most of the volatile components have been released. The remaining carbonaceous residue, mainly char, undergoes secondary pyrolysis, leading to further weight loss. Any inorganic compounds, such as flame retardants or fillers, remain as ash at about 600 ^{o} C. Residual ash may contain oxides and other thermally stable compounds. Figure 2 indicates the stages of thermal decomposition of a

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material, showing a graph of temperature against time for various stages (Chen, Cen, Zhuang, Gan, Zhou, Zhang & Zhang, 2022; Shama, Wooten, Baliga, Lin, Chan & Hajaligol, 2004; Tian, Xu, Jing, Liu & Tian, 2021).

Garriba and Jailani (2023) performed an experiment on Mariscus ligularia natural fibre employing thermogravimetry analysis (TGA) to determine its thermal properties. It was observed that at 258 degrees Celsius, the natural fibre Mariscus ligularia is thermally stable, making it a good candidate for reinforcing composite material. Figure 2 portrays the stages of material thermal decomposition.

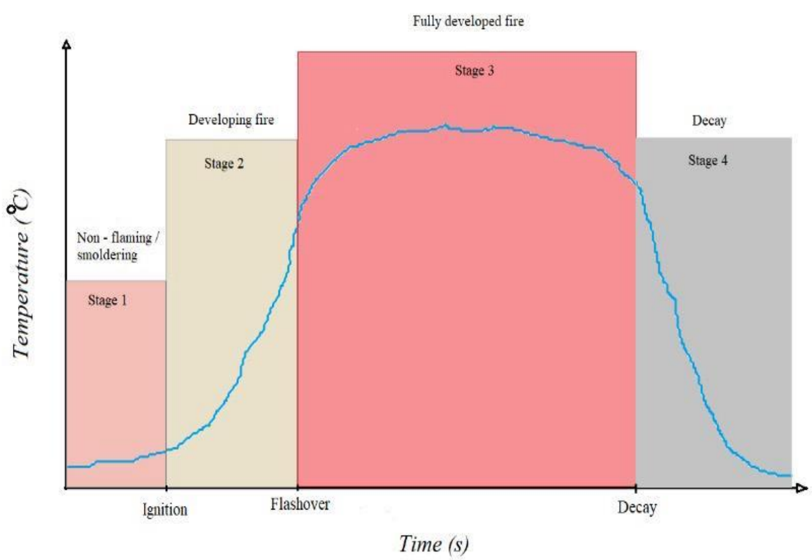

Figure 2. Stages of fire behaviour of a material

Ignition: Natural fibres, being organic, are prone to ignition at relatively low temperatures compared to synthetic fibres. The polymer matrix can also contribute to the early stages of combustion. The ignition time of NFRCs typically ignites faster than synthetic composites due to the high flammability characteristics.

Flame Spread: Once ignited, the fire can spread quickly along the surface of the composite, driven by the combustion of the natural fibres and the volatile gases released from the matrix.

Heat Release: The heat released during combustion can further degrade the composite, leading to a self-sustaining fire. Natural fibers generally exhibit a higher heat release rate (HRR) than other synthetic polymers.

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Smoke and Toxic Gases: Combustion of the matrix and fibres can produce smoke and toxic gases, posing additional hazards. Figure 3 shows the burning processes of the NFRCs.

