EINDHOVEN UNIVERSITY OF TECHNOLOGY

Fire Behaviour of Wooden Facades with Bio-based Coatings

An Experimental Study on Spruce Wood treated with Kaumera, Xyhlo Biofinish and Mycelium-based Coatings

MSc Thesis

Fire Safety Engineering

Laura Dohmen

1887475

June 27th 2025

PEUTZ kaumera XYHLO BIOFINISH MNEXT

Author	L.L.J. Dohmen
Student ID	1887475
Course code	7S45M0
Course name	Graduation project research
Study load	45 ECTS
BPS Research group	Fire Safety Engineering
Track	Building Physics and Services
Department of University	Department of the Built Environment
	Eindhoven University of Technology
Graduation supervision committee	dr. ir. T.A.J. van Hooff
	dr. ir. R.P. Kramer
	ir. R.A.P. van Herpen, FIFireE
(External) supervisor:	ir. R.A.P. van Herpen, FIFireE
Date of defense	2025-07-04

ACKNOWLEDGEMENTS

First and foremost, I would like to express my sincere gratitude to my supervisor, Ruud van Herpen, for his guidance, critical insights and continuous support throughout this thesis. His expertise helped me navigate complex challenges and grow both academically and personally. Through his involvement, I had the opportunity to attend several conferences, where I met many new people and (future) colleagues. Experiences that truly enriched my journey.

In addition, I would like to thank my second reader, Rick Kramer, for reviewing my work, answering my questions and being present at the final colloquium. His time and involvement in this process were much appreciated.

A special word of thanks goes out to my colleagues at Peutz and the Fire Safety Laboratory, for the inspiring discussions, technical support and shared experiences. Whether it was adjusting sensors, preparing test panels or just examining yet another panel that didn't behave, their input sharpened my understanding and kept things interesting. Working with such a dedicated and knowledgeable team made the research process both insightful and enjoyable. I am excited and proud to be joining Peutz after graduation and look forward to continuing our collaboration.

I am also grateful to the companies Kaumera and Xyhlo Biofinish for their contribution to this research. Both provided coatings that were central to the experimental testing. Their willingness to collaborate, deliver materials on short notice and share insights into their products made it possible to complete the work within the planned schedule and scope.

During this thesis, I also had the opportunity to contribute to a broader academic publication. Part of the work on mycelium was conducted within the context of a scientific article, which I co-authored in collaboration with MNEXT – Avans University of Applied Sciences. The paper was presented at the 6th International Conference on Bio-Based Building Materials (ICBBM) in Rio de Janeiro. I am grateful for the opportunity to be part of this collaborative research effort and to share the findings at an international level.

Beyond the research itself, I am thankful to my friends for their patience, understanding and for always being just a message away when I needed a break from my screen. Their encouragement outside the academic setting made a real difference.

I would also like to thank Heather Burns, my building physics teacher during the Built Environment bachelor at Zuyd University of Applied Sciences in Heerlen. Her support extended far beyond the classroom. I am especially grateful for the coffee and catch-up moments, even after completing my bachelor's degree. Her advice has always been thoughtful and her belief in me has been a constant source of encouragement throughout every stage of my academic journey.

To my parents, I cannot thank you enough for your unconditional love, especially during the moments I doubted myself. You have always stood by me and your unwavering support has laid the foundation for everything I have achieved. I am deeply grateful for all the sacrifices you have made along the way and for the unwavering belief you have always had in me.

To my boyfriend, thank you for being my calm in the chaos. Your steady encouragement, patience and sense of humour have kept me grounded, even during the most stressful moments. You always knew when I needed a break and your well-timed reminders to sleep helped me through the toughest moments.

This thesis also includes a few lessons learned the hard way. Like the time I confidently calculated the exact number of screws needed for my panels… only to order completely the wrong amount of wood. It turns out that in fire safety, double-checking isn't just for evacuation plans, it also applies to your materials list!

Looking back, this journey toward my master's degree has been one of growth, learning and discovery. I'm incredibly grateful for the experiences, challenges and connections I've made along the way. This thesis marks the close of a memorable chapter and the start of an exciting new journey.

Thank you to all who walked this journey with me.

Laura Dohmen

Eindhoven, June 2025

HIGHLIGHTS

- Evaluation of the fire behaviour of spruce wooden facades treated with bio-based coatings: Kaumera, Xyhlo Biofinish and Mycelium.
- Assessment of key fire safety parameters including ignition probability, flame spread, material degradation, temperature development and mass loss.
- Application of two experimental methods: the radiant panel test (15 kW/m² radiant heat exposure) and the line burner test (30 kW/m² direct flame exposure).
- Coating thickness is a critical factor influencing ignition resistance, thermal protection and flame spread.
- Findings indicate that Kaumera and Xyhlo Biofinish improve fire resistance, particularly when applied in two or more layers.
- Quantitative comparison of produced and received surface heat flux confirms that triple-layer Kaumera and Xyhlo coatings produce less heat than they receive. This indicates that the panels do not release sufficient energy to maintain combustion once the external heat source is removed, resulting in self-extinguishing behaviour under radiant heat exposure.
- While Mycelium prevents flaming combustion, significant mass loss and detachment of the layer occur under heat exposure.
- Recognition that bio-based coatings can slow ignition and reduce fire spread, but are insufficient as a standalone alternative to conventional fire barriers.
- Highlighting the importance of hybrid facade systems, where bio-based coatings are combined with fire stops and other protective features to ensure adequate fire safety.
- Recommendation to further investigate emissions, environmental durability and standardized application techniques for bio-based coatings.

ABSTRACT

The construction industry is under pressure to reduce its environmental footprint, focusing on integrating renewable, bio-based materials. Derived from biological sources such as plants, fungi or waste streams, these materials offer lower carbon emissions and improved sustainability. However, their application in buildings raises fire safety concerns. Their combustibility remains a major obstacle to the widespread use of bio-based facade systems.

This research explores the potential of three bio-based coatings, namely Kaumera, Xyhlo Biofinish and Mycelium. The objective is to assess whether these coatings can lower the risk of ignition, slow down flame spread and improve resistance to material degradation. The scope of the study is restricted to spruce wooden facades exposed to realistic fire conditions.

Two experimental testing methods were used to evaluate fire behaviour. The radiant panel test exposed panels to constant radiant heat of 15 kW/m² to assess ignition resistance, temperature development and mass loss. The second method, the line burner test, exposed panels to direct flames with a heat intensity of 30 kW/m², simulating severe fire exposure along the facade. To investigate the influence of coating thickness, samples were prepared with up to three layers of bio-based coating.

The results demonstrate that Kaumera and Xyhlo Biofinish improve fire performance, especially when applied in two or three layers. These coatings delayed ignition, lowered surface temperatures and reduced material combustion compared to untreated spruce wood. Despite these improvements, they did not prevent complete burning, indicating that they cannot replace conventional fire protection on their own. The Mycelium-treated panels showed no flaming combustion under radiant heat and could potentially prevent fire from spreading into building interiors. However, high mass loss rates and detachment of the mycelium layer under heat exposure raise concerns about durability and reliability.

The study also revealed fire-related risks, such as the release of vapours and gases at high temperatures. Furthermore, structural factors like ventilated cavities behind facade panels contributed to accelerated vertical flame spread, highlighting the need for carefully designed facade systems.

In conclusion, bio-based coatings like Kaumera and Xyhlo Biofinish can contribute to fire safety by delaying ignition and slowing fire development, making them a promising addition to sustainable facade solutions. However, they are most effective when combined with conventional protective measures, such as fire stops and cavity barriers. Further research is needed to explore emissions, long-term environmental durability and standardized application techniques, ensuring that the environmental benefits of these coatings do not compromise building safety.

SAMENVATTING

De bouwsector staat voor de uitdaging om de milieu-impact te verlagen, met steeds meer aandacht voor hernieuwbare, bio-based materialen. Deze materialen, afkomstig van biologische bronnen zoals planten, schimmels en reststromen, kunnen de CO_2-uitstoot verminderen en bijdragen aan duurzamer bouwen. Hun toepassing in gebouwen brengt echter ook nieuwe risico's met zich mee, vooral op het gebied van brandveiligheid. De hoge brandbaarheid van bio-based materialen vormt een belangrijke drempel voor grootschalig gebruik in gevelsystemen.

Dit onderzoek richt zich op drie bio-based coatings: Kaumera, Xyhlo Biofinish en Mycelium. Het doel was om te onderzoeken in hoeverre deze coatings het risico op ontsteking en vlamverspreiding verlagen, en de materiaalaantasting van houten gevelbekleding verminderen. De studie richt zich specifiek op gevels van vurenhout, getest onder realistische brandomstandigheden.

Twee experimentele testmethoden zijn toegepast om het brandgedrag te analyseren. Bij de test met het stralingspaneel zijn de vurenhouten panelen gedurende 30 minuten blootgesteld aan een constante warmtestralingsflux van 15 kW/m². Hierbij werden het ontstekingsgedrag, de temperatuurontwikkeling en het massaverlies gemeten. Bij de tweede methode, de lijnbrander test, werden de vurenhouten panelen blootgesteld aan een directe vlam van 30 kW/m², waarmee zware brandbelasting en vlamverspreiding langs de gevel zijn nagebootst. Daarnaast is onderzocht wat het effect is van de laagdikte, door coatings in één, twee of drie lagen aan te brengen.

Uit de resultaten blijkt dat Kaumera en Xyhlo Biofinish de brandprestatie van vurenhout verbeteren, vooral bij toepassing van twee of drie lagen. Deze coatings vertraagden de ontsteking, verlaagden de oppervlaktetemperaturen en beperkten het materiaalverlies vergeleken met onbehandeld vurenhout. Desondanks konden ze volledige verbranding niet voorkomen, waardoor ze geen vervanging vormen voor conventionele brandwerende bescherming. Panelen behandeld met Mycelium vertoonden geen vlamvorming, wat kan helpen om verticale branduitbreiding naar het interieur van een gebouw te beperken. Tegelijkertijd leidde blootstelling aan hitte voor het loslaten van de mycelium laag en hiermee voor een aanzienlijk massaverlies, wat twijfels oproept over de duurzaamheid en betrouwbaarheid.

Het onderzoek bracht daarnaast ook aanvullende risico's aan het licht, zoals de uitstoot van dampen en gassen bij hoge temperaturen. Ook structurele factoren, zoals geventileerde spouwconstructies achter de gevelpanelen, leidden tot versnelde verticale vlamverspreiding. Dit benadrukt het belang van een doordacht gevelontwerp.

Concluderend kunnen bio-based coatings zoals Kaumera en Xyhlo Biofinish bijdragen aan het vertragen van brandontwikkeling en het verbeteren van de duurzaamheid van gevelsystemen. Hun toepassing is het meest effectief in combinatie met bestaande beschermingsmaatregelen, zoals brandstops of onbrandbare lagen. Aanvullend onderzoek naar emissies, duurzaamheid op de lange termijn en gestandaardiseerde applicatiemethoden is essentieel om bio-based materialen veilig en verantwoord toe te passen in de bouw, zonder in te leveren op brandveiligheid.

Table of Contents

LIST OF FIGURES

LIST OF TABLES

List of Abbreviations

Abbreviation	Definition
BPS	Building Physics and Services
CLT	Cross-laminated Timber
FSE	Fire Safety Engineering
GHG	Greenhouse Gas
HRR	Heat Release Rate
ISO	International Organization for Standardization
NIPV	Nederlands Instituut Publieke Veiligheid
RHR	Rate of Heat Release
SVHC	Substances of Very High Concern
TK	Thermocouple

1 INTRODUCTION

The construction industry is a major contributor to global carbon and nitrogen emissions, largely due to the use of conventional building materials such as concrete, steel and plastics, which are associated with high energy consumption and significant waste generation [1]. These materials rely heavily on non-renewable resources and often have limited potential for reuse or recycling, making them incompatible with the principles of a circular economy [2], [3].

In response to these challenges, bio-based materials have emerged as promising, more sustainable alternatives. Derived from renewable sources such as plants, microorganisms and organic waste streams, they typically have a lower embodied carbon footprint. Moreover, they are often biodegradable and can reduce dependency on fossil resources [4], [5]. Their use supports environmentally responsible construction practices and aligns with the growing demand for circularity and resource efficiency in the built environment [6].

However, the broader adoption of bio-based materials is hindered by a critical limitation: fire safety. Bio-based materials are inherently more prone to ignition and rapid flame spread compared to non-combustible alternatives like steel and concrete. Studies show that untreated wood and other lignocellulosic materials ignite quickly, contribute significantly to fire load and can produce high heat release rates [7]. This poses a major challenge for applications in buildings with strict fire safety requirements, such as residential buildings, healthcare facilities and public facilities.

To mitigate fire risks, the construction sector has traditionally relied on synthetic or mineral-based flame retardants. While effective in enhancing the reaction and resistance to fire, many of these treatments are fossil-based and may contain substances of very high concern (SVHC), raising concerns about their long-term environmental and health impacts [8], [9]. This underscores a key challenge in sustainable construction: balancing environmental performance with adequate fire safety.

This research explores the potential of bio-based fire retardant coatings to bridge that gap. Three promising innovations are central to this study: Kaumera, Xyhlo Biofinish and Mycelium. These materials offer significant environmental advantages, but their fire performance remains underexplored. This study investigates the fire behaviour of wood treated with these coatings, with the aim of evaluating their effectiveness as sustainable fire-retardant solutions.

1.1 PROBLEM DESCRIPTION AND RESEARCH QUESTIONS

Despite the growing use in research and experimental projects, the specific fire behaviour of the bio-based coatings mentioned above has not been systematically assessed. Without reliable data on ignition characteristics, fire spread potential or thermal resistance, it remains unclear whether these materials can be safely applied in real-world building contexts. The goal is to evaluate their performance under conditions representative of external fire exposure, contributing to a better understanding of both their risks and potential as sustainable fire protection solutions.

RESEARCH GOAL

The primary objective of this research is to assess the fire behaviour of spruce wood facades treated with Kaumera, Xyhlo Biofinish or Mycelium-based composites. The main focus will be on key fire performance parameters such as ignition, fire spread and mass loss. The findings will support the development of bio-based facade solutions that combine sustainability with fire safety.

Research Question

The central research question guiding this study is:

> **"How do the bio-based coatings Kaumera, Xyhlo Biofinish and Mycelium impact the fire risk and behaviour of spruce wooden facades under radiant heat and direct flame exposure?"**

Sub-Questions

1. What is the **probability of ignition** for the bio-based treated facades under radiant and direct flame exposure?
2. What is the **structural and thermal degradation** of these bio-based facade materials during external fire exposure, and what implications might this have for fire safety?
3. Which **parameters** influence horizontal and vertical fire spread across the treated facades?
4. What **fire risks** arise from the use of these coatings in facade applications?
5. How is the **balance between fire safety and sustainability** reflected in the experimental results?

1.2 Objectives and Relevance

This research aims to increase the understanding of fire behaviour in spruce wooden facades treated with the bio-based coatings Kaumera, Xyhlo Biofinish and Mycelium. The results will contribute to the development of facade solutions that combine environmental responsibility with reliable fire performance, facilitating broader adoption of bio-based materials in construction.

Scientific Relevance of the Research

This research addresses a key knowledge gap in the fire safety performance of bio-based coatings applied to external facades. Coatings such as Kaumera, Xyhlo Biofinish or Mycelium are increasingly explored for their potential to protect bio-based construction materials from environmental factors. However, their fire behaviour remains underexplored. By experimentally assessing their performance, this study contributes to the safe integration of bio-based coatings in buildings and supports progress toward Sustainable Development Goal 11: Sustainable Cities and Communities [10].

Figure 1: United Nation's Sustainable Development Goal 11 [10]

BPS Relevance of the Research

The study provides Building Physics and Services (BPS) engineers with valuable data on the fire response of bio-based facade systems. These insights support the design of safe, sustainable building envelopes and help integrate new materials into practice without compromising fire performance.

1.3 Scope

This research focuses on evaluating the fire performance of spruce wooden facade panels treated with the bio-based coatings Kaumera, Xyhlo Biofinish and Mycelium. The scope is limited to understanding how these coatings influence key fire behaviour parameters, including ignition probability, fire spread, material degradation and surface temperature development, under controlled laboratory conditions using specific fire testing methods with well-defined boundary conditions.

This study does not address the broader functional properties of the materials, such as their roles in moisture regulation, biodegradability or long-term weather resistance. It also does not evaluate their overall environmental impact or life cycle performance. Instead, the scope is limited to examining the fire safety implications of these coatings when applied as protective treatments on bio-based facade systems.

To achieve this, experimental tests will be conducted on treated spruce wood panels exposed to radiant heat and direct flame. The analysis includes:

- Ignition probability: the likelihood of the panel igniting under specific thermal exposure.
- Fire spread: the rate and extent of flame propagation across the treated surface.
- Mass loss: the amount of material consumed during burning, as an indicator of fire resilience.
- Temperature development: surface temperatures at different locations to assess heat absorption.

1.4 Outline of the Thesis

This thesis is organized into six chapters, each addressing a key aspect of the research process and outcomes. Below is an overview of each chapter, along with a brief description of its content.

Chapter 1: Introduction

Presents the research context, objectives, scope and relevance, introducing the bio-based materials under investigation and the need for fire performance evaluation.

Chapter 2: Literature Review

Reviews key concepts in fire dynamics and summarizes existing research on bio-based facade materials and protective coatings, identifying the knowledge gap addressed by this study.

Chapter 3: Experimental Testing

Describes the materials, test setup, and procedures used to evaluate the fire behaviour of spruce wood treated with Kaumera, Xyhlo Biofinish and Mycelium.

Chapter 4: Fire Test Results

Presents the outcomes of the fire tests objectively, focusing on ignition time, fire spread, temperature development and mass loss across the different coatings and exposure types.

Chapter 5: Evaluation

Interprets and compares the fire test results in relation to the research questions, highlighting the performance of each coating and reflecting on limitations and implications.

Chapter 6: Conclusion and Recommendations

Places the findings in a broader context, discusses limitations of the research and reflects on implications for the application of bio-based coatings in facade design and fire safety strategies.

2 Literature Review

This literature review begins by outlining core principles of fire dynamics to understand how materials behave during ignition and flame spread. The review then examines the fire performance and limitations of bio-based materials, along with strategies like compartmentation to reduce fire risk. Finally, it highlights the three promising coatings used within this research.

2.1 Fundamentals of Fire Dynamics and Safety

Fire dynamics refers to the scientific study of how fires ignite, develop and spread, and how they interact with the surrounding environment. A solid understanding of these principles is fundamental to assess fire risks, design safer buildings and evaluate the fire performance of materials. In the context of this research, which focuses on bio-based facade systems, the application of fire dynamics is essential to interpreting how materials behave under thermal exposure and how fire might progress across or through construction elements [11].

The Combustion Process

Combustion, the core process of fire, is a chemical reaction that occurs when heat, fuel and an oxidizing agent (typically oxygen) are present in the appropriate proportions. These three components form the basis of the fire triangle, visible in Figure 2. Once the ignition temperature of the fuel is exceeded, the reaction releases energy in the form of heat and light. This energy increases the temperature of nearby materials, facilitating further ignition and enabling fire growth [12].