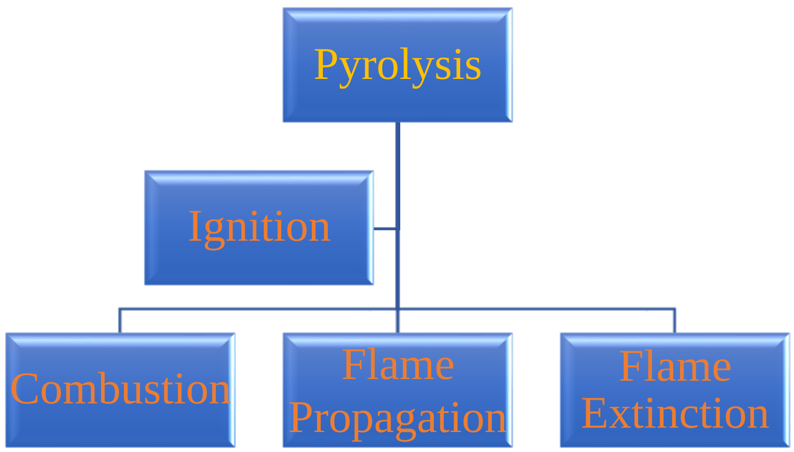

Figure 3: Burning processes of natural fibres

Thermal Degradation Process of NFRCs

The thermal degradation of NFRCs is a multi-stage and complex process involving the decomposition of natural fibre, the polymer matrix, and any additives. This process is influenced by many factors, such as the type of fibre, the matrix, and the flame retardants used in the composite. For example, fibres with higher lignin content (e.g., coir) form more char and offer better thermal stability than fibres with high cellulose content, like jute. The type of polymer matrix using thermoset resins produces more char, while thermoplastics release more flammable gases. Mineral-based flame retardant agent increases thermal stability by absorbing heat and releasing non-flammable gases. Additionally, intumscent systems also enhance the protective char layer. The fiber-matrix interface has a strong bond between fiber and matrix which delays degradation and enhances structural integrity during heating.

Combustibility of Natural Fibre Composites

Natural fibres typically comprise cellulose, hemicellulose, and lignin with some pectin, an organic polymer with high flammability. These components degrade upon exposure to heat conditions, producing volatile gases or by-products that can sustain combustion. The decomposition mainly occurs in three stages. Dehydration occurs at 100 to 200 degrees celsius, where moisture dissipates

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from the fibres, delaying ignition. In active pyrolysis between the temperatures of 200 and 400 o C, cellulose decomposes, releasing combustible gases, including carbon dioxide, methane, and hydrogen (D'Aciemo, 2021). At the next stage, lignin degrades, leaving a carbonaceous residue where char is formed that can act as a protective layer. Some research has been conducted to ascertain the combustibility of the NFRCs (Hiremath, Reddy, Mutra, Sajeev, Dhilipkumar & Naveen, 2024; Kumar, Manna& Dang, 2022).

The fire behaviour of the natural fibre (NF) composites is still insufficient to meet the rigour standards for construction applications. Addressing fire performance issues is crucial to ensuring public safety and adhering to safety regulations for NFRC material in the construction or building sector. It is important to remember that using fire retardants modifies the NFRC and interacts with the characteristics of the FR compounds to boost the fire resistance of the composite.

FLAME RETARDANCY OF NATURAL FIBER REINFORCED COMPOSITES (NFRCs)

Natural Fibre-Reinforced Composite Matrix with Fire-Resistant Agent

Flame retardancy is a crucial property of materials used in construction, transportation, and other safety-related applications. NFRCs inherently face fire resistance challenges due to the natural fibre's flammability and organic polymer matrices. However, various strategies have been developed to enhance the fire retardancy of the NFRC. Materials that exhibit fire retardation burn more slowly and are less prone to catch fire. Fire resistance is essential to lowering flammability and adhering to stringent requirements since natural fibre and polymer-based composites ignite readily above the ignition temperature of their constituents and continue to burn when exposed to heat and oxygen. Stopping or hindering the chain-breaking processes in the combustion process can help materials resist fire. Additionally, lowering the flammability of the fibre reinforcement, polymer matrix, or composite itself can increase the fire retardancy of the composite (Shen, Liang, Lin, Lin, Yu & Wang, 2021). In composites, flame retardant chemical agents can be added in two forms: reactive and additive. During the production processes, the additive can be incorporated into the composite to form one whole unit and act as a barrier preventing further spread of fire. The additives kind of fire retardants include organic, mineral fillers, hybrids, and other chemical components. Conversely, the geometry of polymers can be chemically altered by employing the reactive flame retardant component. This process changes the polymer structure and the functional units (Liu, Zhao & Wang, 2022).

Fire Resistance Compounds used for NFRCs

When selecting environmentally friendly flame retardants (FRs) for natural fibre-reinforced composites (NFRCs) in building applications, the focus is on materials that are non-toxic, biodegradable, and free from halogens (chlorine and bromine). These retardants should also

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complement the mechanical properties of NFRCs. Below are several types of eco-friendly flame retardants suitable for NFRCs:

Halogenated compounds

When exposed to heat or flames, halogenated compounds release halogen radicals (e.g., bromine or chlorine radicals (Sabet, 2024). These radicals react with highly reactive free radicals in the flame, subsequently preventing volatile fuels from oxidising. They then interact with oxygen in the gas phase, lowering its concentration and effectively neutralising them thereby interrupting the chain reaction necessary for combustion as well as putting out the flame. Synergistic agents, including phosphorous and antimony compounds, help halogen radicals to regenerate, and the free radicals are extracted. With time, seeing the halogen elements' environmental effects and health risks, there was a significant concern, and hence, halogen-free compounds were adopted (Shama, Agarwal, Mathur, Singhal &Wadhwa, 2023).

Phosphorus base compounds

These are non-halogenated flame retardants derived from phosphorus-containing compounds (Huo, Song, Yu, Ran, Chevali, Liu & Wang, 2021). Phosphorus compounds work primarily in the condensed phase by promoting the formation of a stable, protective char layer on the material's surface. The char acts as a barrier, reducing heat transfer and releasing flammable gases. Some phosphorus-based retardants also function in the gas phase by releasing phosphoric acid, which scavenges free radicals (Shama, Agarwal, Mathur, Singhal &Wadhwa, 2023). .

Inorganic compounds

These include naturally occurring and synthetic mineral compounds. The most common examples are aluminum hydroxide (ATH) and magnesium hydroxide (MDH). When heated, these compounds decompose endothermically, absorbing heat and releasing water vapour (for ATH and MDH) or inert gases. This cools the material and dilutes the flammable gases around the flame. They are environmentally safer than halogen counterpart. It enhances char production, which improves thermal insulation and is also compatible with intumscent systems for coating (Shama, Agarwal, Mathur, Singhal & Wadhwa, 2023; Huo, Song, Yu, Ran, Chevali, Liu & Wang, 2021; Fatima, Naseer, Gilani, Aamir & Akhtar, 2023; Sauerwein, 2021).

Nitrogen compounds

Nitrogen-based flame retardants are gaining popularity due to their eco-friendliness and thermal stability. During a fire, these compounds decompose to release nitrogen gas. This inert gas reduces the availability of oxygen and flammable gases in the combustion zone, slowing down or

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extinguishing the fire. They are environmentally safe and non-toxic, showing excellent synergistic effects when combined with phosphorus-based retardant giving a high thermal stability (Lu, Feng, Zhang, Hong, Chen, Fan& Chen, 2021; Shama, Agarwal, Mathur, Singhal &Wadhwa, 2023; Huo, Song, Yu, Ran, Chevali, Liu & Wang, 2021).

Intumescent compounds

Intumescent flame retardants are systems designed to swell and form an insulating char layer when exposed to heat. These retardants typically consist of three components: Acid source (e.g., APP), which promotes dehydration and char manufacturing. Then the carbon source, for example, pentaerythritol, provides materials for char and blowing agents such as melamine which releases gases that cause the material to swell (Lu, Feng, Zhang, Hong, Chen, Fan& Chen, 2021)

Mineral compounds

These include clay minerals, silica, and carbon-based nanomaterials, such as carbon nanotubes (CNTs) and graphene oxide. These materials form a physical barrier on the surface, preventing heat and oxygen from reaching the flammable substrate. Some also act as heat sinks, reducing the temperature (Huo, Song, Yu, Ran, Chevali, Liu & Wang, 2021).

Bio -based compouds

These are derived from renewable materials such as lignin, chitosan, phytic acid, or starch, offering a sustainable alternative to synthetic flame retardants. Bio-based flame retardants typically promote char formation and reduce the release of flammable volatiles. They are environmentally sustainable and biodegradable (Sienkiewicz & Czub, 2020).