Figure 2: Fire triangle [13]

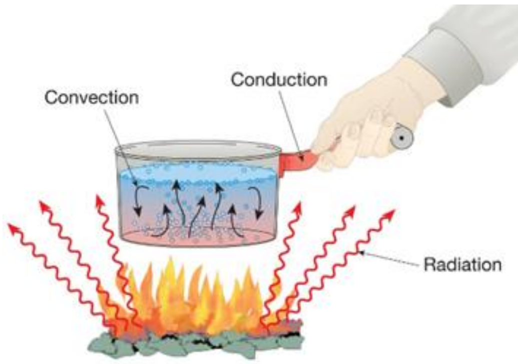


Figure 3: Heat transfer mechanisms [14]

Heat Transfer Mechanisms

Fire spreads primarily through three mechanisms: conduction, convection and radiation [12]. Conduction involves the transfer of heat through direct contact in solid materials and depends on thermal conductivity. For instance, metals facilitate rapid heat transfer, while insulating materials do so more slowly. Convection refers to the movement of heat through fluids, especially gases. In fire scenarios, hot gases rise and transfer heat to upper layers of a compartment, contributing significantly to vertical flame spread. Radiation enables the transfer of energy via electromagnetic waves, allowing heat to travel through air gaps. This mechanism can cause ignition of nearby surfaces without direct flame contact and plays a major role in fire spread across narrow corridors or to adjacent building elements [11].

STAGES OF FIRE DEVELOPMENT

The development of a fire can typically be described in four stages: ignition, growth, fully developed and decay [15]. Ignition marks the onset of flaming combustion and may occur either through piloted ignition or autoignition, depending on material properties and the level of thermal exposure. The growth phase is characterized by rapidly increasing heat release and flame spread. During this stage, conditions may lead to flashover. This is a sudden and hazardous transition in which nearly all combustible materials within a compartment ignite almost simultaneously due to elevated temperatures and radiative heat. Once flashover occurs, the fire enters the fully developed stage, in which all available fuel is burning and peak temperatures are reached. Combustion may become ventilation-controlled if oxygen becomes the limiting factor. Finally, the decay stage begins when either fuel or oxygen becomes insufficient to sustain combustion. While flame activity decreases, smouldering combustion and the presence of toxic gases remain significant hazards [16].

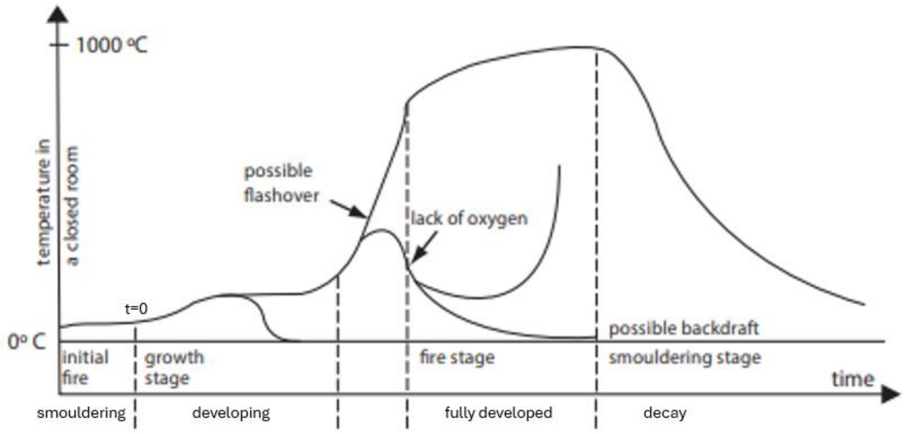


FIGURE 4: FIRE CURVE [17], [15]

INFLUENCING FACTORS ON FIRE BEHAVIOUR

Several factors influence the behaviour of fire in built environments [12]. Fuel characteristics such as chemical composition, density and moisture content play a key role in determining ignition sensitivity and combustion efficiency. Ventilation conditions, defined by openings such as doors and windows, influence both oxygen availability and the movement of hot gases. The thermal properties of materials, particularly thermal conductivity and heat capacity, affect how quickly a material heats up and ignites. Geometry also matters, because flames tend to spread more rapidly on vertical surfaces due to the upward movement of hot gases and radiation. Furthermore, compartment characteristics such as room dimensions and surface reflectivity impact heat accumulation, flashover potential and overall fire progression [11], [18].

KEY FIRE DYNAMICS PARAMETERS

To effectively analyse fire dynamics, it is essential to consider several measurable parameters that together provide a comprehensive understanding of fire behaviour. Among these, the heat release rate (HRR) is one of the most critical, as it quantifies the energy output of a fire and directly correlates with its destructive potential. Closely related is the ignition time, which indicates how quickly a material ignites when exposed to a defined heat flux.

Once ignition occurs, the flame spread rate becomes important, as it measures how rapidly flames move across a surface. This is an essential input for modelling fire growth within enclosures or along building facades. In addition, smoke production plays a key role in occupant safety, affecting visibility and potentially carrying toxic byproducts. Finally, the mass loss rate, provides insight into the fire's development and overall intensity [19].

Fundamentals Fire Safety

Fire safety engineering (FSE) applies the principles of fire dynamics to building design and risk mitigation. A performance-based approach, increasingly common in modern fire safety strategies, enables modified solutions based on the specific characteristics of the building, its materials and its use. Fire characteristics (such as spread potential and intensity) must be evaluated alongside factors such as human behaviour, evacuation procedures and emergency response capacity. Environmental variables, including wind conditions and ambient humidity, also affect fire development and suppression efforts. Together, these factors contribute to comprehensive fire safety strategies that prioritize occupant protection and structural resilience [20].

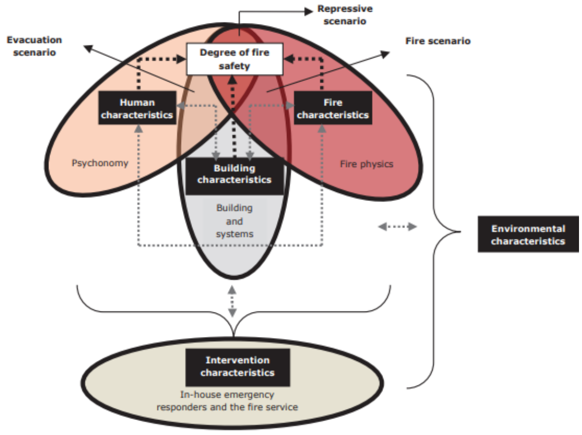


Figure 5: Project specific boundary conditions divided into three collections: building, fire and building user conditions [17]

2.2 Bio-based Materials and Facades

Bio-based materials are gaining attention in the construction sector as sustainable alternatives to conventional resources like steel, concrete and plastics. Derived from renewable biological sources, such as plants, fungi or agricultural by-products, these materials typically have low embodied energy and greenhouse gas (GHG) emissions [21]. Their production often involves less energy-intensive processes. Moreover, they are frequently biodegradable, compostable or recyclable. Studies have shown that timber-, straw- and hemp-based solutions can significantly reduce the embodied GHG emissions of building envelopes in Europe [22]. These findings align with broader climate goals in the construction sector, which is under increasing pressure to minimize its environmental footprint.

2.2.1 Types of Bio-based Materials

Materials such as cross-laminated timber (CLT), hempcrete, straw panels and bamboo are being adopted in a growing number of architectural contexts. They each offer a distinct combination of structural, thermal and environmental benefits. Among these, CLT has gained widespread recognition in multi-storey construction due to its favourable strength-to-weight ratio. Moreover, it has a significant capacity to store carbon throughout the building's lifecycle [4]. In a different application category, hempcrete (a composite of hemp hurds and lime) is used primarily for non-load-bearing infill walls. It performs exceptionally well in regulating moisture and maintaining thermal comfort [23].

Similarly, straw bale construction is receiving reintroduced attention, especially in low-rise or rural buildings. This due to its high thermal resistance (R-value) and low embodied energy. While less common in urban settings, it represents an effective insulation strategy rooted in agricultural byproducts [4]. Another material with outstanding insulation potential is cork. In addition to being recyclable and lightweight, it naturally resists fire and contributes to acoustic performance, making it attractive for both facade and interior applications [23].

In regions where rapid renewability and tensile strength are valued, bamboo is increasingly used in structural frames and cladding systems. Although it requires treatment to resist pests and decay, properly processed bamboo is both durable and visually appealing. Similarly, reed (or thatch), traditionally used in roofing and exterior walls, is being reconsidered in sustainable architecture for its fast growth and natural insulation properties [24]. Innovative developments are also developing with mycelium composites, formed by growing fungal networks on agricultural waste. These materials are lightweight, biodegradable and can offer mold and fire resistance, with appropriate treatment. This makes them an attractive choice for facade elements and interior panels [23].

Altogether, this expanding range of bio-based materials demonstrates the flexibility and adaptability of renewable resources in meeting a range of architectural and environmental needs. However, each material presents unique characteristics in terms of structure, durability and integration with building systems. Therefore, their application must be carefully matched to the specific context and requirements of each project [24].

2.2.2 Barriers to Adoption and Regional Variation

The facade of a building plays a vital role in controlling thermal performance and moisture movement. These are domains in which bio-based materials have shown significant promise [4]. However, their broader adoption in facade systems is hindered by concerns over durability and standardization, especially in high-rise or urban contexts with strict regulations. Although coatings are being developed to enhance fire resistance, further testing and certification is needed before bio-based materials can be used at scale [24].

In addition to technical barriers, structural and organizational challenges also slow down the adoption of bio-based construction. Divided supply chains, industry conservatism and regulatory inaction continue to hinder progress toward bio-based construction [24]. Adoption also varies regionally, with bamboo playing a central role in countries like China and India, while Germany and Italy have focused more on wood-based systems. These differences underscore the importance of context-specific innovation. Furthermore, implementation is often delayed by cost concerns, performance uncertainty and lack of expertise [25].

2.2.3 Fire Safety of Bio-based Facades

While bio-based materials contribute to climate goals, their combustibility presents a significant challenge in facade systems. This is especially critical in taller buildings and high-occupancy structures, where vertical fire spread is a primary concern [26], [4]. Unlike non-combustible materials like concrete or glass, bio-based materials are flammable and contribute to the overall fire load. Once ignited, they can accelerate flame spread, generate high volumes of smoke, and release toxic gases. These risks require not only improved material formulations, but also full-scale fire testing to demonstrate safe use in real building conditions [26].

2.2.3.1 Regulatory and Performance Standards

Fire classification systems such as the European EN 13501-1 [27] require building materials used in external walls to meet minimum reaction-to-fire ratings. Untreated spruce wood typically falls into fire class E, meaning it is combustible and contributes to fire. Solutions such as Xyhlo Biofinish, a fungal-derived coating, have demonstrated potential to improve the fire classification of timber from E to D, using an environmental friendly method [28].

2.2.3.2 Compartmentation and Architectural Strategies

Compartmentation is an architectural strategy for reducing fire spread in facade systems that incorporate combustible materials such as timber or bio-based cladding. In ventilated facades, particularly those with continuous air cavities, fire can travel rapidly through the cavity due to the so-called "chimney effect". To mitigate this risk, fire stops are installed to compartmentalize the cavity and reduce flame propagation. These typically are horizontal and/or vertical barriers made from non-combustible materials like mineral wool or metal sheets [29]. Fire stops are particularly crucial around openings such as windows, doors and balcony junctions, where fire and smoke are likely to bypass untreated joints if not properly detailed.

Current regulations support the use of bio-based materials in hybrid facade systems. In these systems, combustible facade components (like timber panels) are paired with non-combustible insulation and strategically positioned fire stops. This solution aims to retain the environmental benefits of bio-based materials while meeting fire safety regulations [30].

2.2.3.3 Innovations in Bio-based Flame Retardants

Most conventional flame retardants are based on halogenated or fossil-derived compounds. They pose environmental and health hazards due to toxicity and poor biodegradability [31]. In contrast, bio-based flame-retardant strategies prioritize sustainability and compatibility with natural life cycles. For example, chitosan-itaconate coatings form char layers when exposed to heat and are fully biodegradable, making them well-suited for environmentally responsible wood protection [32]. Similarly, chemically modified mycelium coatings have demonstrated improved thermal stability and reduced flammability [33].

Other promising solutions include intumescent coatings derived from bio-sourced compounds such as phytic acid and tannins. These reduce flame spread and insulate underlying materials, offering a safer alternative to toxic synthetic options [34]. A developing research area involves integrating fire resistance at the material source. For example, enhancing plant-based fibres during cultivation or early processing. By incorporating thermal stabilizers or modifying growth conditions, researchers have improved fire resistance without relying solely on external treatments. These in-situ strategies could significantly reduce chemical use and simplify material production [35].

2.3 Bio-based Protection Layers

As the demand for sustainable construction materials increases, the development of bio-based protection layers has gained significant attention. Bio-based protection layers are derived from natural, renewable resources, providing an environmentally friendly alternative to traditional synthetic coatings. In addition to their biodegradability and low environmental impact, these materials often offer additional benefits, such as improved insulation, moisture resistance and self-healing properties.

Among the most notable bio-based protection materials are Mycelium, Kaumera and Xyhlo Biofinish. Mycelium, a fungal-based material, has shown potential as an insulating and protective layer, although its fire-retardant performance remains under investigation. Kaumera, a biopolymer extracted from wastewater treatment, demonstrates water-repellent and flame-retardant properties. Xyhlo Biofinish, derived from an interaction between fungus and oil-treated wood, provides durable and self-healing protection for timber facades. This section explores the properties and applications of these materials.

2.3.1 MYCELIUM

Mycelium, the root-like network [36] of fungal threads known as hyphae [37], is drawing interest for its rapid growth, biodegradability and architectural flexibility [38]. The potential of mycelium as a building material was showcased in 2014 with the construction of the "Hy-Fi" tower by the architecture collective The Living [39]. This temporary structure, located in Manhattan, was made entirely of 10,000 mycelium bricks grown on agricultural waste. The concept was inspired by Ecovative, a company known for creating mycelium-based packaging for wine bottles. While mycelium bricks lack the strength of traditional bricks, they are significantly lighter. Conventional bricks can withstand pressures of at least 28 MPa, whereas mycelium bricks can handle only 0.2 MPa. However, their weight is just 43 kg/m³, compared to the 2400 kg/m³ of traditional concrete brick, making them 60 times lighter. Still, mycelium is better suited for non-load-bearing applications, including thermal insulation, interior walls and exterior cladding [37].

FIGURE 6: CONSTRUCTION THE "HY-FI" [39]

FIGURE 7: THE GROWING PAVILION PROJECT [40]

FIGURE 8: MYCELIUM WALL COVERING PANELS [41]

An important clarification is that mycelium used in architectural applications is no longer biologically active. After growth, the material is dried, stopping fungal activity and spore release. This ensures that the mycelium no longer grows and cannot consume or degrade the underlying substrate. This principle is demonstrated in the Growing Pavilion project, where 88 mycelium panels form the facade skin. Once dried, the panels become water-repellent, lightweight and acoustically absorbent. In combination with the right natural coating, the panels are suitable as facade panel outside [42].

Despite its promise, mycelium's use as a fire-retardant coating on bio-based panels faces challenges. A literature review yielded only a limited number of relevant studies, indicating that research on this topic is still in its early stages. The shortage of relevant studies indicates that further investigation is needed to explore the potential of mycelium as a fire-resistant solution in sustainable building applications.

Throughout the review process, it became evident that applying mycelium protection onto hemp- and wood-based panels posed significant challenges. Issues related to adhesion, growth conditions and compatibility with these substrates hindered the development of a stable and effective mycelium layer. Later, after small sample pieces were obtained from a second mycelium producer, two radiant panel tests were conducted on mycelium-coated spruce wood. These tests provided preliminary insight into fire behaviour, but were restricted due to the small size of the samples. Larger panels, suitable for the line burner test, were not available, making it impossible to include mycelium in the full-scale comparative analysis. The methodology and setup of both the radiant panel and line burner tests are described in the next chapter: 3 Experimental Testing. As a result, research focus shifted toward more practical alternatives: Kaumera and Xyhlo Biofinish. Detailed information about Kaumera and Xyhlo Biofinish can be found in the following sections, 2.3.2 and 2.3.3.

2.3.2 KAUMERA

Kaumera is a multifunctional biopolymer extracted from the granular sludge produced during the Nereda® wastewater treatment process. The name Kaumera, meaning "chameleon" in Māori, reflects its versatility in different industrial and environmental contexts. As a product derived from wastewater treatment, Kaumera is best described as eco-friendly. Its extraction helps reduce sludge volumes and associated CO_2 emissions, contributing to improved resource efficiency in water treatment systems [43]. The first Kaumera extraction facility opened in Zutphen (the Netherlands) in 2019, followed by a second in Epe in 2020. They integrate a Nereda® treatment plant [44] with a Kaumera extraction unit, processing industrial wastewater from dairy industries [45].

FIGURE 9: KAUMERA [46]

2.3.2.1 Extraction Process

The Kaumera extraction installation begins with a buffer *(1)* that ensures a continuous flow of Nereda® granular sludge into the process. This sludge is thickened via a belt system *(2)*, with added coagulants promoting particle aggregation. It is then heated in two stages via heat exchangers *(3)* to 80 degrees Celsius before entering an extraction reactor *(4)*. Here, another coagulant increases the pH, separating Kaumera from the sludge during a controlled residence period. The mixture is then cooled again using heat recovery *(5)* before further separation in a decanter centrifuge *(6)*. The Kaumera-rich water is treated with a final coagulant to lower the pH and induce flocculation. The resulting solid polymer is isolated via a disc centrifuge *(7)* and stored in a silo *(8)*, ready for further use [47].

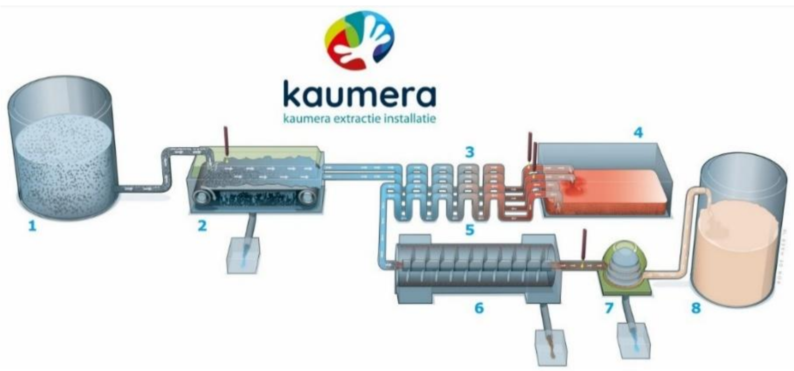


FIGURE 10: KAUMERA EXTRACTION PROCESS [47]

2.3.2.2 Applications

Kaumera's ability to retain or repel water, combined with its binding properties, makes it highly versatile [43]. In agriculture, it is used as a seed and fertilizer coating to improve moisture retention and nutrient absorption, boosting crop resilience even under drought conditions [48]. In construction, it has been tested as a flame-retardant additive and binder in composites [49]. Research suggests that the phosphate and nitrogen content in Kaumera promotes char formation, enhancing fire resistance even at relatively low concentrations [50]. However, the composition of Kaumera can vary significantly depending on the wastewater source and treatment process, which raises concerns about reproducibility and the consistent performance of Kaumera in fire protection or material applications. Moreover, Kaumera's ability to protect wood surfaces from environmental factors such as rain, UV exposure and temperature fluctuations is still under investigation. It is not yet clear whether its properties are sufficient to provide long-term outdoor protection, especially when applied as a standalone coating.

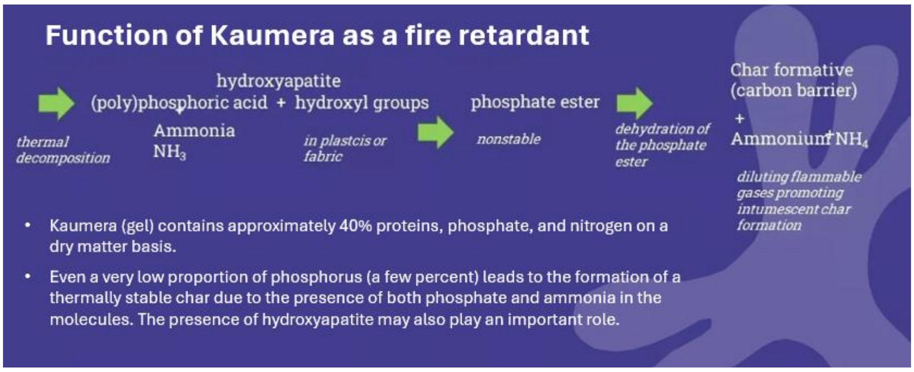


FIGURE 11: FUNCTION OF KAUMERA AS A FIRE RETARDANT [51]

2.3.3 XYHLO BIOFINISH

Xyhlo Biofinish originated from research by Dr. Michael Sailer in 1996. The study discovered that a naturally occurring fungus, Aureobasidium pullulans, formed a protective, self-healing coating when combined with oil-treated wood. This biological layer offered resistance to UV radiation, moisture, microorganisms and cracking. Research continued at TNO in the Netherlands, where the product was refined and brought to market with industry support [52].

2.3.3.1 About Xyhlo Biofinish

Xyhlo Biofinish is a sustainable method for protecting wood in outdoor applications. It combines an oil treatment with a biological coating made from a harmless, naturally occurring fungus. This living black layer is self-repairing, resistant to UV radiation and moisture, and improves during its initial years of use. Unlike conventional coatings that degrade over time, this biofinish offers long-term durability with low maintenance requirements [53]. The materials used are fully biological and locally sourced, making Xyhlo Biofinish a circular product. At the end of its lifecycle, treated wood is CO_2-neutral and can be reused, burned as biofuel or returned to nature. This contrasts with chemically treated wood, which often results in toxic waste [54].

FIGURE 12: XYHLO BIOFINISH [54]

2.3.3.2 Wood Protection

The protective mechanism relies on fungal cells and chlamydospores that bind to wood using biopolymers. This biological film shields the surface from environmental stress, microbial attacks and UV radiation. Because the coating regenerates damaged areas as long as nutrients are present, it significantly reduces the need for maintenance. The system is biocide-free and currently available in black, with research ongoing into additional colours [53].

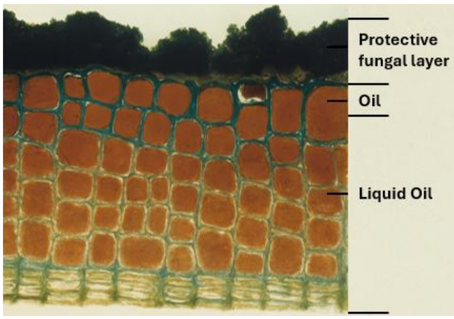


FIGURE 13: CROSS-SECTION OF PINE SAPWOOD TREATED WITH XYHLO BIOFINISH [53]

2.3.3.3 Applications

Wood is a widely valued construction material due to its natural strength, insulation properties and visual appeal. However, many commonly used European softwoods, such as pine and spruce, require additional protection against environmental influences like moisture, UV radiation and fungal decay. Traditional preservation methods often rely on toxic chemicals or energy-intensive processes, raising concerns about sustainability and environmental impact [55].

Xyhlo Biofinish offers a natural and sustainable alternative for wood protection, aligning with the growing demand for environmentally friendly construction materials. Wood already has a low environmental footprint and when treated with Xyhlo Biofinish, it becomes suitable for applications such as facades or garden structures. By applying the biological coating made from a naturally occurring fungus to oil-treated wood, it provides durable protection without the use of synthetic substances [56]. The black biofinish layer extends the lifespan of low-durability wood species and supports eco-conscious building practices. Its self-repairing properties help recover from cracks and impact damage, reducing the need for frequent maintenance. Re-oiling is only required after the first decade and then every 3 to 5 years. This makes it a low-maintenance, circular and biocide-free solution for sustainable construction [57].

3 Experimental Testing

This chapter presents the experimental methods used to evaluate the fire behaviour of bio-based facades treated with the different protective layers, mentioned in section 2.3 Bio-based Protection Layers. Tests were conducted at the Peutz Group's Fire Safety Laboratory using two primary methods: the radiant panel test and the line burner test. These tests were selected to assess key fire performance parameters such as ignition resistance, flame spread, temperature development and mass loss. Detailed descriptions of the test configurations and measurement techniques are provided in the following sections.

3.1 Location - Peutz Group

The fire tests described in this study were conducted at the Peutz Fire Safety Laboratory in Haps, the Netherlands, which offers advanced testing facilities in accordance with international standards [58]. The Peutz Group is a consortium of independent engineering consultancies with expertise in building physics, acoustics, environmental technology and fire safety. Established in 1954, the group operates across 12 locations in the Netherlands, Belgium, Germany and France. Since 1963, Peutz has functioned as a private enterprise, with in-house accredited laboratories for acoustics, wind technology and fire safety.

Figure 14: Peutz laboratory for fire safety in Haps [59]

3.2 Experimental Setup

To evaluate fire behaviour, two small-scale methods were used: the radiant panel test and the line burner test. These allow for the systematic analysis of ignition, flame spread and material degradation under controlled heat flux conditions. High-resolution cameras captured the visual flame propagation, while thermocouples recorded temperature changes in real time. A balance placed beneath the test constructions, connected to a data acquisition system, continuously measured mass loss.

Although the main experimental setup focuses on Kaumera and Xyhlo coatings, two additional small-scale radiant panel tests were conducted using mycelium samples obtained from an external supplier, mentioned in section 2.3.1 Mycelium. These small samples offered an opportunity to observe some preliminary fire behaviour of mycelium-treated materials. However, due to the limited dimensions of the samples, they could not be used in the line burner test.

Coating Application and Measurement

The coatings were applied in accordance with the manufacturers recommendations to ensure consistency and repeatability. Kaumera coatings, including both the Epe and Zutphen variants, were applied using a Colour Expert 50 mm brush, while Xyhlo Biofinish was applied using a small roller. After application, each layer was allowed to dry for a minimum of two and a half hours under standard laboratory conditions. These conditions were set at approximately 16°C and 50% relative humidity. Panels were never tested on the same day as coating. Instead, a minimum drying time of 24 hours ensured that the coatings were fully cured before exposure to fire.

The mycelium coating was applied using a different technique. Spruce wood panels and mycelium mats were weighed separately, then bonded using a hot-press at 140°C under a pressure of 43 tonnes for ten minutes. Only the top plate of the press was heated. This method allowed the mycelium to adhere to the wood surface, likely due to the presence of natural binding agents such as chitin and glucans found in fungal cell walls [60]. After the heat-pressing process, the panel with mycelium was weighed again to determine the final mass of the assembled mycelium-wood samples.

FIGURE 15: WOOD PANEL WITH MYCELIUM BEFORE HEAT-PRESSING [61]

PANEL STORAGE AND CONDITIONING

The spruce wood used for all test panels has an average moisture content of approximately 10%, determined using the oven-dry method at 105°C in accordance with EN 1363-1, Annex F [62]. Details of the moisture content measurements are provided in Appendix A1. The panels have a specific mass of 450 kg/m³. Typical thermal and combustion properties for untreated spruce include a specific heat capacity of 1650 J/kg·K and a heat of combustion of 19 MJ/kg [63]. In terms of reaction to fire, uncoated spruce wood typically falls under Euroclass E, which is one of the lowest performance classifications for tested materials. It indicates a very combustible material, with very limited fire resistance and rapid flame spread under standard testing conditions.

After the coating process and drying period, all panels were stored in the fire safety laboratory, with a stable environment of approximately 16°C and 50% relative humidity. This storage environment was consistent with the coating drying conditions and ensured that all panels were sufficiently conditioned before testing.

VISUAL COMPARISON AND BASELINE REFERENCE

To illustrate the visual appearance of the different panels, photographs were taken of untreated spruce wood panels and of those treated with the coatings. These pictures are shown in Table 1 below. The untreated panel serves as a baseline reference. This enables visual comparison and supports later analysis by providing context for how the coated spruce wood panels differ from the uncoated spruce wood.

TABLE 1: PICTURES SHOWING SPRUCE WOOD WITHOUT AND WITH THE FOUR DIFFERENT TYPES OF COATINGS

Spruce wood without coating:	**Spruce wood with Kaumera Epe:**	**Spruce wood with Kaumera Zutphen:**	**Spruce wood with Xyhlo biofinish:**	**Spruce wood with Mycelium:**
				

3.2.1 Radiant Panel Test

The radiant panel test evaluates the ignition resistance of materials when exposed to a constant level of radiant heat. The setup is based on NEN 6068 [64], which determines the resistance to fire penetration and fire spread between spaces.

Test Configuration

The following configurations were tested:

- Spruce wood without coating
- Spruce wood with Kaumera Epe (1, 2 and 3 layers)
- Spruce wood with Kaumera Zutphen (1, 2 and 3 layers)
- Spruce wood with Xyhlo biofinish (1, 2 and 3 layers)
- Spruce wood with Mycelium (1 layer)

The radiant panel tests were conducted on flat spruce wood panels measuring 400 × 300 × 18 millimetres. Each panel was mounted vertically at a fixed distance from the radiant heat source, ensuring consistent exposure conditions. The heat flux in the centre of the sample was set at 15 kW/m² for a duration of 30 minutes. The heat flux was verified prior to each test using a flux meter positioned at the location of the sample and by carefully measuring the distance between the radiant panel and the test surface. After the 30-minute exposure, a pilot flame was introduced to determine whether the material would ignite and to observe its behaviour post-ignition.

To ensure the reliability of the experimental data, each test configuration was conducted in duplicate. Although statistical metrics such as standard deviation are not reported, the repeated tests help verify consistency in fire behaviour. Any significant differences between repeated tests were noted and considered in the interpretation of the results.

Figure 16: Heat flux meter in front of radiant panel

Figure 17: Radiant panel test setup

Figure 18: Uncoated spruce wood panel connected to the test setup

MEASURED PARAMETERS

During the test, several key parameters were monitored. If ignition did not occur during the 30-minute radiant exposure, time to ignition was measured from the moment the pilot flame was introduced to the appearance of a sustained flame. Charring patterns, smoke production and flame spread were visually documented throughout the test duration. Thermocouples were placed on the surface of the wooden panel and distributed across it to monitor temperature development over time, as shown in Figure 19. Mass loss was continuously measured using a balance beneath the test setup, with data recorded at 0.25-second intervals. These measurements were used to generate a cumulative mass loss curve, from which a linear trend was derived to estimate the average rate of combustion in kilograms per minute [65]. The accuracy of this fit was evaluated using the coefficient of determination (R^2). Values approaching 1 indicate stable and predictable mass loss, whereas lower values suggest more variable or irregular burning behaviour [66].

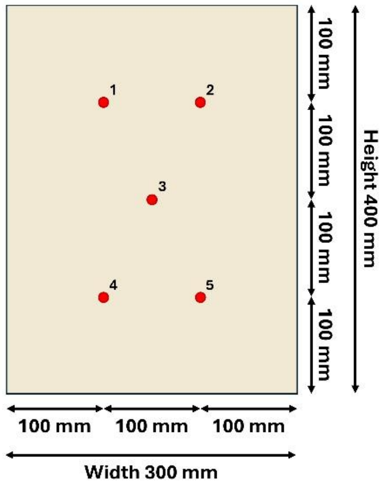


FIGURE 19: RADIANT PANEL TEST PANEL – FRONT VIEW

FIGURE 20: COMPLETE RADIANT PANEL SETUP

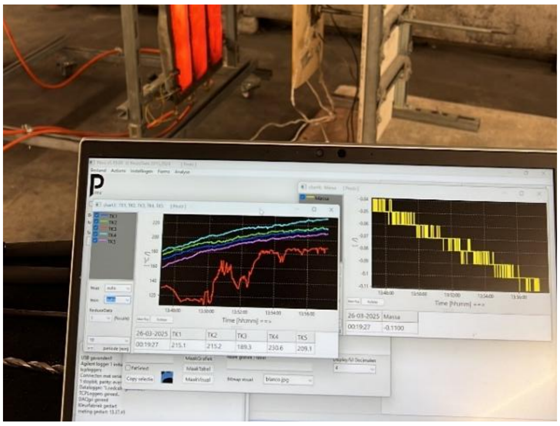


FIGURE 21: LAPTOP SCREEN WITH MEASUREMENTS DURING A RADIANT PANEL TEST

To further quantify the fire behaviour of the samples, the average Heat Release Rate (HRR) and the produced surface heat flux will be calculated [19]. These parameters provide insight into the thermal output and fire intensity associated with each material configuration [12]. The corresponding formulas used for these calculations are presented below.

$$Mass\ loss\ rate\ [kg/s] = \frac{Mass\ loss\ rate\ [kg/min]}{60}$$

$$Produced\ energy\ [kW] = Mass\ loss\ rate\ [kg/s] * 19\ [MJ/kg] * 1000\ \ [63]$$

$$Produced\ surface\ heat\ flux\ [kW/m^2] = \frac{Produced\ energy\ [kW]}{Sample\ size\ [m^2]} = \frac{Produced\ energy\ [kW]}{0.12\ m^2}$$

3.2.2 Line Burner Test

The line burner test was designed to evaluate the fire performance of facade materials exposed to a direct flame source. This test setup follows the ISO 13785-1 [67], which describes intermediate-scale fire tests for evaluating facade systems and materials.

Test Configuration

The same material configurations tested in the radiant panel test were used in the line burner test, excluding mycelium due to the limited dimensions of the samples. In total, ten tests were performed. These covered uncoated panels as well as those treated with Kaumera Epe, Kaumera Zutphen and Xyhlo Biofinish in one, two and three layers. In contrast to the radiant panel tests, none of the configurations in the line burner test were repeated, due to time limitations and restricted material availability.

Measured Parameters

Each test panel was mounted vertically in a steel frame and exposed to a line burner placed at the bottom edge of the specimen. The burner operated at a thermal output of 30 kW/m², with direct flame exposure lasting 30 minutes. Ignition occurred at the beginning of each test, following the procedure outlined in the ISO standard. As in the radiant panel test, thermocouples were used to monitor temperature development. Ten were positioned on the surface of the panel and one on the backside, as illustrated in Figure 26 and 27. Mass loss was measured in the same way, using a balance placed beneath the construction, with data recorded at 0.25 second intervals.

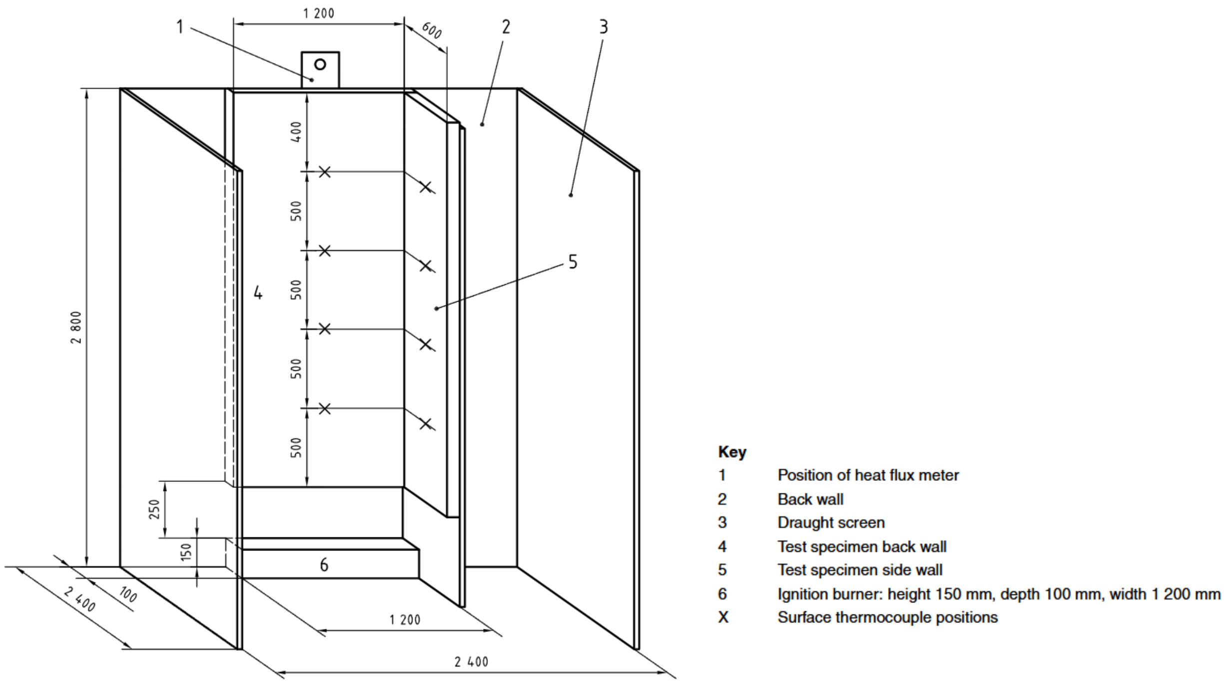


Figure 22: Test setup ISO 13785-1, dimensions in millimetres [67]

Tested Panels

Unlike the flat boards used in the radiant panel tests, the line burner test panels were built as layered spruce wooden constructions. The complete assembly measured 1200 × 569 × 62 millimetres and is designed to resemble a simplified facade. From exterior to interior, the construction consists of:

- 6 spruce wooden slats (each measuring 1200 x 94 x 18 mm)
- Mounted on 3 horizontal battens (569 x 48 x 22 mm)
- Supported by 2 vertical battens (1200 x 48 x 22 mm)

Although ISO 13785-1 specifies larger panels measuring 2400 by 1200 millimetres [67], this study used a reduced format with approximately the same ratio due to the lower output capacity of the available burner. The smaller size ensured proportional results under the modified conditions.

Real-world facades with wooden cladding often include gaps between slats or overlapping arrangements such as “potdeksel” (a Dutch term for horizontally overlapping boards). The test panels in this study were constructed differently, using tightly fitted slats without any spacing between them. This approach aimed to highlight the fire performance differences between coatings more clearly.

Moreover, both the front and rear sides of each panel were coated. Although this setup does not reflect realistic facade construction, it allowed for consistent and maximized exposure to the effects of the coatings. Behind the facade panels, stone wool has been applied. This creates an air cavity at the back, formed by the batten system between the spruce wooden slats and the stone wool. Testing with a cavity replicates actual building practice, making the results relevant to real-life applications.

Figure 23: Line burner test panels as layered wooden constructions

Figure 24: Line burner test setup

Figure 25: Uncoated test panel connected to the test setup

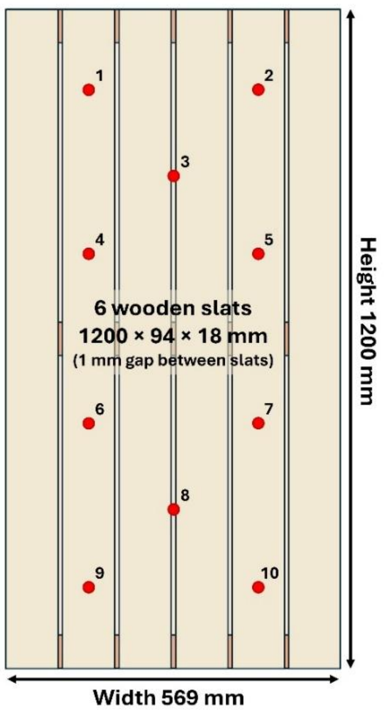


FIGURE 26: LINE BURNER TEST PANEL – FRONT VIEW

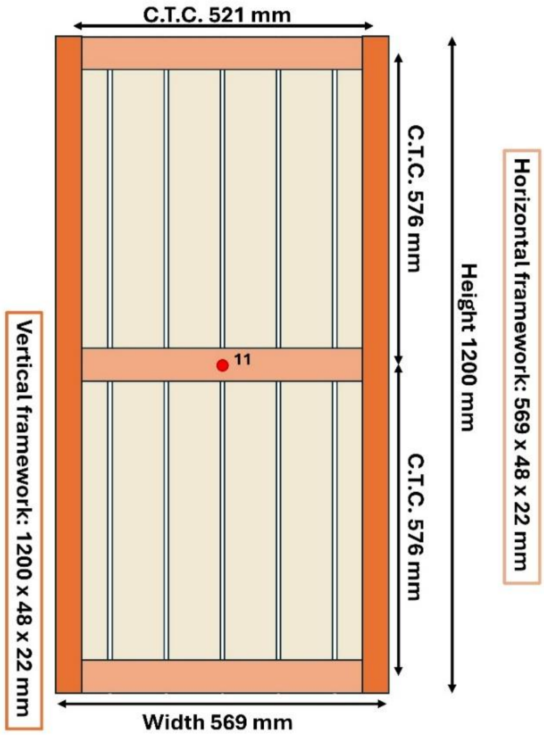


FIGURE 27: LINE BURNER TEST PANEL – BACK VIEW

4 Fire Test Results

This chapter presents the analysis and interpretation of the experimental data collected during the fire performance tests. The results are systematically organized into three main sections. Section 4.1 provides an overview of the coating combinations and panel configurations included in the study, offering a clear reference framework for interpreting the findings. Sections 4.2 and 4.3 present the outcomes of the two fire test methods: the radiant panel test and the line burner test, respectively. Each section includes general observations made before and during the tests, followed by a quantitative analysis of temperature development and mass loss over time. The data is supported by detailed graphs, which are provided in Appendix A3 through A7 for clarity and ease of interpretation.