Hybride compounds

Hybrid systems combine multiple types of flame retardants to maximise performance by leveraging synergistic effects. The mechanisms depend on the components but typically include condensed-phase (char formation) and gas-phase (radical scavenging) actions. They are environmentally friendly, sustainable, and biodegradable. Hybrid systems combine multiple types of flame retardants to maximise performance by leveraging synergistic effects. The mechanisms depend on the components but typically include both condensed-phase (char formation) and gas-phase (radical scavenging) actions (Huo, Song, Yu, Ran, Chevali, Liu & Wang, 2021; Sienkiewicz & Czub, 2020).

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Coating with Flame Retardant Agents on NFRCs

Flame retardant coatings, also known as flame retardant spray, are noncombustible chemicals used in industrial, business, and home construction for some purposes, such as lowering the intensity of a flame, slowing its spread, and decreasing smoke production. Flame retardant coatings are one of the most tried-and-true and effective techniques for shielding a substrate from flame. High concentrations of the smoke gas phase with oxygen, lowering its concentration and putting out the flame, as do hydrochloric acid fumes (Feuchter, Poutch & Beard, 2023). One popular technique for shielding substrates from flame is insulation. Low heat conductivity, nonflammability, excellent adherence to the surface substrate, environmental durability, lightweight, wear resistance, thinness, and affordability are all desirable qualities in a coating (Sienkiewicz & Czub, 2020; Feuchter, Poutch & Beard, 2023).

Coatings that are flame retardant come in two varieties: intumescent and nonintumescent. Non-intumescent coatings, mostly architectural and decorative, contain flame-retardant chemicals that limit the spread of smoke and flame on flammable surfaces. Their ability to contribute to flame and smoke determines whether they are further categorised as class A, B, or C. The substrate and film thickness impact the rate of flame spread for these kinds of coatings (Agnihotri, Sheikh, Singh & Behera, 2024).

The Role of Flame Retardant Additives in the Polymer Matrix

The polymer matrix plays a significant role in enhancing fire resistance by incorporating additives. Inorganic flame retardant additives such as aluminum hydroxide ($AL(OH_3)$) and magnesium hydroxide ($Mg(OH)_2$) decompose endothermically under the temperature of 300 to 320 degrees celsius, releasing water vapour that cools the material and dilutes flammable gases. Using phosphorus-based retardant promotes the formation of a stable char layer while suppressing smoke production. Synergistic combinations are often employed to achieve enhanced flame retardancy. For example, magnesium hydroxide can be paired with antimony trioxide to improve char formation and reduce toxic emissions (Shen, Liang, Lin, Lin, Yu& Wang, 2021;) .

Fire Retardant Mechanisms in Natural Fiber-Reinforced Composites (NFRCs)

Fire retardancy in NFRCs relies on physical, chemical, and thermal strategies. The first line of defence against fire in NFRCs involves treating the surface of the natural fibre with fire retardant agents. This treatment works in several ways, including forming a barrier. Flame retardants such as boron-based compounds form a protective glassy layer upon heating, shielding the underlying

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material from direct flame exposure. Chemical cooling using phosphate and borate solution releases water vapour or non-flammable gases, cooling the surface and slowing the combustion process. Surface treatment with chemicals also reduces volatility and alters the fibre, lowering the production of volatile compounds that could be sustained in a flame. Figures 4 and 5 show the mechanism and effectiveness of flame retardants (Kim, Lee & Yoon, 2021; Mbamalu, Chioma & Epere, 2024; Vickers, Van Riessen & Rickard, 2015).

It can be foreseen that the use of NFRCs will increase in the future, especially in Ghana, if there is more understanding of its various applications, education of the public on the need for sustainable materials, and enactment of regulations to ensure implementation. According to a review study by Abdollahiparsa, Shahmirzaloo, Teuffel, and Blok (2023), NFRCs are also becoming more widely accepted by civil engineers as a good substitute for conventional materials for concrete reinforcement for load-supporting structural elements like building beams and bridge slabs.