4.1 Comparisons

This section provides an overview of all coating types and configurations included in the analysis. It outlines the key variables used to compare the performance of treated and untreated samples.

Table 2: Comparison of coating options and layer combinations

Comparison number	Material 1 Number of layers	Material 2 Number of layers	Material 3 Number of layers	Material 4 Number of layers	Material 5 (only radiant panel)
1	Spruce wood N.A.	Kaumera Epe **1** layer	Kaumera Zutphen **1** layer	Xyhlo Biofinish **1** layer	Mycelium
2	Spruce wood N.A.	Kaumera Epe **2** layers	Kaumera Zutphen **2** layers	Xyhlo Biofinish **2** layers	Mycelium
3	Spruce wood N.A.	Kaumera Epe **3** layers	Kaumera Zutphen **3** layers	Xyhlo Biofinish **3** layers	Mycelium
4	Spruce wood N.A.	Kaumera Epe **1** layer	Kaumera Epe **2** layers	Kaumera Epe **3** layers	-
5	Spruce wood N.A.	Kaumera Zutphen **1** layer	Kaumera Zutphen **2** layers	Kaumera Zutphen **3** layers	-
6	Spruce wood N.A.	Xyhlo Biofinish **1** layer	Xyhlo Biofinish **2** layers	Xyhlo Biofinish **3** layers	-

4.2 Radiant Panel Test

This section presents the results of the radiant panel test, conducted to assess the fire behaviour of the panels under a controlled heat flux of 15 kW/m², as measured in the centre of the panel. The test simulates continued radiant heat exposure and offers insight into ignition behaviour, mass loss and material degradation. The analysis is divided into three subsections. Section 4.2.1 reports general observations recorded before and during the tests. This includes preparation conditions and visible fire behaviour. Section 4.2.2 presents the temperature development of the panels during testing, based on thermocouple data. Finally, Section 4.2.3 focuses on mass loss, comparing pre- and post-test weights to assess the extent of combustion and the protective effect of each coating type.

4.2.1 General Notes Before and During Testing

This subsection captures notable visual and technical observations related to the radiant panel tests, offering qualitative insights that support the interpretation of the quantitative results.

4.2.1.1 Notes before testing

It was noted that thermocouples (TKs) do not function optimally if not applied correctly. Therefore, all TKs were inserted through the panels and positioned on the exterior surface.

Each test was conducted for 30 minutes, after which pilot ignition was used to initiate flaming combustion. The test ended once there were no longer visible flames and the material transitioned into smouldering. This point was chosen as the endpoint to maintain a consistent visual reference for comparing results across samples.

The applied heat flux of 15 kW/m² only represents the intensity at the centre of the sample. Towards the edges, the radiant flux gradually decreases. To provide a more representative value for the entire panel, it is more accurate to determine the average radiant flux across the full surface area of the sample. As shown in the calculated values in Appendix A2, the corners of the panel received 11.36 kW/m², while the centre reached 14.98 kW/m². Based on these values, the average radiant heat flux over the entire panel is: $\frac{11.36+14.98}{2} = 13.17\ kW/m^2$. This average is notably lower than the intended 15 kW/m².

4.2.1.2 Visible notes during testing

As observed during the tests, only piloted ignition was possible. Spontaneous ignition did not occur under the applied conditions. Literature indicates that spontaneous ignition of wood typically requires a heat flux of around 20 kW/m² [68] [69], suggesting that the average 13 kW/m² applied here was insufficient to initiate spontaneous ignition. The lower average heat flux may also explain the absence of uniform charring in untreated wood. No clear signs of combustion were observed in the corners of the panel, where the exposure was lower. If the entire surface had been exposed to 15 kW/m², more severe degradation would likely have occurred.

Applying multiple layers of bio-based coating seemed to have a positive influence on the fire performance, possibly enhancing the protective characteristics of the panel.

A visual abnormality was noted, as a dark line was visible on the panels. However, this was the result of external lighting conditions rather than the coating or the panel itself.

Additionally, it was observed that once the pilot of ignition was applied, the back of the sample also ignited due to the absence of rock wool insulation behind the panel.

All three different coatings (Kaumera, Xyhlo and mycelium) produced noticeable amounts of visible vapours and gases during the test, suggesting the release of possible dangerous compounds during heating. Kaumera, in particular, also emitted an unpleasant smell both before and during testing. In contrast, Xyhlo and mycelium were nearly odourless.

PILOT IGNITION OBSERVATIONS

The pilot ignition procedure was applied to each test after the 30-minute period of radiant heat exposure. In general, ignition was achieved consistently. Several sample types ignited immediately upon the first attempt, indicating low resistance to ignition. These included:

- Uncoated spruce wood
- Spruce wood treated with 1 or 2 layers of Kaumera Epe
- Spruce wood treated with 1 or 2 layers of Kaumera Zutphen
- Spruce wood treated with 1, 2 or 3 layers of Xyhlo Biofinish

In contrast, the samples treated with three layers of Kaumera (both Epe and Zutphen variants) demonstrated greater resistance to ignition and required multiple ignition attempts:

- Kaumera Epe, 3 layers, sample 1:
  The first attempt failed, the second resulted in partial ignition, the third resulted in full ignition.
- Kaumera Epe, 3 layers, sample 2:
  The first attempt failed, the second attempt achieved full ignition.
- Kaumera Zutphen, 3 layers, sample 1:
  The first attempt failed, the second attempt achieved full ignition.
- Kaumera Zutphen, 3 layers, sample 2:
  The first attempt failed, the second was nearly successful, the third resulted in full ignition.

These results suggest that the Kaumera coating, particularly when applied in multiple layers, can increase resistance to ignition.

A different but similarly positive result was observed for the two samples treated with mycelium. These panels did not ignite at all during the pilot ignition phase. Although the visible mycelium layer had partially detached in some areas, both samples still demonstrated flame suppression. This aligns with findings in literature [70], which shows that residual biopolymers left behind by the mycelium layer, such as chitin and glucans, promote char formation and surface protection. This contributes to continued fire retardance even in the absence of an intact mycelium layer.

FIGURE 28: VISIBLE VAPOURS AND SMOKE DURING TEST

FIGURE 29: VISIBLE FLAMES AFTER PILOT IGNITION

FIGURE 30: MYCELIUM AFTER THE TEST AND NO IGNITION

4.2.2 Results Temperature Profiles

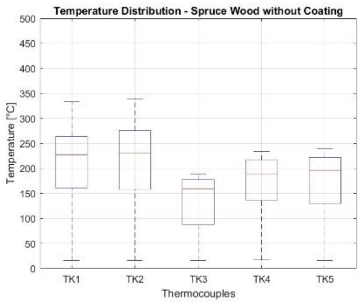
The temperatures were measured using five thermocouples (TK1 to TK5) placed at predefined positions on the sample surface, shown in Figure 19. The data is presented as boxplots to visualize the distribution, median and variability of temperatures. To complement the boxplot interpretation, the 80% temperature range was used and is defined as the range between the 10th percentile (P10) and the 90th percentile (P90) of recorded temperatures. It captures the central 80% of the data and excludes extreme outliers, giving a more robust view of how the majority of the temperature values are distributed [71].

The untreated spruce wood exhibited some of the highest peak temperatures across nearly all thermocouple positions, especially at TK1 and TK2. This is likely due to heat accumulation at the top of the panel. Contrary to initial expectations, the mycelium-treated sample exhibited even higher median and peak temperatures than the untreated wood across nearly all thermocouple positions. This suggests that the mycelium layer may in fact have contributed to earlier degradation.

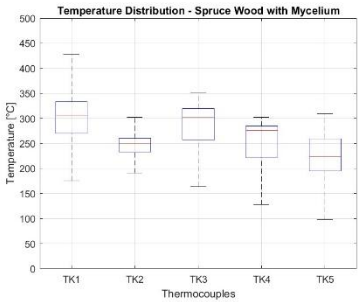
The Xyhlo Biofinish samples also performed well, demonstrating consistent results even with just a single layer. Their tightly clustered boxplots across all thermocouples indicate strong thermal stability and superior performance compared to untreated wood.

The Kaumera Epe and Zutphen coatings demonstrate a clear trend: the application of the coating is associated with improved thermal performance. Samples treated with two or three layers of Kaumera exhibited notably lower and more consistent median temperatures across all thermocouples. These samples also show significantly narrower 80% temperature ranges, indicating both reduced peak exposure and more uniform thermal behaviour. The Xyhlo Biofinish samples also performed well, demonstrating consistent results even with just a single layer. The tightly clustered boxplots across all thermocouples show its better performance compared to untreated wood. An exception to this trend is observed in the 1-layer Kaumera samples. Specifically, TK2 (Kaumera Zutphen) and TK4 (Kaumera Epe) recorded unusually low temperatures. These irregularities are due to instrumentation issues and are not reliable for drawing conclusions.

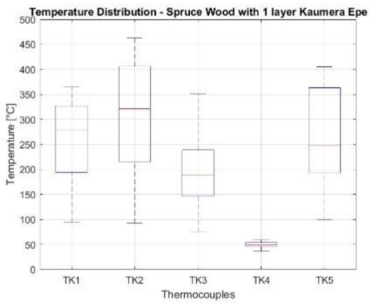
Uncoated spruce wood



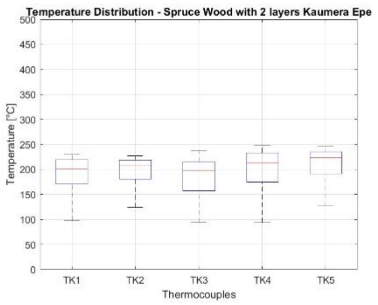
Mycelium



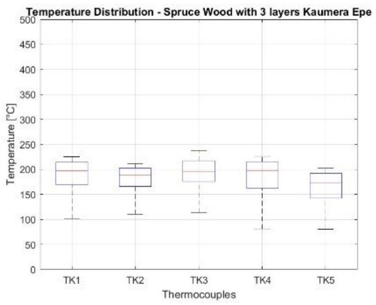
Kaumera Epe, 1 layer



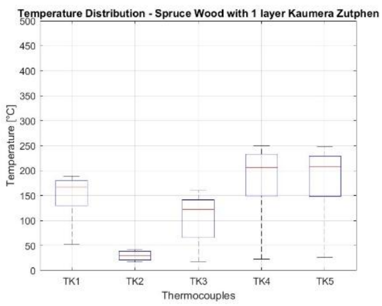
Kaumera Epe, 2 layers



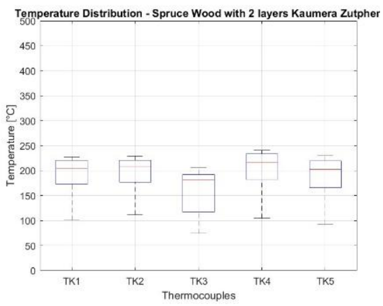
Kaumera Epe, 3 layers



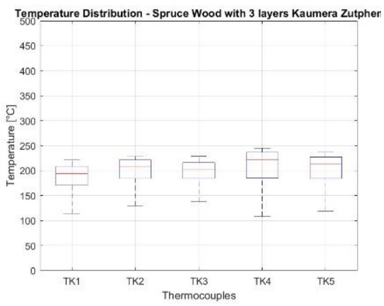
Kaumera Zutphen, 1 layer



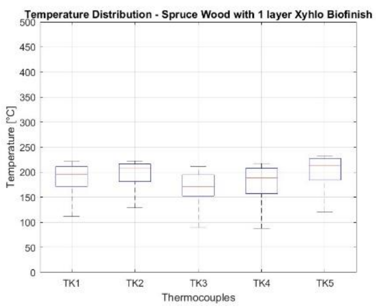
Kaumera Zutphen, 2 layers



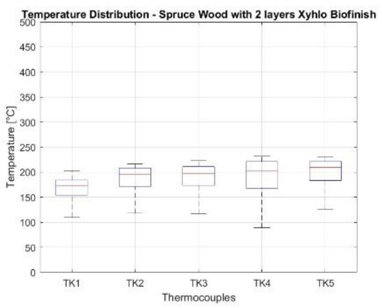
Kaumera Zutphen, 3 layers



Xyhlo Biofinish, 1 layer



Xyhlo Biofinish, 2 layers



Xyhlo Biofinish, 3 layers

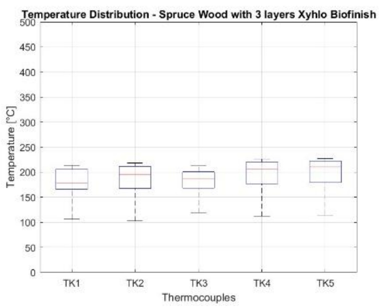


FIGURE 31: BOXPLOTS OF MEASURED TEMPERATURES FOR DIFFERENT THERMOCOUPLE POSITIONS – RADIANT PANEL TESTS

4.2.3 Results Mass Loss

The mass loss of each panel during the radiant panel test was recorded at 0.25-second intervals and used to generate cumulative mass loss curves. Linear trend lines were fitted to each curve to determine the mass loss rate (kg/min). The coefficient of determination (R^2) was calculated to evaluate the regularity of mass loss over time. Table 3 summarizes the mass loss rates and R^2 values for each sample configuration.

The untreated wood samples showed a steady mass loss rate of 0.084 kg/min/m^2 with a high R^2 value (0.978), indicating relatively consistent burning behaviour. Among the treated samples, the mycelium panels showed the highest combustion rates at 0.16 kg/min/m^2, suggesting limited fire resistance under the test conditions. However, as discussed in section 4.2.1.2, despite the high mass loss, the residual layer that remained attached to the wood surface demonstrated fire-retardant behaviour. This layer appears to suppress ignition and flame spread even when the visible mycelium layer is detached [70].

It should be noted that in the case of the mycelium samples, the initial mass loss was influenced not only by the evaporation of moisture, but also by the detachment of the mycelium layer. For a more representative assessment of combustion behaviour, a second trend line was fitted over the interval from 15 minutes until the end of the test. This corrected analysis resulted in a lower mass loss rate of 0.114 kg/min/m^2, with an improved R^2 value of 0.988. A similar approach was applied in an attempt to improve the R^2 value for the untreated spruce wood, as a linear mass loss trend is expected [65]. However, this resulted in a negligible improvement and thus the full dataset was used for comparison. This refinement was not necessary for the other coatings, as their outer layers were negligible in mass. Additionally, both their R^2 values and the trends shown in Figure 32 confirm that their mass loss behaviour was already nearly fully linear.

Table 3: Mass loss trendline parameters over full test duration – radiant panel tests

Samples	Mass loss rate (per 0.12 m²)	Mass loss rate (per m²)	Coefficient of determination R^2
Without coating	0.0101 kg/min	0.084 kg/min/m²	0.978
Kaumera Epe, 1 layer	0.0157 kg/min	0.131 kg/min/m²	0.984
Kaumera Epe, 2 layers	0.0057 kg/min	0.048 kg/min/m²	0.989
Kaumera Epe, 3 layers	0.0050 kg/min	0.042 kg/min/m²	0.982
Kaumera Zutphen, 1 layer	0.0077 kg/min	0.064 kg/min/m²	0.990
Kaumera Zutphen, 2 layers	0.0054 kg/min	0.045 kg/min/m²	0.985
Kaumera Zutphen, 3 layers	0.0047 kg/min	0.039 kg/min/m²	0.984
Xyhlo biofinish, 1 layer	0.0052 kg/min	0.043 kg/min/m²	0.968
Xyhlo biofinish, 2 layers	0.0052 kg/min	0.043 kg/min/m²	0.969
Xyhlo biofinish, 3 layers	0.0046 kg/min	0.038 kg/min/m²	0.977
Mycelium	0.0192 kg/min	0.160 kg/min/m²	0.980
Mycelium (15-30 minutes)	0.0137 kg/min	0.114 kg/min/m²	0.988

The other panel coatings influenced fire behaviour through a different mechanism, primarily by reducing combustion rates as the number of applied layers increased. For example, panels with 3 layers of Kaumera Zutphen or Xyhlo Biofinish recorded the lowest rates at 0.039 kg/min/m^2 and 0.038 kg/min/m^2, respectively. These reductions demonstrate the potential of the coatings to slow down material degradation during thermal exposure.

Across all tested configurations, all R^2 values remained relatively high (≥ 0.968), reflecting a generally stable and predictable mass loss. Minor variations are likely due to differences in ignition timing or variations in how evenly the coatings were applied, which could affect the uniformity of thermal degradation.

An important consideration is that the combustion rate result for the Kaumera Epe, 1 layer sample (0.131 kg/min/m^2) is considered unreliable. A measurement error in the balance beneath the test setup resulted in unrealistic values, changing the mass loss curve and the fitted trend line. Based on the trend in similar samples, the actual rate is expected to be closer to that of Kaumera Zutphen, 1 layer (0.064 kg/min/m^2). This value should therefore be interpreted with caution and is regarded as an outlier.

Mass Loss after Ignition and Flame Duration

To interpret the combustion behaviour of the tested panels, the period following ignition was evaluated in terms of mass loss rate and duration of visible flames. While total mass loss was discussed earlier, the post-ignition phase provides additional insight into how each treatment performs during active flaming combustion. Table 4 below shows all the results.

The untreated reference samples exhibit a rapid increase in mass loss immediately after ignition and sustained visible flames for approximately 3 minutes, consistent with their high combustion rate and lack of any fire-retardant treatment.

The panels treated with multiple layers of Kaumera Epe don't show any significant change in post-ignition mass loss rate. However, the flame duration consistently decreases with the number of layers applied: from around 3 minutes with one layer to approximately 1 minute with three layers. A similar trend is visible for Kaumera Zutphen.

The Xyhlo Biofinish samples show faster post-ignition mass loss in the one- and two-layer configurations, but the three-layer configuration demonstrates a significant improvement. It shows a more stable mass loss profile and the flame duration was reduced to 1.5 minutes.

The Mycelium-treated panels behaved differently. Although overall mass loss was relatively high, the post-ignition mass loss was slower, as much of the combustible material had already degraded or detached prior to ignition, as mentioned on the previous page. Furthermore, no flaming phase was observed.

Table 4: Post-ignition mass loss behaviour and duration of visible flames – radiant panel tests

Samples	Post ignition mass loss	Duration of visible flames
Without coating	Faster	± 3 minutes
Kaumera Epe, 1 layer	Faster	± 3 minutes
Kaumera Epe, 2 layers	Same	± 1.5 minutes
Kaumera Epe, 3 layers	Same	± 1 minute
Kaumera Zutphen, 1 layer	Faster	± 2.5 minutes
Kaumera Zutphen, 2 layers	Same	± 1.5 minutes
Kaumera Zutphen, 3 layers	Same	± 1 minute
Xyhlo biofinish, 1 layer	Faster	± 2.5 minutes
Xyhlo biofinish, 2 layers	Faster	± 2 minutes
Xyhlo biofinish, 3 layers	Same	± 1.5 minutes
Mycelium	Slower	0 minutes

Received and Produced Surface Heat Flux

To further quantify the fire behaviour of the tested samples, both the received and the produced surface heat flux were evaluated. These parameters provide insight into the thermal energy applied to the panels and the energy released by the material during combustion, offering a more complete understanding of the fire intensity and self-sustaining burning potential.

The received heat flux represents the thermal energy applied to the panels by the radiant heat source. As detailed in section 4.2.1.1, the average heat flux across the entire surface of the panel was calculated to be 13.17 kW/m^2. In contrast, the produced heat flux reflects the thermal energy generated by the material itself during combustion. This value was determined based on the measured mass loss rate, using the calculation method presented in section 3.2.1. The mass loss rates were derived from the linear trend of the cumulative mass loss curves, as described in the beginning of section 4.2.3. These values were then used to calculate the produced heat flux for each tested sample.

By comparing the produced heat flux to the received heat flux, additional insight can be gained into the material's ability to sustain combustion. If the produced heat flux is lower than the received heat flux, it indicates that the panel does not release sufficient energy to maintain combustion once the external heat source is removed, resulting in self-extinguishing behaviour. Conversely, if the produced heat flux exceeds the received heat flux, the material may generate enough energy to support self-sustained burning even after the heat source is taken away.

Table 5: Produced and received surface heat flux – radiant panel tests

Samples	Mass loss rate (per 0.12 m^2)	Produced energy	Produced surface heat flux	Received heat flux	Interpretation
Without coating	0.0101 kg/min	3.20 kW	26.65 kW/m^2	13.17 kW/m^2	Produced > received
Kaumera Epe, 1 layer	0.0157 kg/min	4.97 kW	41.43 kW/m^2	13.17 kW/m^2	Produced > received
Kaumera Epe, 2 layers	0.0057 kg/min	1.81 kW	15.04 kW/m^2	13.17 kW/m^2	Produced > received
Kaumera Epe, 3 layers	0.0050 kg/min	1.58 kW	13.19 kW/m^2	13.17 kW/m^2	Produced ≈ received
Kaumera Zutphen, 1 layer	0.0077 kg/min	2.44 kW	20.32 kW/m^2	13.17 kW/m^2	Produced > received
Kaumera Zutphen, 2 layers	0.0054 kg/min	1.71 kW	14.25 kW/m^2	13.17 kW/m^2	Produced > received
Kaumera Zutphen, 3 layers	0.0047 kg/min	1.49 kW	12.40 kW/m^2	13.17 kW/m^2	Produced < received
Xyhlo biofinish, 1 layer	0.0052 kg/min	1.65 kW	13.72 kW/m^2	13.17 kW/m^2	Produced > received
Xyhlo biofinish, 2 layers	0.0052 kg/min	1.65 kW	13.72 kW/m^2	13.17 kW/m^2	Produced > received
Xyhlo biofinish, 3 layers	0.0046 kg/min	1.46 kW	12.14 kW/m^2	13.17 kW/m^2	Produced < received
Mycelium (15-30 minutes)	0.0137 kg/min	4.34 kW	36.15 kW/m^2	13.17 kW/m^2	Produced > received

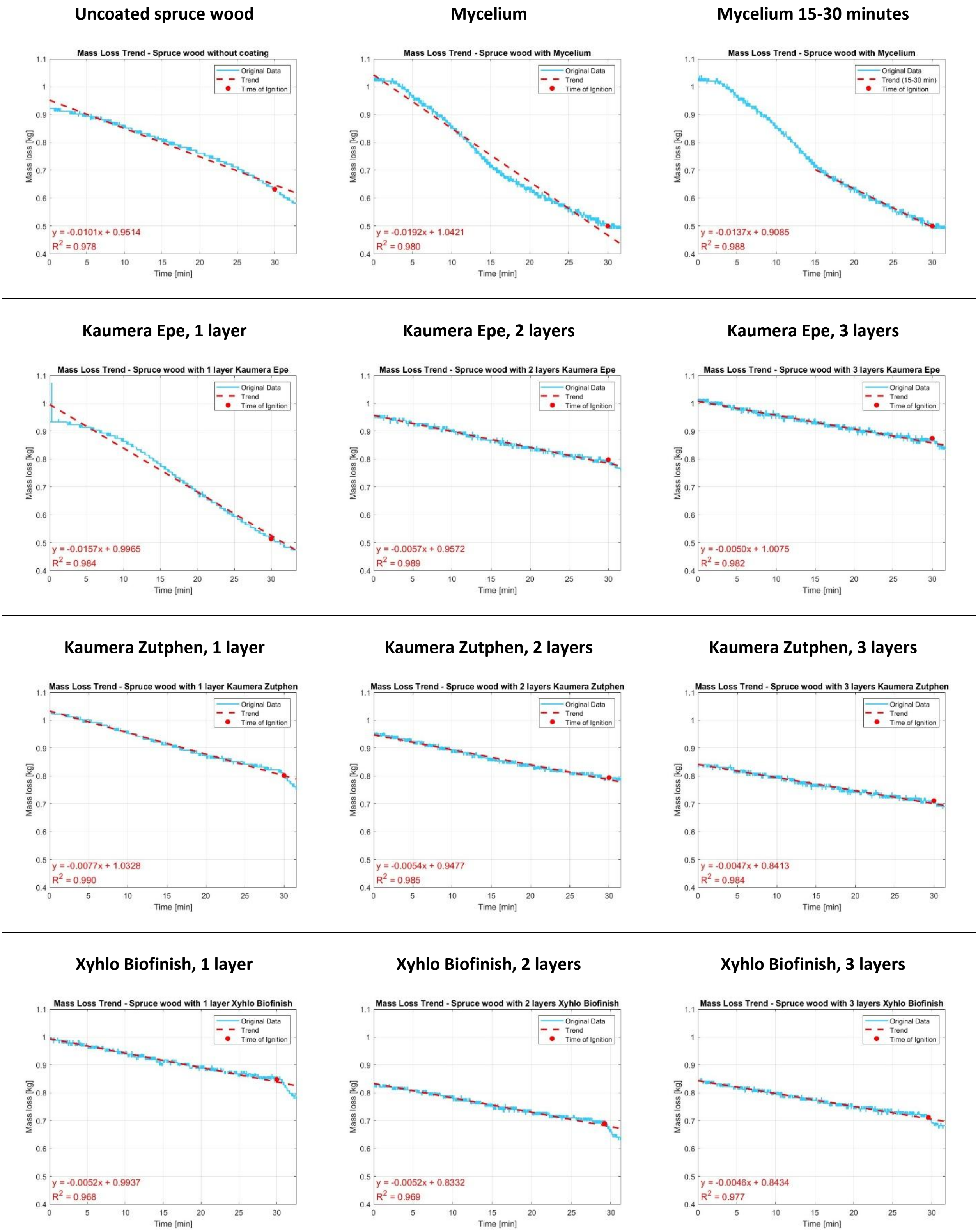


FIGURE 32: MASS LOSS WITH LINEAR TRENDLINE OVER ENTIRE TEST DURATION AND IGNITION POINT – RADIANT PANEL TESTS

4.3 LINE BURNER TEST

This section presents the results of the line burner test, which was designed to assess the fire behaviour of the facade panels under direct flame exposure at a heat flux of 30 kW/m². This test simulates more intense fire conditions and allows for the evaluation of flame spread resistance and material breakdown. The analysis follows the same structure as the radiant panel test. It includes general observations, temperature development and mass loss.

4.3.1 GENERAL NOTES BEFORE AND DURING TESTING

This subsection describes notable visual and technical observations related to the line burner tests, offering qualitative insights that support the interpretation of the quantitative results.

4.3.1.1 Notes before testing

The line burner test represents a continuous flame exposure, similar to what can occur near a window opening during a fully developed (post-flashover) fire. Unlike short ignition sources, the flame in this setup stays active throughout the test, meaning that flames continue to affect the panel the entire time. Because of this, a flaming fire will almost always be seen on the surface of the test panel. This setup provides insight into flame spread and material behaviour under constant heat, especially in areas where flames project outward and upward from openings, increasing heat exposure on the facade above.

4.3.1.2 Visible notes during testing

During the line burner tests, none of the samples withstood the full 30-minute exposure period. In all cases, the fire led to significant degradation before the scheduled end of the test. However, panels treated with multiple layers of bio-based coating performed noticeably better than those with only a single layer or no coating at all. The multi-layer coatings delayed flame spread and showed improved resistance to thermal breakdown.

An important observation relates to the test setup, specifically the ventilated cavity that was constructed behind the facade panels. This cavity led to substantial heat build-up during testing, contributing to the development of a so called chimney effect. This intensified the upward movement of hot gases and flames along the panel surface, accelerating the fire's vertical spread and reducing the test duration.

When analysing the results, it is important to neglect the phase in which large sections of panel fragments began to fall off. At that point, the panel had already undergone severe degradation and the coating was no longer actively influencing the fire behaviour. The assessment of coating performance should therefore only focus on the period during which the panel remained largely structurally intact.

FIGURE 33: EARLY-STAGE DEGRADATION OF UNCOATED PANEL

FIGURE 34: SIDE VIEW OF CHIMNEY EFFECT DURING LINE BURNER TEST

FIGURE 35: ADVANCED PANEL FAILURE NEAR TEST TERMINATION

4.3.2 RESULTS TEMPERATURE PROFILES

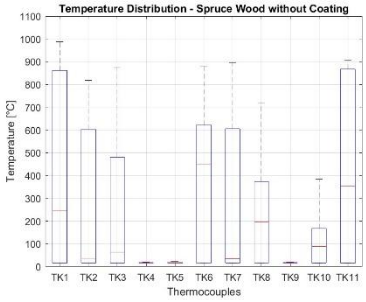
The temperature distribution during the line burner test was recorded using 11 thermocouples (TKs) positioned across the test panels. TK1 to TK10 were placed on the front side of the panel, distributed from top to bottom in a staggered pattern, as shown in Figure 26. TK11 was the only thermocouple located in the centre on the backside, visible in Figure 27.

Several thermocouples (TKs) failed during testing, which impacted the completeness of some temperature recordings. Failures occurred primarily due to extreme heat exposure. In many cases, the adhesive tape used to secure the TKs released as temperatures increased, causing the sensors to detach. In other cases, the thermocouples themselves were damaged or destroyed by direct flame contact. These failures were most common in the middle and lower regions of the panel, where flame intensity was highest (typically TK6 to TK10). As a result, not all TKs recorded the full test duration and some temperature readings are incomplete or missing in the corresponding graphs.

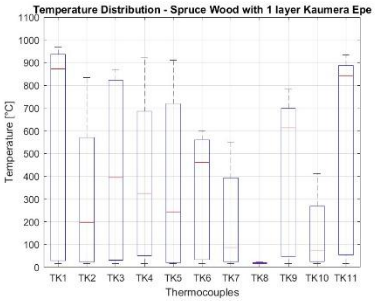
The reference test with uncoated spruce wood shows very high temperature readings, especially in the middle region (TK3 to TK7), with several thermocouples exceeding 900°C. This aligns with expectations of rapid flame spread and high heat exposure due to the absence of any protective layer. However, TK8 and TK10 result in lower recorded values that do not reflect the full temperature exposure, because they detached partway through the test. TK4, TK5 and TK9 were already damaged at the start of the test and therefore did not produce any reliable data.

The working TKs for each Kaumera Epe test show a clear mitigation effect with increasing layer thickness. One layer has little impact, with temperature distributions similar to the uncoated panel. Two and three layers reduce temperatures, indicating delayed ignition and heat penetration. Kaumera Zutphen shows a similar trend, though the two-layer test was affected by external factors such as airflow interference. This causes abnormal fire growth and unusually high temperatures. This data should be interpreted with caution. Lastly, the panels treated with Xyhlo Biofinish also display temperature reductions across all three layer configurations. The three-layer sample, in particular, shows the most working TKs and reduced median temperatures.

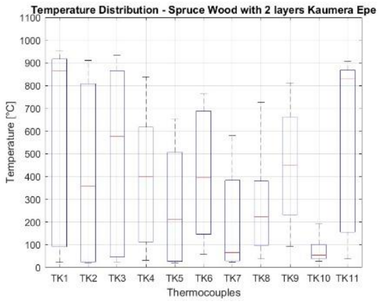
Uncoated spruce wood



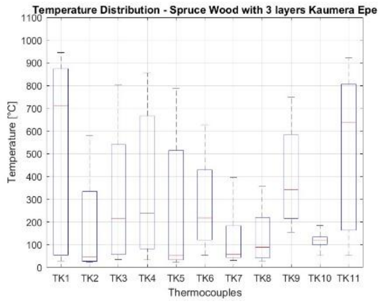
Kaumera Epe, 1 layer



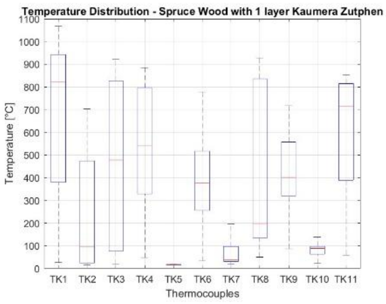
Kaumera Epe, 2 layers



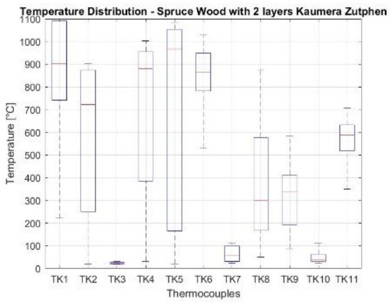
Kaumera Epe, 3 layers



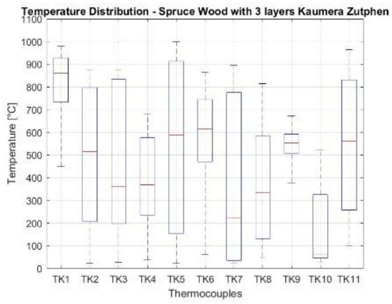
Kaumera Zutphen, 1 layer



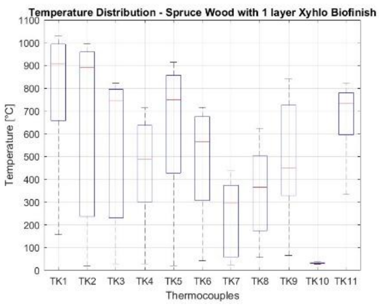
Kaumera Zutphen, 2 layers



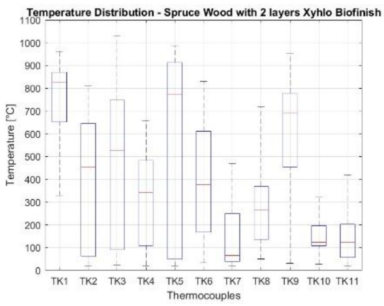
Kaumera Zutphen, 3 layers



Xyhlo Biofinish, 1 layer



Xyhlo Biofinish, 2 layers



Xyhlo Biofinish, 3 layers

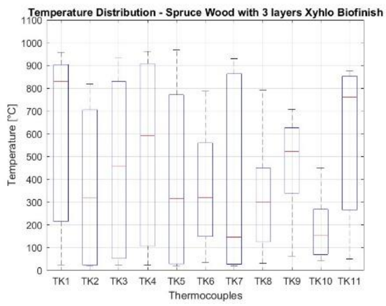


FIGURE 36: BOXPLOTS OF MEASURED TEMPERATURES FOR DIFFERENT THERMOCOUPLE POSITIONS – LINE BURNER TESTS

4.3.3 Results Mass Loss

Two types of trend analyses were conducted on the mass loss data: one considering the entire test duration (Table 6) and one focusing specifically on the active burning phase (Table 7).

The mass loss trendlines fitted over the full test duration provide insights into the total combustion behaviour of the test samples. The uncoated panel shows a mass loss rate of 0.664 kg/min/m² with an R^2 of 0.951, which serves as the reference for evaluating the effectiveness of the coatings.

The Kaumera Epe series shows a clear trend: increasing the number of layers reduces the mass loss rate significantly. With one layer, the mass loss rate is 0.723 kg/min/m², which is higher than the uncoated panel. However, with two and three layers, the rate drops to 0.522 kg/min/m² and 0.455 kg/min/m². Notably, the coefficient of determination declines with more layers, suggesting that the mass loss becomes less linear with increasing protection.

This is supported by the trendline graphs in Figure 37 on the next page. For the Kaumera Epe 1-layer coating, the mass loss follows a nearly linear pattern (R^2 = 0.988), suggesting a consistent rate of degradation. In contrast, the 3-layer coating graph displays a curve, deviating from the linear trend (R^2 = 0.850). This non-linear behaviour suggests a delayed or phased combustion process, where the thicker coating slows down ignition and burning more gradually, offering protection in a non-uniform manner.

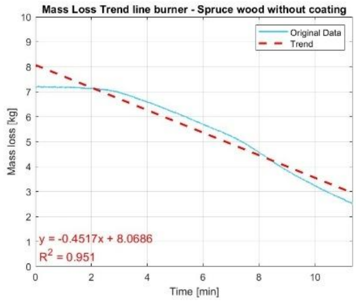
Table 6: Mass loss trendline parameters over full test duration – line burner tests

Samples	Mass loss rate (per 0.68 m²)	Mass loss rate (per m²)	Coefficient of determination R^2
Without coating	0.4517 kg/min	0.664 kg/min/m²	0.951
Kaumera Epe, 1 layer	0.4950 kg/min	0.723 kg/min/m²	0.988
Kaumera Epe, 2 layers	0.3551 kg/min	0.522 kg/min/m²	0.921
Kaumera Epe, 3 layers	0.3097 kg/min	0.455 kg/min/m²	0.850
Kaumera Zutphen, 1 layer	0.3769 kg/min	0.554 kg/min/m²	0.953
Kaumera Zutphen, 2 layers	0.4735 kg/min	0.696 kg/min/m²	0.963
Kaumera Zutphen, 3 layers	0.4426 kg/min	0.651 kg/min/m²	0.968
Xyhlo biofinish, 1 layer	0.5154 kg/min	0.758 kg/min/m²	0.989
Xyhlo biofinish, 2 layers	0.4961 kg/min	0.730 kg/min/m²	0.968
Xyhlo biofinish, 3 layers	0.4152 kg/min	0.611 kg/min/m²	0.924

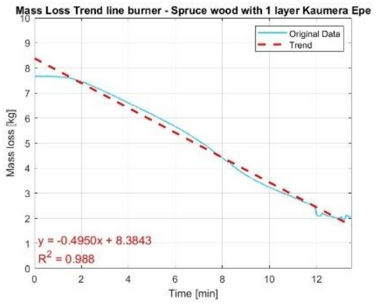
The Kaumera Zutphen samples showed inconsistent trends in the line burner tests. While the 1-layer sample appeared to perform better than the uncoated panel, the 2- and 3-layer samples unexpectedly showed higher mass loss rates. This contrasts with the radiant panel results, where Zutphen and Epe performed similarly. These inconsistencies may be due to experimental variability, such as uneven coating, surface defects in the wood or slight misalignment of the panel relative to the line burner during testing.

The Xyhlo Biofinish samples show relatively high mass loss rates overall, especially with one and two layers (0.758 and 0.730 kg/min/m²). However, the results show a clear improvement with increased coating thickness, as the 3-layer sample achieved a lower mass loss rate of 0.611 kg/min/m². Similar to the Kaumera Epe samples, the trendline graphs indicate a more curved mass loss profile as the number of layers increases, suggesting that the thicker coating slows down the combustion process in a non-linear manner.