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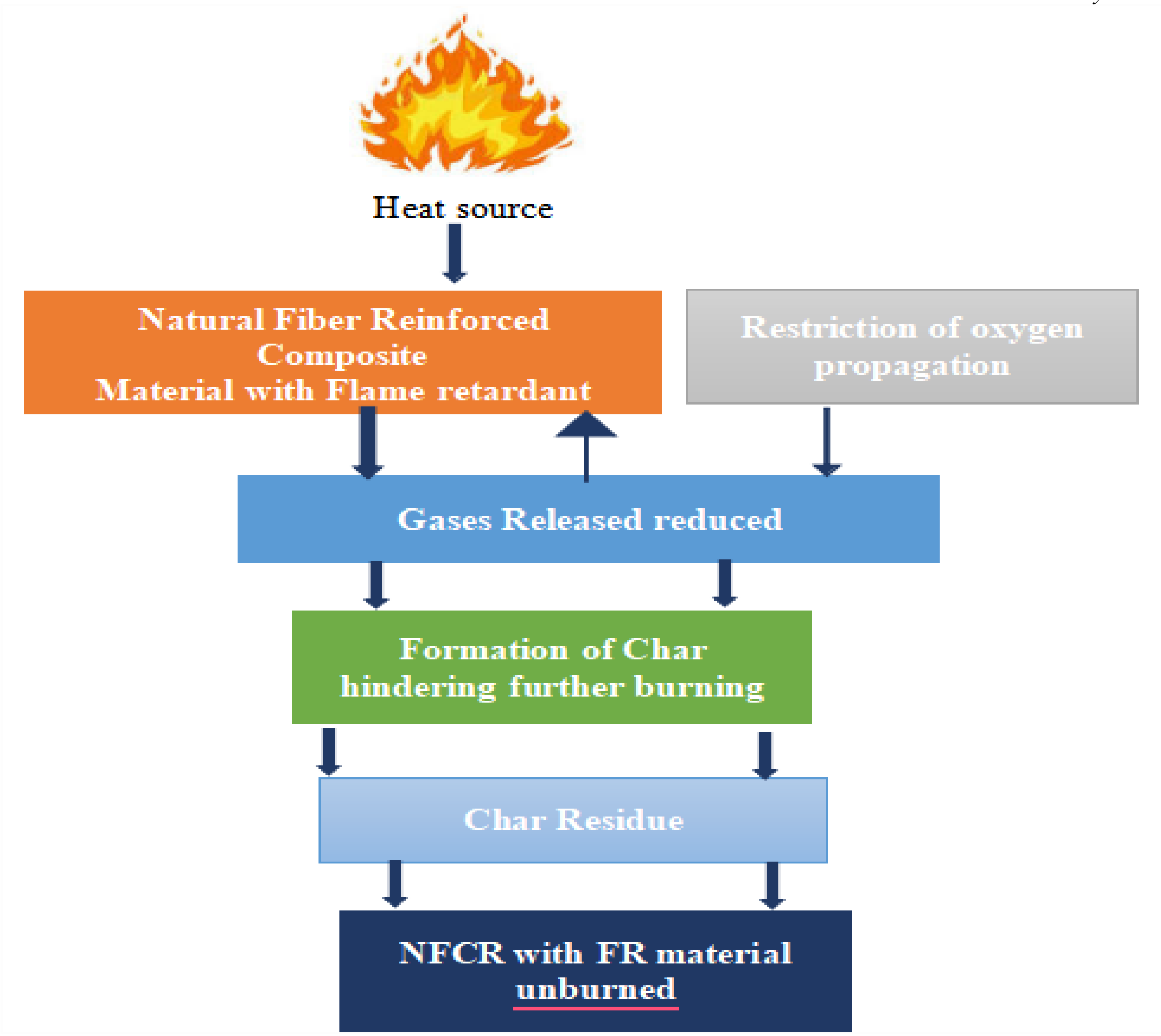

Figure 4. The mechanism and effectiveness of flame retardants.