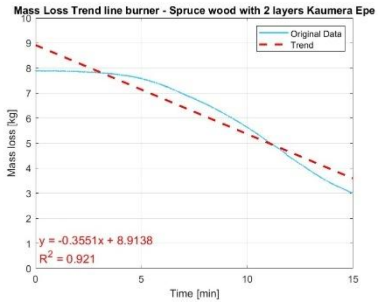
Mass loss uncoated panel



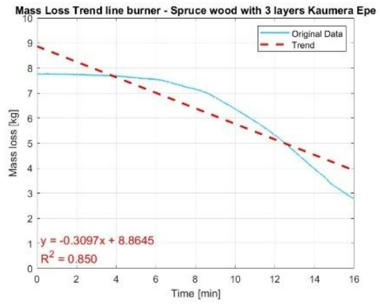
Kaumera Epe, 1 layer



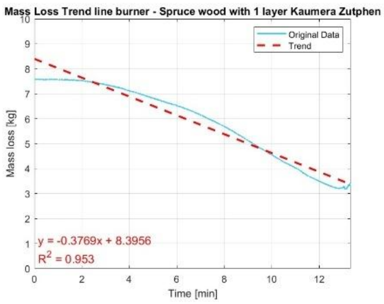
Kaumera Epe, 2 layers



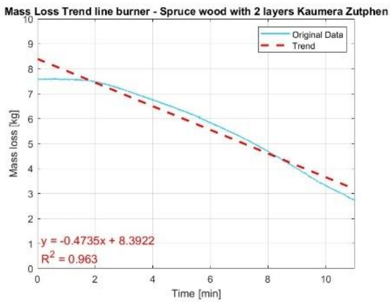
Kaumera Epe, 3 layers



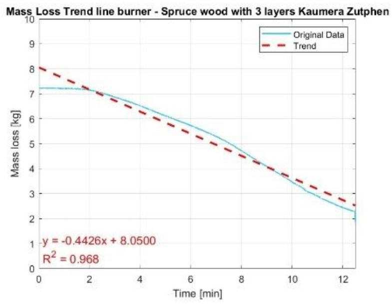
Kaumera Zutphen, 1 layer



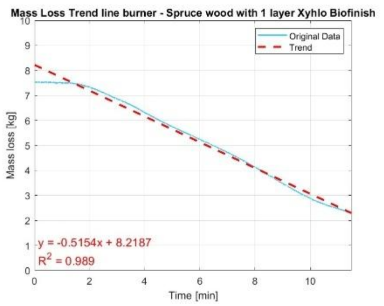
Kaumera Zutphen, 2 layers



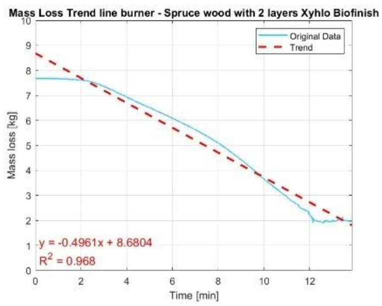
Kaumera Zutphen, 3 layers



Xyhlo Biofinish, 1 layer



Xyhlo Biofinish, 2 layers



Xyhlo Biofinish, 3 layers

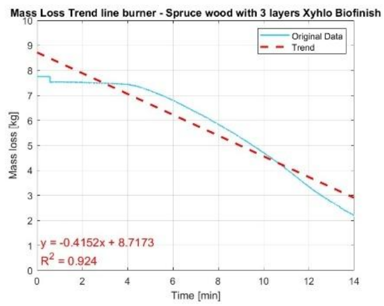


FIGURE 37: MASS LOSS WITH LINEAR TRENDLINE OVER ENTIRE TEST DURATION – LINE BURNER TESTS

To better compare combustion behaviour under direct flame exposure, a second trend analysis was performed on the active burning phase only. The results are visible in Table 7. By excluding the initial heating and post-degradation periods, this approach gives a clearer view of the burn rate after full ignition. All samples showed R^2 values above 0.990, indicating a highly linear and stable mass loss during this phase.

As expected, the mass loss rates during this active phase are higher than those calculated over the full test duration. This is because combustion is the most intense during this period. The uncoated panel recorded the highest mass loss rate at 0.889 kg/min/m², which serves as the benchmark for evaluating the performance of the coated samples.

The Kaumera Epe samples demonstrate a consistent reduction in burning rate with the addition of coating layers. While the 1-layer sample shows a slightly lower rate than the reference, the 2- and 3-layer panels both dropped to 0.738 and 0.737 kg/min/m². This suggests that the major benefit of the coating is already achieved with two layers and additional layers provide minor benefits.

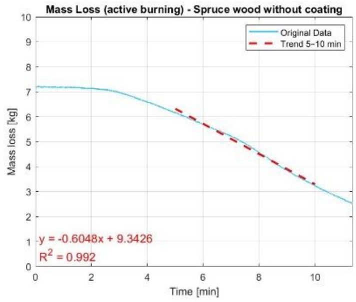
The Kaumera Zutphen samples, however, showed more variation. The 1-layer sample performed moderately well. Although the 2-layer panel unexpectedly shows a higher burn rate, the 3-layer panel improved again to 0.793 kg/min/m². The trend is not consistent, but the values still indicate some level of improvement compared to the uncoated sample. These results align with the inconsistencies observed over the full test duration and may again point to experimental variability or inconsistencies in coating application.

Table 7: Mass loss trendline parameters during active burning phase – line burner tests

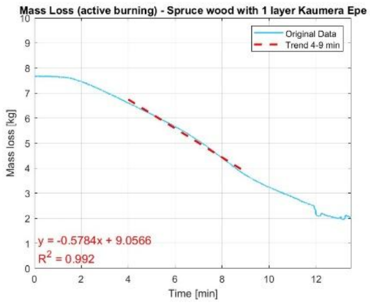
Samples	Mass loss rate (per 0.68 m²)	Mass loss rate (per m²)	Coefficient of determination R^2
Without coating	0.6048 kg/min	0.889 kg/min/m²	0.992
Kaumera Epe, 1 layer	0.5784 kg/min	0.851 kg/min/m²	0.992
Kaumera Epe, 2 layers	0.5019 kg/min	0.738 kg/min/m²	0.994
Kaumera Epe, 3 layers	0.5011 kg/min	0.737 kg/min/m²	0.993
Kaumera Zutphen, 1 layer	0.5212 kg/min	0.766 kg/min/m²	0.996
Kaumera Zutphen, 2 layers	0.6114 kg/min	0.899 kg/min/m²	0.996
Kaumera Zutphen, 3 layers	0.5392 kg/min	0.793 kg/min/m²	0.992
Xyhlo biofinish, 1 layer	0.5812 kg/min	0.855 kg/min/m²	0.997
Xyhlo biofinish, 2 layers	0.5584 kg/min	0.821 kg/min/m²	0.988
Xyhlo biofinish, 3 layers	0.5215 kg/min	0.767 kg/min/m²	0.997

The Xyhlo Biofinish series shows a clearer and more expected trend. Mass loss rates decreased progressively from 0.855 kg/min/m² (1 layer) to 0.767 kg/min/m² with 3 layers. This matches the performance level of the Kaumera Epe 3-layer sample.

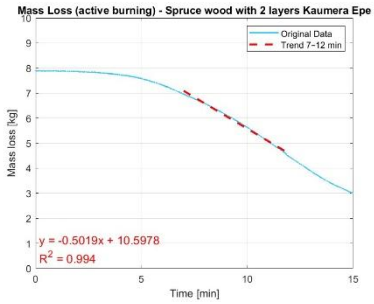
Mass loss uncoated panel



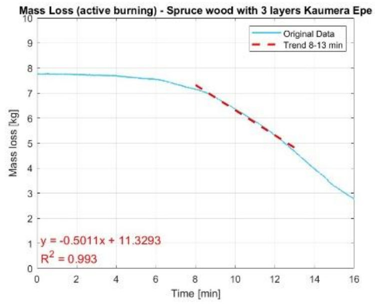
Kaumera Epe, 1 layer



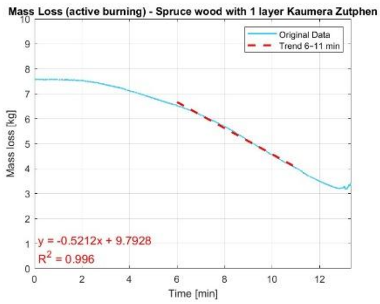
Kaumera Epe, 2 layers



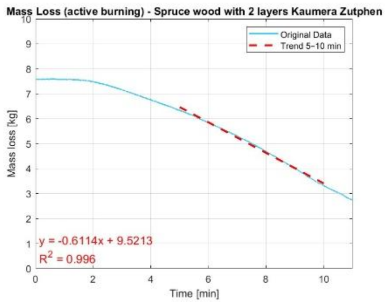
Kaumera Epe, 3 layers



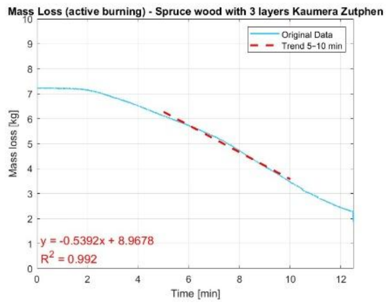
Kaumera Zutphen, 1 layer



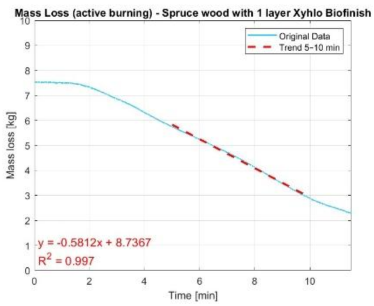
Kaumera Zutphen, 2 layers



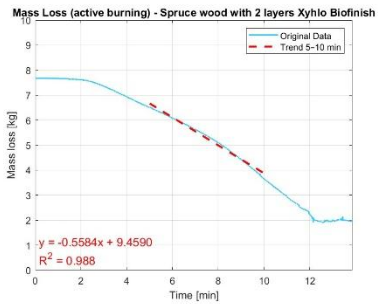
Kaumera Zutphen, 3 layers



Xyhlo Biofinish, 1 layer



Xyhlo Biofinish, 2 layers



Xyhlo Biofinish, 3 layers

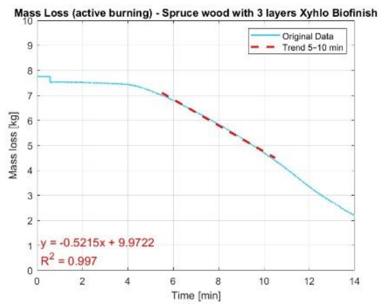


FIGURE 38: MASS LOSS WITH LINEAR TRENDLINE DURING ACTIVE BURNING PHASE – LINE BURNER TESTS

5 Evaluation

This chapter provides a critical evaluation of the experimental results in relation to the research sub-questions introduced in section 1.1. By analysing the fire performance of the treated facades, the chapter explores how these coatings influenced ignition behaviour, thermal degradation, fire spread and associated risks. Each section addresses one specific aspect of the fire behaviour, based on the structure of the sub-questions.

5.1 Ignition Behaviour of Treated Facades

The results from the radiant panel tests revealed that untreated wood and most single- and double-layer coatings (Kaumera and Xyhlo) ignited quickly after exposure to the pilot flame. However, triple-layer Kaumera samples showed increased resistance to ignition, requiring multiple attempts. This suggests that layer thickness significantly affects ignition resistance, with Kaumera outperforming Xyhlo in this respect. Mycelium-treated panels did not ignite at all, showing no visible flames and indicating a suppression of flaming combustion. While this is promising, it should be interpreted with caution due to the high mass loss rate, which raises concerns about long-term stability.

In the line burner tests, all samples ignited eventually, given the continuous direct flame exposure. However, coating thickness once again influenced the ignition timeline and flame spread, with multi-layered Kaumera and Xyhlo panels showing slower and more delayed ignition patterns than untreated wood or thinner coatings.

Overall, while ignition could not be prevented under intense flame exposure, the probability of ignition under radiant heat was clearly reduced by increasing coating thickness. Mycelium also showed strong potential in suppressing flaming combustion, despite concerns regarding its adhesion.

5.2 Thermal and Structural Degradation

Thermal degradation was assessed through visible observations, temperature profiles and mass loss rates. Under radiant heat, untreated wood reached the highest temperatures, confirming its vulnerability. Kaumera-treated panels (especially with 2 or 3 layers) demonstrated lower and most stable temperatures, indicating effective insulation and thermal protection. Xyhlo Biofinish also improved thermal stability, showing consistent performance across samples. Mycelium-treated panels exhibited unexpectedly high surface temperatures, likely due to detachment of the surface layer, suggesting that while they suppressed flaming, they do not prevent heat transfer effectively.

In addition to visual observations and temperature profiles, the produced surface heat flux was compared to the received heat flux to assess the panels' ability to sustain combustion. As explained in section 4.2.3, the average received heat flux across the panel surface was calculated as 13.17 kW/m^2. When comparing this to the produced surface heat flux derived from mass loss rates, differences were observed between configurations. Untreated wood and most single-layer coatings generated a produced heat flux significantly higher than the received heat flux, indicating a potential for self-sustained combustion once the external heat source is removed. However, panels treated with multiple layers of Kaumera or Xyhlo showed a notable reduction in produced heat flux. In particular, samples with three layers of Kaumera Zutphen or Xyhlo Biofinish produced less heat than they received, confirming self-extinguishing behaviour. These results quantitatively support earlier observations. They suggest that applying multiple bio-based coating layers can limit combustion intensity and reduce the likelihood of sustained burning.

In the line burner tests, all coatings eventually failed to prevent material breakdown. However, degradation was noticeably slower for panels with three layers of Kaumera or Xyhlo. Nevertheless, once the panels began to lose structural integrity through delamination, the coatings could no longer provide meaningful protection. From a fire safety perspective, these findings imply that bio-based coatings can delay structural degradation and thermal transfer, but they cannot replace non-combustible barriers.

5.3 Factors Influencing Fire Spread

The spread of fire across the facade panels was influenced by several associated parameters. One of the most critical factors was the coating thickness. Panels treated with multiple layers of Kaumera or Xyhlo showed significantly slower vertical flame spread compared to untreated or thinly coated samples. Thicker coatings were more successful in delaying fire growth, as they provided additional thermal resistance and expanded the integrity of the protective layer during the early stages of exposure.

The ratio between produced and received surface heat flux further illustrates these dynamics. As shown in the radiant panel tests, untreated wood and thinly coated samples exhibited produced heat flux values exceeding the received heat flux, indicating that the energy released by the material itself was sufficient to support continued combustion and flame spread. In contrast, panels with more layers of the bio-based coatings produced less heat than they received, resulting in self-extinguishing behaviour and reduced flame spread potential. These findings underline that reducing combustion intensity through optimised coatings plays a crucial role in limiting fire spread.

Material composition also played an important role. Kaumera Epe tended to outperform Kaumera Zutphen and Xyhlo in resisting flame spread, particularly in the line burner tests. This difference could be related to subtle variations in the chemical or physical structure of the coatings. Moreover, the consistency of coating application plays a role. Panels with unevenly applied coatings, especially near edges or joints, often exhibited earlier ignition points or local flame acceleration.

The experimental setup itself further impacted flame propagation. The ventilated cavity behind the panels in the line burner test created a chimney effect that intensified the upward movement of heat and flames, resulting in accelerated vertical fire spread. This effect mimics real-world scenarios where ventilated facades or poorly compartmentalized cavities can lead to rapid fire escalation.

Taken together, these findings demonstrate that both material-related and setup-related parameters interact to influence fire spread dynamics. Even coatings with strong fire-retardant potential can be compromised by structural weaknesses, detailing flaws or heat buildup driven by ventilation. As a result, effective fire spread prevention cannot depend only on material performance. It must also account for facade system design, including coating continuity and cavity detailing.

5.4 Fire Risks of Bio-based Coatings

The application of bio-based coatings introduces both fire-retardant benefits and new fire risks that must be critically considered in facade design. One major concern is the emission of visible vapours and potentially hazardous gases during heating. This was particularly noted in the Kaumera samples, which released a strong odour and visible smoke. While this was not quantitatively analysed in the current study, it suggests the possibility of toxic compounds released during combustion.

Additionally, none of the coatings fully prevented fire spread or combustion under prolonged flame exposure, highlighting their limitations when used without complementary fire-resistant barriers. The results also revealed sample-to-sample variability in coating behaviour, likely due to minor inconsistencies in application or panel quality, which can introduce unpredictable behaviour during fire events.

5.5 Fire Safety and Sustainability Balance

The experimental findings illustrate the complex relationship between sustainability and fire safety when using bio-based coatings. Both Kaumera and Xyhlo Biofinish show a slight improvement in fire performance, particularly by reducing ignition risk and slowing combustion. However, Kaumera is still in an early stage of development. While it shows potential in the fire tests, its environmental durability is still under investigation. In particular, Kaumera's ability to protect wood surfaces against rain, UV exposure and temperature fluctuations remains uncertain. It is not yet clear whether Kaumera can function as a reliable outdoor coating on its own. Until further data is available, its role may be best suited to protected or hybrid façade systems.

Xyhlo Biofinish, on the other hand, is a biologically based coating specifically designed for outdoor use, as described in section 2.3.3.1. It combines durability, moisture resistance and self-repairing properties with a fully circular material cycle. These characteristics contribute to strong environmental performance and make it suitable for long-term facade protection, particularly where reduced maintenance is desired.

The balance between sustainability and safety is also influenced by coating thickness. Applying more layers enhances fire protection, but it also increases material usage, which could offset some of the environmental advantages. Remarkably, while these coatings improved fire performance compared to untreated wood, they did not match the reliability of synthetic or mineral-based fire-resistant systems.

This means that achieving sustainability gains with bio-based coatings must involve trade-offs. Their implementation should always be supported by broader structural fire safety measures. These coatings may be particularly useful in combination with fire stops or applied in low-rise timber construction, where delayed ignition and flame spread can still provide a meaningfully reduction in fire risk.

6 Conclusion and Recommendations

This chapter presents a concluding overview based on the evaluation of experimental results. It directly addresses the central research question concerning the fire behaviour of Kaumera, Xyhlo Biofinish and Mycelium when applied to spruce wooden facades. The aim is to determine not only whether these coatings offer effective fire protection, but also how they can be responsibly applied in practice and what limitations currently exist.

6.1 Conclusion

In addressing the primary research question, "*How do the bio-based coatings Kaumera, Xyhlo Biofinish and Mycelium impact the fire risk and behaviour of spruce wooden facades under radiant heat and direct flame exposure?*", several key findings have emerged.

Kaumera coatings, particularly when applied in two or three layers, consistently demonstrated improvement in fire behaviour. These coatings reduced ignition probability, suppressed flame duration, lowered surface temperatures and limited material degradation during exposure to both radiant heat and direct flames. Xyhlo Biofinish also contributed positively to fire performance, showing stable thermal behaviour and reduced combustion rates. Across these tested materials, coating thickness emerged as a critical factor. Thicker coatings consistently led to better fire resistance outcomes, including delayed ignition and slower mass loss.

A clear, quantitative finding for the observed improvements in combustion resistance was provided by the relationship between the produced and received surface heat flux. The received heat flux across the panel surface averaged 13.17 kW/m², representing the thermal energy applied by the radiant source. Untreated wood and most single-layer coatings produced more heat than they received, indicating potential for sustained combustion. In contrast, multiple layers of Kaumera or Xyhlo significantly reduced the produced heat flux. With three layers of Kaumera Zutphen or Xyhlo Biofinish, the produced heat flux dropped below the received value, confirming self-extinguishing behaviour.

However, despite these improvements, none of the tested bio-based coatings were able to prevent full combustion or sustained flame spread under prolonged fire exposure. This highlights that while such coatings enhance fire performance, they remain insufficient as stand-alone fire protection and must be combined with other safety measures.