The potency of flame retardants in NFRCs depends on their ability to hamper the combustion process. The main mechanisms by which flame retardants operate include:

Endothermic Decomposition

Mechanism: Certain flame retardants, particularly mineral-based ones like aluminum hydroxide (ATH) and magnesium hydroxide (MDH), decay endothermically when exposed to heat. This

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decomposition absorbs energy from the fire, reducing the composite's temperature and slackening the burning process (Viretto, Sonnier, Tanquet, Otazaghine, Ferry, Lopez-Cuesta & Lagreve, 2016).

Reaction: ATH decomposes to release water vapour at around 200°C, cooling the material and diluting combustible gases. This mechanism effectively delays ignition and reduces heat release but may require high loading levels, impacting the composite's mechanical properties.

Char Production/Generation

Mechanism: Char generation is a pivotal mechanism for fire retardancy in NFRCs. Certain flame retardants, particularly phosphorus-based ones, promote the formation of a char layer on the composite's surface during combustion. This char acts as an insulating barrier that protects the underlying material from heat and oxygen, slowing combustion (Tshai, 2020).

Reaction: Phosphorus compounds can promote dehydration and cross-linking reactions that lead to char formation. For example, ammonium polyphosphate (APP) decomposes to produce phosphoric acid, catalysing the polymer matrix's dehydration and forming a stable char layer. Char formation effectively reduces flame spread and heat release but must be well-controlled to ensure that the char layer is stable and does not crack or degrade during prolonged exposure to fire. Figures 4 and 5 describe the flame-retardant mechanisms of NFRCs (Tshai, 2020).

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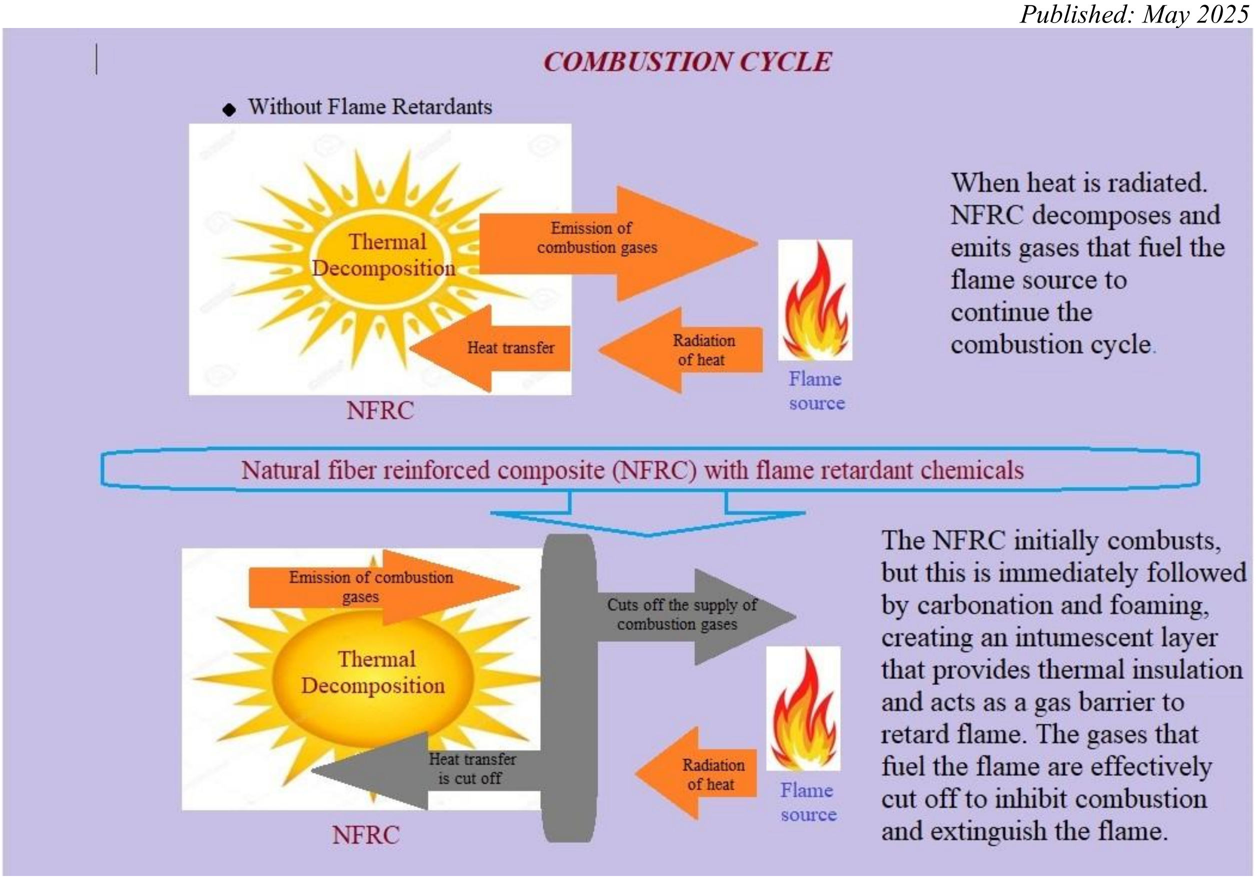