Mycelium, the third tested material, showed promising resistance to ignition under radiant exposure and showed no flaming combustion, which could be beneficial for limiting fire penetration to building interiors. This non-flaming behaviour is especially relevant in preventing upward fire spread along facades, as there are no flames that could reach or bridge over a fire stop. As a result, although Mycelium may not meet formal fire classification requirements, it could still offer a targeted fire safety solution by limiting vertical fire development in facade zones.

The study also identified several fire-related risks, such as the release of vapours and gases during heating, most notably from Kaumera. Moreover, the detachment of coating layers, especially in the case of Mycelium, raises concerns regarding long-term adhesion and mechanical stability. These findings underline the importance of integrating bio-based coatings into a broader fire safety concept, ideally involving additional passive or active protective measures such as fire stops, thermal barriers, or non-combustible backing layers.

6.2 Recommendations

Based on the experimental findings of this study, several practical recommendations can be made regarding the use of bio-based coatings in facade applications.

Before further research into fire performance, it is strongly recommended to first determine whether these bio-based coatings can function effectively as wood protection agents. Their long-term value depends on offering reliable resistance to environmental factors such as moisture, UV exposure and biological degradation. Only when durability is confirmed it becomes meaningful to investigate their combustion properties. This is because their practical relevance relies on combining protective durability with fire-retardant properties.

Once durability is established, optimising fire performance should focus on applying at least two to three layers of Kaumera or Xyhlo Biofinish. Thicker coatings demonstrated more stable temperature profiles, reduced flame duration and slower combustion rates, making them more suitable for use in building envelopes where limited fire exposure resistance is required. However, these coatings should never be used in isolation. They should be incorporated into facade systems that include additional fire safety features, such as fire stops or cavity barriers. In this context, the coatings serve a supportive function, improving but not replacing more established protection systems.

A further recommendation concerns emissions safety. During testing, vapour emissions were observed, raising questions about the potential release of toxic compounds during combustion. Manufacturers should be encouraged to conduct emissions testing and clearly communicate the chemical composition and combustion byproducts of their coatings. Comprehensive fire safety documentation and labelling should accompany the commercial use of these materials.

Finally, the study underscores the importance of quality control during coating application. Small inconsistencies in thickness or substrate condition were shown to influence fire performance, highlighting the need for standardized application procedures. Consistent and well-documented installation is essential to ensure reproducible behaviour in practice.

Ultimately, bio-based coatings like Kaumera, Xyhlo Biofinish and Mycelium offer a valuable contribution to the sustainable development of building envelopes. Their capacity to delay ignition and reduce fire spread supports a more balanced approach to combining environmental performance with fire safety. Nevertheless, their role is best understood as complementary, enhancing but not replacing traditional fire safety strategies. Their future lies in hybrid systems where sustainability and fire protection go hand in hand.

6.3 Limitations and Assumptions

To accurately interpret the findings of this study, it is important to acknowledge its limitations and the assumptions made during the research process.

6.3.1 Research Limitations

This research was conducted within a defined experimental scope and under laboratory conditions, which introduced several limitations. The study focused exclusively on external facade applications and did not extend to interior uses of Kaumera or Xyhlo Biofinish. While the tests provide valuable comparative data, they do not fully replicate the dynamic and unpredictable nature of real fire scenarios. Environmental conditions such as wind, moisture and architectural detailing could significantly influence fire behaviour in real applications.

In the radiant panel test, the average radiant heat flux was lower than intended due to geometry and setup limitations, reaching approximately 13 kW/m² instead of the target 15 kW/m². This may have reduced ignition likelihood. Similarly, in the line burner test, the cavity created behind the panels intensified the vertical spread of flames due to a chimney effect. This could have been mitigated by sealing the top of the cavity with a non-combustible material, such as stone wool, which would have reduced convective heat transfer and resulted in a more controlled evaluation of coating performance.

Durability aspects of the coatings were not assessed in this study. This includes their resistance to UV exposure, ability to protect wood surfaces against rain and biological degradation. These factors are essential to determining the long-term viability of bio-based coatings in real façade systems and must be confirmed before further optimisation of their performance is meaningful.

6.3.2 Research Assumptions

Several assumptions were made to maintain the feasibility and focus of this study. First, it was assumed that the tested bio-based materials exhibited consistent properties across all samples. This assumption allowed for meaningful comparison between configurations, although minor fluctuations in material composition or behaviour may have occurred.

It was also assumed that the manual application of coatings, using a brush or roller, produced representative and repeatable coating layers. While some variation in coating thickness and surface coverage was expected, these were considered small enough not to compromise the validity of the experimental trends.

Furthermore, the laboratory-scale fire testing methods were assumed to provide reliable indicators of facade fire behaviour, even though they cannot fully replicate the complexity of real-world fire scenarios. Variables such as wind, moisture, ventilation effects and building geometry were not simulated, but the test conditions were designed to reflect key aspects of thermal exposure and flame spread.

Lastly, it was assumed that the fire behaviour of Mycelium, as observed in the small-scale radiant panel test, could still provide valuable insights. This was considered valid despite the material not being included in the larger-scale line burner tests due to sample limitations. This assumption was supported by the key observation of smouldering without visible flames, which is an outcome that could shape fire-safety strategies for bio-based facades.

6.4 Future Research

To enable the practical use of bio-based coatings on timber facades, it is essential that these products first provide reliable durability, including protection against moisture and biological degradation. Fire protection can then be added as an additional benefit. This approach is crucial for the successful market implementation of bio-based coatings, as shown by Xyhlo Biofinish, which primarily improves weather resistance while also contributing to fire safety. Whether products such as Kaumera can achieve a similar dual function requires further research. Future bio-based innovations should follow the same principle, with durability and material protection as the starting point before focusing on fire-retardant properties.

Building upon the results of this study, several other directions for future research are recommended. A logical next step is to conduct full-scale facade fire tests using the bio-based coatings. These tests should evaluate performance in realistic facade assemblies, including elements such as windows, cavity insulation and substructure joints. In parallel, future research should explore the chemical composition of vapours and gases released during combustion. Understanding the emissions profile is critical for evaluating health risks to occupants and firefighters, as well as for assessing environmental impact. Emission analysis should be paired with toxicity testing to ensure safe material use in inhabited buildings.

Further research should also focus on standardizing coating application. Coating thickness should be measured to ensure consistency and reproducibility. Exploring automated application techniques, such as controlled spraying, could also improve the uniformity and performance of these coatings.

Finally, there is potential in developing integrated facade systems that combine bio-based coatings with fire stops or other passive fire protection layers. Such hybrid systems could balance sustainability with safety, offering new possibilities in timber-based architecture. The role of bio-based coatings within broader building envelope strategies should be explored through interdisciplinary collaboration between fire engineers, material scientists and architects.

REFERENCES

[1] Asdrubali, F., D'Alessandro, F., & Schiavoni, S. (2015). *A review of unconventional sustainable building insulation materials.* https://doi.org/10.1016/j.susmat.2015.05.002: Sustainable Materials and Technologies, ScienceDirect.

[2] Verspeek, S., & van der Burgh, F. (2019). *Performance of bio-based facades.* 3rd International Conference on Bio-Based Building Materials: Agrodome.

[3] Pomponi, F., & Moncaster, A. (2017). *Circular economy for the built environment: A research framework.* https://doi.org/10.1016/j.jclepro.2016.12.055: Journal of Cleaner Production, ScienceDirect.

[4] Yadav, M., & Agarwal, M. (2021). *Biobased building materials for sustainable future: An overview.* https://doi.org/10.1016/j.matpr.2021.01.165: Materials Today Proceedings, 43, 2895-2902.

[5] Cosentino, L., Fernandes, J., & Mateus, R. (2023). *A Review of Natural Bio-Based Insulation Materials.* https://doi.org/10.3390/en16124676: Energies, MDPI.

[6] Lacy, P., & Rutqvist, J. (2015). *Waste to Wealth - The Circular Economy Advantage.* Palgrave Macmillan London: https://doi.org/10.1057/9781137530707.

[7] Schartel, B., & Hull, T. (2007). *Development of fire-retarded materials—Interpretation of cone calorimeter data.* https://doi.org/10.1002/fam.949: Fire and Materials.

[8] Ecomatters. (2024). *SVHC screening*. Retrieved from Ecomatters - Sustainability: https://www.ecomatters.nl/nl/services/wetgeving/reach/svhc-screening/

[9] Brommer, S., & Harrad, S. (2015). *Sources and human exposure implications of concentrations of organophosphate flame retardants in dust from UK cars, classrooms, living rooms, and offices.* https://doi.org/10.1016/j.envint.2015.07.002: Environment International, ScienceDirect.

[10] United Nations. (2023). *Goal 11: Make cities inclusive, safe, resilient and sustainable*. Retrieved from Sustainable development goals: https://www.un.org/sustainabledevelopment/cities/

[11] Drysdale, D. (2011). *An Introduction to Fire Dynamics, 3rd Edition.* University of Edinburgh, Scotland, UK: John Wiley & Sons.

[12] Quintiere, J. (2006). *Fundamentals of Fire Phenomena.* University of Maryland, USA: John Wiley & Sons.

[13] City Fire Protection. (2020). *Understanding The Fire Triangle*. Retrieved from https://www.cityfire.co.uk/news/understanding-the-fire-triangle/

[14] Science Ready. (2025). *Heat Transfer: Conduction, Convection and Radiation*. Retrieved from https://scienceready.com.au/pages/conduction-convection-and-radiation.

[15] van Herpen, R. (2023). 2. Natural fires. Eindhoven University of Technology: 7LY4M0 Fire Safety.

[16] Karlsson, B., & Quintiere, J. (2000). *Enclosure Fire Dynamics.* Florida, U.S.: CRC Press LLC.

[17] Hagen, R., & Witloks, L. (2014). *The Basis for Fire Safety.* Fire Safety Professorship: https://www.europeanfiresafetyalliance.org/publications/the-basis-for-fire-safety-substantiating-fire-protection-in-buildings/.

[18] Babrauskas, V. (2003). *Ignition Handbook.* Issaquah WA, USA: Fire Science Publishers.

[19] Babrauskas, V., & Grayson, S. (1992). *Heat release in fires.* Barking: Elsevier Applied Science.

[20] Hurley, M. (2016). *SFPE Handbook of Fire Protection Engineering.* Society of Fire Protection Engineers: Springer Science+Business Media LLC New York.

[21] Mouton, L., Trigaux, D., Allacker, K., & Röck, M. (2022). *Low-tech passive solar design concepts and bio-based material solutions for reducing life cycle GHG emissions of buildings – Life cycle assessment of regenerative design strategies (2/2).* https://doi.org/10.1016/j.enbuild.2022.112678: Energy and Buildings, ScienceDirect.

[22] Allacker, K., Mouton, L., & Röck, M. (2022). *Bio-based building material solutions for environmental benefits over conventional construction products – Life cycle assessment of regenerative design strategies (1/2).* https://doi.org/10.1016/j.enbuild.2022.112767: Energy and Buildings, ScienceDirect.

[23] Bourbia, S., Kazeoui, H., & Belarbi, R. (2023). *A review on recent research on bio-based building materials and their applications.* https://doi.org/10.1007/s40243-023-00234-7: Materials for Renewable and Sustainable Energy, 12(2), 117–139.

[24] Mazzoni, F., & Losacker, S. (2024). *What hinders the transition towards a bio-based construction sector? A global innovation system perspective on its value chain.* https://doi.org/10.1016/j.peg.2024.100023: Progress in Economic Geography.

[25] Lee, P.-H., Juan, Y.-K., Han, Q., & de Vries, B. (2023). *An investigation on construction companies' attitudes towards importance and adoption of circular economy strategies.* https://doi.org/10.1016/j.asej.2023.102219: Ain Shams Engineering Journal.

[26] Belahoucine, M. (2025). *Bio-based Fire-Resistant Materials: A Revolution in Sustainable Construction*. Retrieved from https://www.greendesignconsulting.com/single-post/bio-based-fire-resistant-materials-a-revolution-in-sustainable-construction.

[27] NEN-EN 13501-1. (2019). *Fire classification of construction products and building elements - Part 1: Classification using data from reaction to fire tests.* Koninklijk Nederlands Normalisatie Instituut.

[28] Peutz. (2024). *Classificatie Xyhlo Biofinish.* Laboratorium voor brandveiligheid: EN 13823 - SBI - Meetblad beproeving.

[29] Engel, T., & Werther, N. (2023). *Structural Means for Fire-Safe Wooden Façade Design*. https://doi.org/10.1007/s10694-021-01174-2: Fire Technol 59, 117–151.

[30] WFM Media. (2024, May 21). *Façade Designing and Material Selection for Fire-Safe Buildings*. Retrieved from https://wfmmedia.com/facade-designing-and-material-selection-for-ensuring-fire-protection/.

[31] Ngo, T. (2020). *Development of sustainable flame-retardant materials*. https://doi.org/10.1680/jgrma.19.00060: Green Materials, 8(3), 101–122.

[32] Münstermann, N., & Weichold, O. (2024). *A fire-retardant coating for wood made from chitosan itaconate*. https://doi.org/10.1016/j.porgcoat.2024.108793: Progress in Organic Coatings, ScienceDirect.

[33] Chulikavit, N., Wang, C., Huynh, T., Yuen, A. C., Khatibi, A., & Kandare, E. (2023). *Fireproofing flammable composites using mycelium: Investigating the effect of deacetylation on the thermal stability and fire reaction properties of mycelium*. https://doi.org/10.1016/j.polymdegradstab.2023.110419: Polymer Degradation and Stability, ScienceDirect.

[34] Lee, Y. X., Wang, W., Lei, Y., Xu, L., Agarwal, V., Wang, C., & Yeoh, G. H. (2024). *Flame-retardant coatings for wooden structures*. https://doi.org/10.1016/j.porgcoat.2024.108903: Progress in Organic Coatings, ScienceDirect.

[35] Zhang, X., Fan, X., Han, C., Li, Y., Price, E., Wnek, G., . . . Yu, X. (. (2021). *Novel strategies to grow natural fibers with improved thermal stability and fire resistance*. https://doi.org/10.1016/j.jclepro.2021.128729: Journal of Cleaner Production, ScienceDirect.

[36] Reinasan. (2024). *Wat zijn Hyfen?* Retrieved from https://reinasan.nl/kennisbank/schimmels/hyfen/

[37] van der Hoeven, D. (2020, April 7). *Mycelium als bouwmateriaal*. Retrieved from BioBasedPress: https://www.biobasedpress.eu/nl/2020/04/mycelium-als-bouwmateriaal/

[38] Alaneme, K., Anaele, J., Oke, T., Kareem, S., Adediran, M., Ajibuwa, O., & Anabaranze, Y. (2023). *Mycelium based composites: A review of their bio-fabrication procedures, material properties and potential for green building and construction applications*. Elsevier: https://www.sciencedirect.com/science/article/pii/S1110016823008979.

[39] Holcim Foundation. (2014). *Hy-Fi*. Retrieved from https://www.holcimfoundation.org/projects/hy-fi

[40] Biobased Creations. (2024, February 9). *The Growing Pavilion*. Retrieved from https://biobasedcreations.com/project/the-growing-pavilion/

[41] Material matters. (2023). *Mycelium Lab*. Retrieved from https://materialmatters.design/Mycelium-Lab

[42] The Growing Pavilion. (2022). *Material Atlas*. Retrieved from https://thegrowingpavilion.com/material-atlas/

[43] Kaumera, Het project. (2025). *Over Kaumera*. Retrieved from https://kaumera.com/nl/over-kaumera/het-project

[44] Kaumera, Nereda® Zuiveringstechnologie. (2025). *Technologie*. Retrieved from https://kaumera.com/nl/technologie/neredar-zuiveringstechnologie

[45] Kaumera, Grondstoffabrieken. (2025). *Technologie*. Retrieved from https://kaumera.com/nl/technologie/grondstoffabrieken-zutphen-epe

[46] HDSR. (2024). *Kaumera*. Retrieved from Hoogheemraadschap De Stichtse Rijnlanden: https://www.hdsr.nl/werk/werken-we-samen/rioolwaterzuivering/kaumera/

[47] Kaumera, Extractieproces. (2025). *Technologie*. Retrieved from https://kaumera.com/nl/technologie/kaumera-extractieproces

[48] Kaumera, Bodem en gewas. (2025). *Marktsegmenten*. Retrieved from https://kaumera.com/nl/marktsegmenten/ecologische-versterking-bodem-gewas

[49] Kaumera, Industrie en bouw. (2025). *Marktsegmenten*. Retrieved from https://kaumera.com/nl/marktsegmenten/natuurlijke-grondstof-industrie-bouw

[50] Kim, N. K., Mao, N., Lin, R., Bhattacharyya, D., van Loosdrecht, M. C., & Lin, Y. (2019). *Flame retardant property of flax fabrics coated by extracellular polymeric substances recovered from both activated sludge and aerobic granular sludge.* https://doi.org/10.1016/j.watres.2019.115344: Water Research, ScienceDirect.

[51] Kaumera, Vlamvertraging. (2025). *Projecten industrieel gebruik*. Retrieved from https://kaumera.com/nl/vlamvertraging

[52] Xyhlo Biofinish, History. (2025). *Geschiedenis*. Retrieved from https://www.xyhlo.com/bio-finish/geschiedenis/

[53] Xyhlo Biofinish, Innovation in Wood Protection. (2025). *Innovatie houtbescherming*. Retrieved from https://www.xyhlo.com/bio-finish/innovatie-houtbescherming/

[54] Xyhlo Biofinish, About. (2025). *Over Xyhlo biofinish*. Retrieved from https://www.xyhlo.com/bio-finish/

[55] Xyhlo Biofinish, Applications. (2025). *Toepassingen*. Retrieved from https://www.xyhlo.com/toepassingen/

[56] Xyhlo Biofinish, Housing Construction. (2025). *Woningbouw*. Retrieved from https://www.xyhlo.com/toepassingen/woningbouw/

[57] Xyhlo Biofinish, Facade Protection. (2025). *Gevelbekleding*. Retrieved from https://www.xyhlo.com/toepassingen/gevelbekleding/

[58] Peutz Group. (2025). *About Peutz*. Retrieved from https://www.peutz.nl/over-peutz/peutz-group

[59] Isolatie4all. (2024, June 19). *Peutz: Pioniers in(brand-)testen*. Retrieved from https://isolatie4all.nl/peutz-pioniers-inbrand-testen/

[60] Sun, W., Hafez, I., Cole, B. J., & Tajvidi, M. (2024). *A closer examination of white-rot fungal mycelia assisted wood bonding.* https://doi.org/10.1039/d4lf00061g: Royal Society of Chemistry.

[61] Heruc, S., van Herpen, R., Peuling, S., Ortega, F., van Impe, D., & Dohmen, L. (2025). *SBI Fire Testing: Innovative Bio-Based Building Materials.* Presented at the 6th International Conference on Bio-Based Building Materials (ICBBM), Rio de Janeiro, Brazil.

[62] NEN-EN 1363-1. (2020). *Fire resistance tests - Part 1: General requirements - Annex F: Guidance on conditioning.* Koninklijk Nederlands Normalisatie Instituut.

[63] Swedish Wood. (2025). *Properties of softwood*. Retrieved from https://www.swedishwood.com/wood-facts/about-wood/from-log-to-plank/properties-of-softwood/

[64] NEN 6068. (2024). *Determination of the resistance to fire movement between spaces.* Koninklijk Nederlands Normalisatie Instituut.

[65] van Poppel, S. (2023). *Brandgedrag van kruislaaghout onder invloed van warmtestraling.* Enschede: Saxion, Forensisch onderzoek.

[66] Newcastle University. (2025). *Coefficient of Determination, R-squared*. Retrieved from Numeracy, Maths and Statistics - Academic Skills Kit: https://www.ncl.ac.uk/webtemplate/ask-assets/external/maths-resources/statistics/regression-and-correlation/coefficient-of-determination-r-squared.html

[67] ISO 13785-1. (2002). *Reaction-to-fire tests for façades - Part 1: Intermediate-scale test.* International Standard.