Figure 5. The mechanism and effectiveness of flame retardants (Source: IIyas, Sapuan, Asyraf, Dayana, Amelia, Rani & Razman, 2021; Maksym, Prabhakar & Jung-il, 2022).

CONCLUSION

NRFC has been considered a natural resource used extensively as a construction material, revered for its durability, lightweight, and very suitable for insulation and natural aesthetics. Nevertheless, with forests being degraded across the globe to meet our demands, it is appropriate to look towards and engage in an alternative solution, and NFRC is desirable as it can replace the properties of solid or traditional materials. The present review offers insight into the thermal deterioration of NFRCs and the substrate that causes flames to erupt. The best materials to utilise for flame retardant systems must be chosen carefully. To ensure successful implementation, it is also essential to thoroughly understand the specific concepts and operation of the intumescent flame-

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retardant solutions selected for a particular application. In addition, the choice of fillers, binders, and additives is crucial for the intumescent to significantly reduce the spread of flame.

Understanding the fire reactions and flame resistance mechanisms of Natural Fiber Reinforced Composites (NFRCs) is crucial to their successful application as sustainable building materials in Ghana. While NFRCs offer numerous advantages, such as environmental sustainability, cost-effectiveness, and the utilisation of locally available natural fibers like coconut coir and sisal, their inherent flammability poses significant safety concerns in construction. Addressing these challenges ensures their viability in modern, fire-resilient structures.

NFRCs are susceptible to fire due to the organic nature of natural fibres (NF), which can swiftly ignite and sustain combustion. However, advancements in flame retardant technologies provide solutions to intensify the fire performance of these materials. Techniques such as chemical treatments, intumescent coatings, and the integration of flame retardant additives have proven effective in reducing ignition potential, slowing flame spread, and promoting char formation, which acts as a defensive barrier. Phosphorus-based (P-based), nitrogen-based (N-based, and bio-based fire resistance are promising due to their environmental compatibility and synergistic effects with natural fibres.

In Ghana, where sustainability and resource efficiency are key priorities, improving the fire behaviour of NFRCs aligns with safety and environmental goals. By enhancing the flame resistance of NFRCs, the construction industry can more confidently adopt these materials, supporting the transition to greener building practices while reducing dependency on non-renewable resources. Additionally, local production and innovation in flame retardant systems can stimulate economic growth, particularly in rural communities, by creating value from agricultural byproducts.

Despite the progress in flame retardant research, challenges remain in balancing cost, environmental impact, and long-term performance. Researchers, engineers, and policymakers must collaborate to develop standardised solutions tailored to Ghana's specific environmental and construction needs. Education and awareness about the safe and effective use of NFRCs will further drive their adoption as reliable building materials. These environmentally friendly flame retardants ensure fire safety while maintaining the sustainable profile of NFRCs, making them highly worthy of building activities for both residential and commercial settings.

Addressing NFRCS' fire behaviour through advanced flame retardant mechanisms is a critical step in unlocking their full potential as sustainable building materials in Ghana. By combining innovation, sustainability, and safety, NFRCs can contribute significantly to a resilient, environmentally conscious, and economically vibrant construction sector.

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