[68] Jaskolowski, W., Ogrodnik, P., & Lukaszek-Chmielewska, A. (2014). *The study of time to ignition of woods under external heat flux by piloted ignition and autoignition.* Annals of Warsaw University of Life Sciences: Faculty of Fire Safety Engineering, The Main School of Fire Service (SGSP).

[69] Rantuch, P., Hrusovsky, I., Martinka, J., Balog, K., & Hirle, S. (2017). *Determination of the critical heat flux for floating flooring.* Slovak Republic: Slovak University of Technology in Bratislava, Faculty of Materials Science and Technology In Trnava.

[70] Jones, M., Bhat, T., Kandare, E., Thomas, A., Joseph, P., Dekiwadia, C., . . . Wang, C.-H. (2018). *Thermal Degradation and Fire Properties of Fungal Mycelium and Mycelium - Biomass Composite Materials.* https://doi.org/10.1038/s41598-018-36032-9: Scientific Reports 8, 17583.

[71] NEN-EN 1991-1-2+NB. (2019). *Eurocode 1: Actions on structures - Part 1-2: General actions - Actions on structures exposed to fire.* Koninklijk Nederlands Normalisatie Instituut.

Appendix

A1. Moisture Content Determination of Spruce Wood (Oven-dry Method)

Heat panel test - Sample 1

Sample before drying	Length [mm]	Width [mm]	Thickness/Height [mm]	Weight [g]
Original sample dimensions	298	130	17	298.7

Drying temperature → 105°C

Drying	Date and time of measurement [d-m-y h:m]	Drying time [hours]	Weight [g]	Weight loss of sample	
Measurement 1	28-05-2025 14:39	Dried in oven	298,69	Mass [g]	Relative [%]
Measurement 2	02-06-2025 11:18	>=24	272,24	26,45	8,9
Measurement 3	10-06-2025 11:34	>=24	271,89	0,35	0,1
Measurement 4	17-06-2025 09:02	>=24	271,63	0,26	0,1
				Moisture content of the sample [%]	**10.0**

Heat panel test - Sample 2

Sample before drying	Length [mm]	Width [mm]	Thickness/Height [mm]	Weight [g]
Original sample dimensions	298	129	17	314,9

Drying temperature → 105°C

Drying	Date and time of measurement [d-m-y h:m]	Drying time [hours]	Weight [g]	Weight loss of sample	
Measurement 1	28-05-2025 14:39	Dried in oven	314,87	Mass [g]	Relative [%]
Measurement 2	02-06-2025 11:18	>=24	286,40	28,47	9,0
Measurement 3	10-06-2025 11:34	>=24	286,01	0,39	0,1
Measurement 4	17-06-2025 09:02	>=24	285,79	0,22	0,1
				Moisture content of the sample [%]	**10.2**

HEAT PANEL TEST - SAMPLE 3

Sample before drying	Length [mm]	Width [mm]	Thickness/Height [mm]	Weight [g]
Original sample dimensions	298	126	17	291,3

Drying temperature → 105°C

Drying	Date and time of measurement [d-m-y h:m]	Drying time [hours]	Weight [g]	Weight loss of sample	
Measurement 1	28-05-2025 14:39	Dried in oven	291,25	Mass [g]	Relative [%]
Measurement 2	02-06-2025 11:18	>=24	265,38	25,87	8,9
Measurement 3	10-06-2025 11:34	>=24	265,02	0,36	0,1
Measurement 4	17-06-2025 09:02	>=24	265,06	-0,04	0,0
				Moisture content of the sample [%]	**9.9**

LINE BURNER TEST - SAMPLE 1

Sample before drying	Length [mm]	Width [mm]	Thickness/Height [mm]	Weight [g]
Original sample dimensions	281	93	17	224,1

Drying temperature → 105°C

Drying	Date and time of measurement [d-m-y h:m]	Drying time [hours]	Weight [g]	Weight loss of sample	
Measurement 1	28-05-2025 13:31	Dried in oven	224,06	Mass [g]	Relative [%]
Measurement 2	02-06-2025 11:18	>=24	205,42	18,64	8,3
Measurement 3	10-06-2025 16:48	>=24	205,16	0,26	0,1
Measurement 4	17-06-2025 08:54	>=24	204,98	0,18	0,1
				Moisture content of the sample [%]	**9.3**

LINE BURNER TEST - SAMPLE 2

Sample before drying	Length [mm]	Width [mm]	Thickness/Height [mm]	Weight [g]
Original sample dimensions	275	93	17	181,4

Drying temperature → 105°C

Drying	Date and time of measurement [d-m-y h:m]	Drying time [hours]	Weight [g]	Weight loss of sample	
Measurement 1	28-05-2025 13:31	Dried in oven	181,40	Mass [g]	Relative [%]
Measurement 2	02-06-2025 11:18	>=24	166,10	15,30	8,4
Measurement 3	10-06-2025 16:48	>=24	165,91	0,19	0,1
Measurement 4	17-06-2025 08:54	>=24	165,81	0,10	0,1
				Moisture content of the sample [%]	**9.4**

LINE BURNER TEST - SAMPLE 3

Sample before drying	Length [mm]	Width [mm]	Thickness/Height [mm]	Weight [g]
Original sample dimensions	282	93	18	233,3

Drying temperature → 105°C

Drying	Date and time of measurement [d-m-y h:m]	Drying time [hours]	Weight [g]	Weight loss of sample	
Measurement 1	28-05-2025 13:31	Dried in oven	233,26	Mass [g]	Relative [%]
Measurement 2	02-06-2025 11:18	>=24	214,12	19,14	8,2
Measurement 3	10-06-2025 16:48	>=24	213,84	0,28	0,1
Measurement 4	17-06-2025 08:54	>=24	213,73	0,11	0,1
				Moisture content of the sample [%]	**9.1**

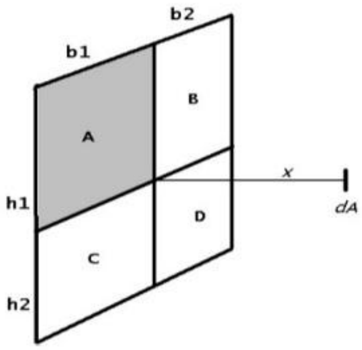
A2. Calculation of Radiant Heat Flux across Test Panel Surface

Radiant Heat Flux at the Centre of the Panel

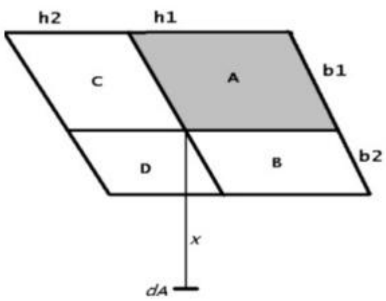
ZICHTFACTOR EN WARMTESTRALINGSFLUX
IN EEN OBSERVATIEPUNT, GELEGEN VOOR EEN STRALEND VLAK

Brongegevens

Qbron =	82	kW/m2	bronstraling
T =	1,0		transmissiecoefficient



stralingsoverdracht tussen vertikale vlakken



stralingsoverdracht tussen horizontale vlakken

Geometrische gegevens

afstand tot vlak x = 0,41 m

hoogte	h1 =	0,20 m		h1/x =	0,4878
	h2 =	0,20 m		h2/x =	0,4878
breedte	b1 =	0,15 m		b1/x =	0,3659
	b2 =	0,15 m		b2/x =	0,3659

zichtfaktoren

F(A) =	0,046	F(C) =	0,046
F(B) =	0,046	F(D) =	0,046

Resultaat

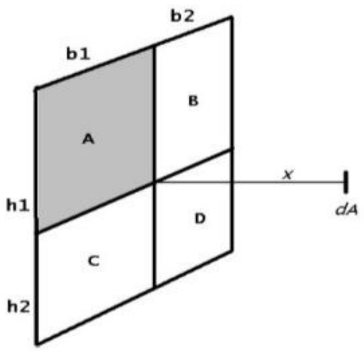
Zichtfaktor (f)	0,183
Warmtestraling	14,98 kW/m^2

RADIANT HEAT FLUX AT THE CORNER OF THE PANEL

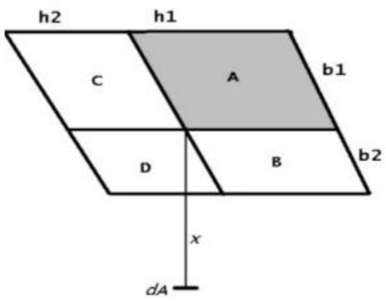
ZICHTFACTOR EN WARMTESTRALINGSFLUX
IN EEN OBSERVATIEPUNT, GELEGEN VOOR EEN STRALEND VLAK

Brongegevens

Qbron =	82	kW/m2	bronstraling
T =	1,0		transmissiecoefficient



stralingsoverdracht tussen vertikale vlakken



stralingsoverdracht tussen horizontale vlakken

Geometrische gegevens

afstand tot vlak x = 0,41 m

hoogte	h1 =	0,04	m	h1/x =	0,0976
	h2 =	0,36	m	h2/x =	0,8780
breedte	b1 =	0,04	m	b1/x =	0,0976
	b2 =	0,26	m	b2/x =	0,6341

zichtfaktoren

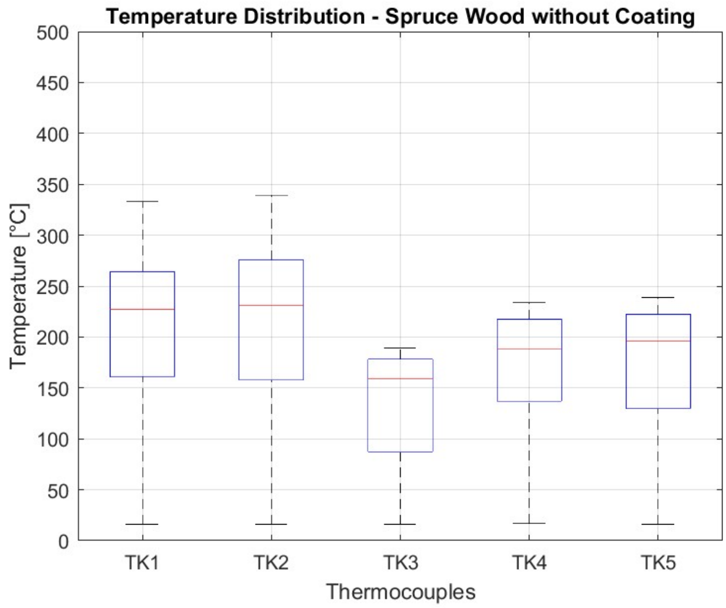
F(A) =	0,003	F(C) =	0,019
F(B) =	0,016	F(D) =	0,101

Resultaat

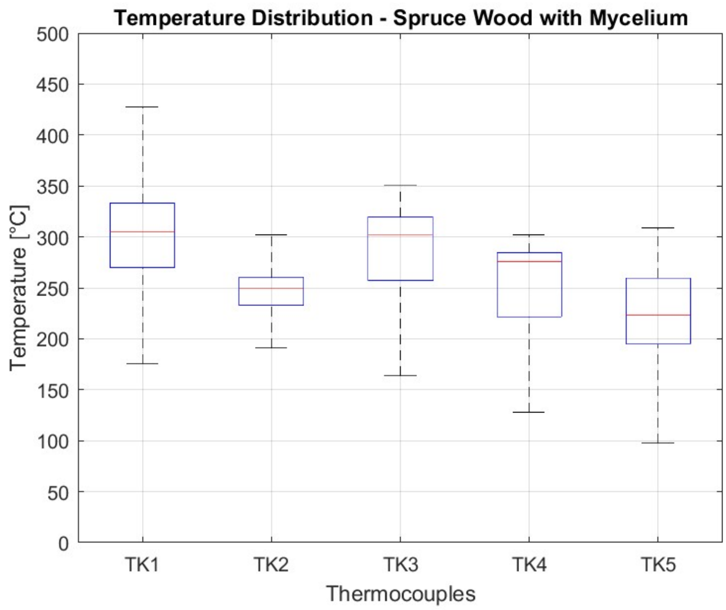
Zichtfaktor (f)	0,139
Warmtestraling	11,36 kW/m^2

A3. Boxplots of Measured Temperatures for different Thermocouple Positions – Radiant panel tests

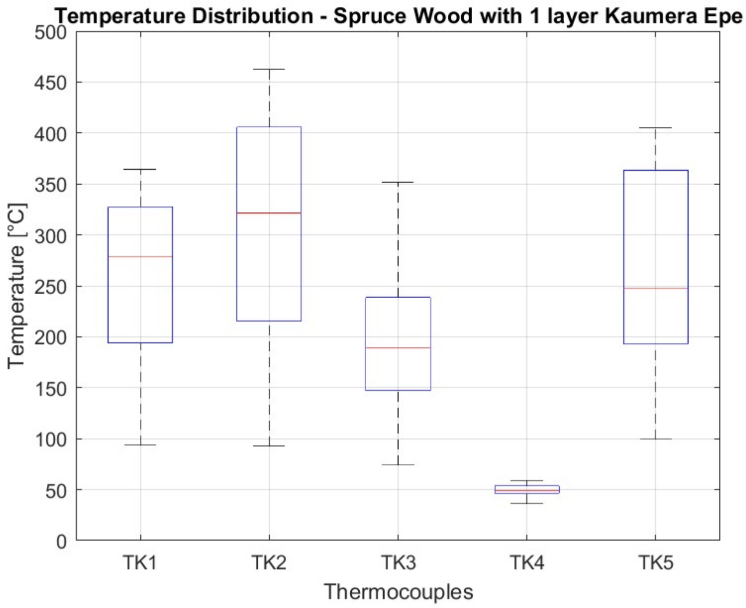
Uncoated spruce wood



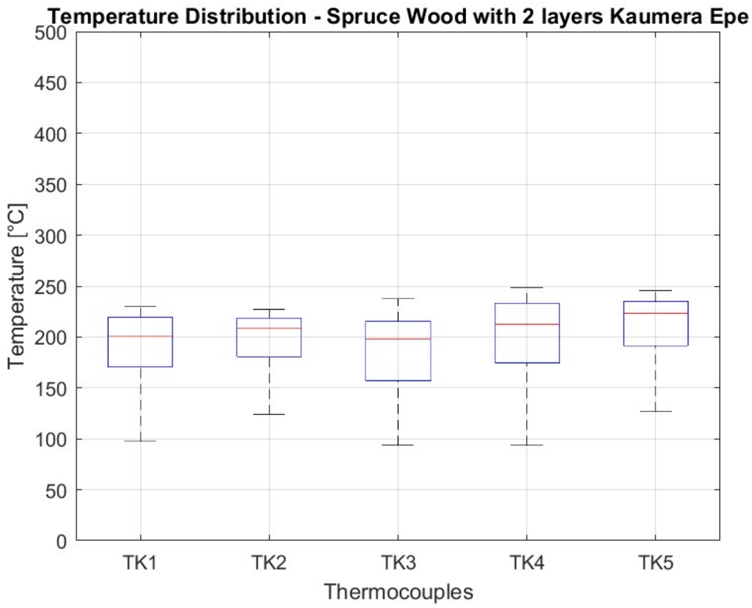
Mycelium



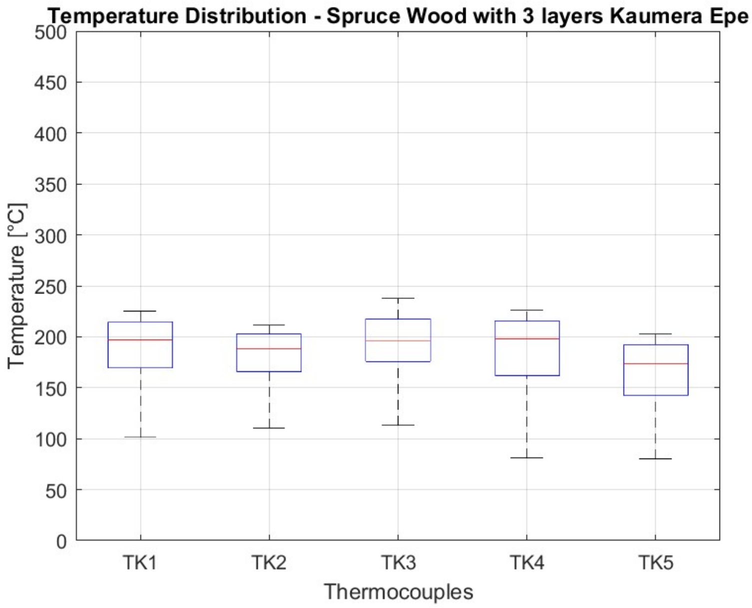
KAUMERA EPE, 1 LAYER



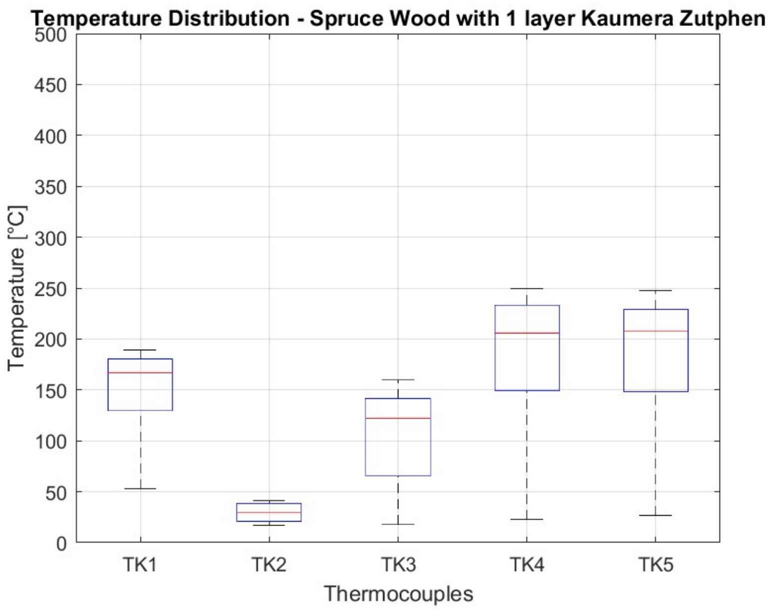
KAUMERA EPE, 2 LAYERS



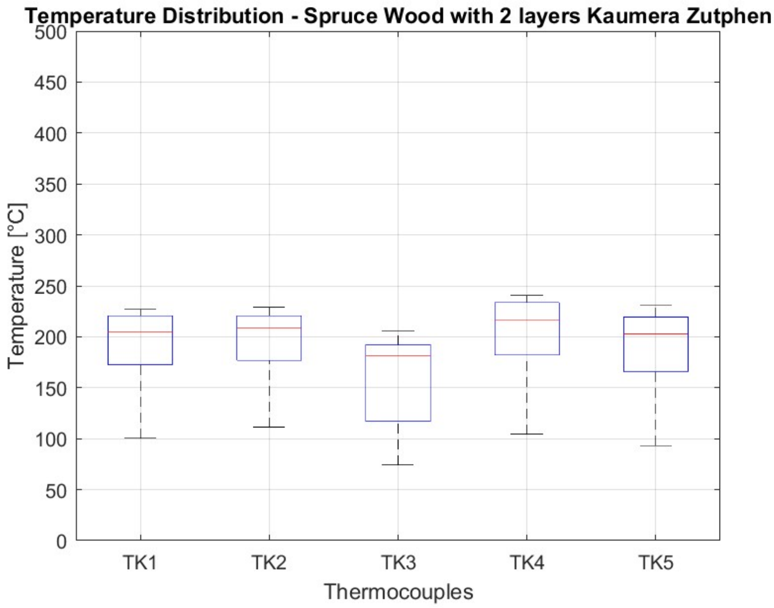
KAUMERA EPE, 3 LAYERS



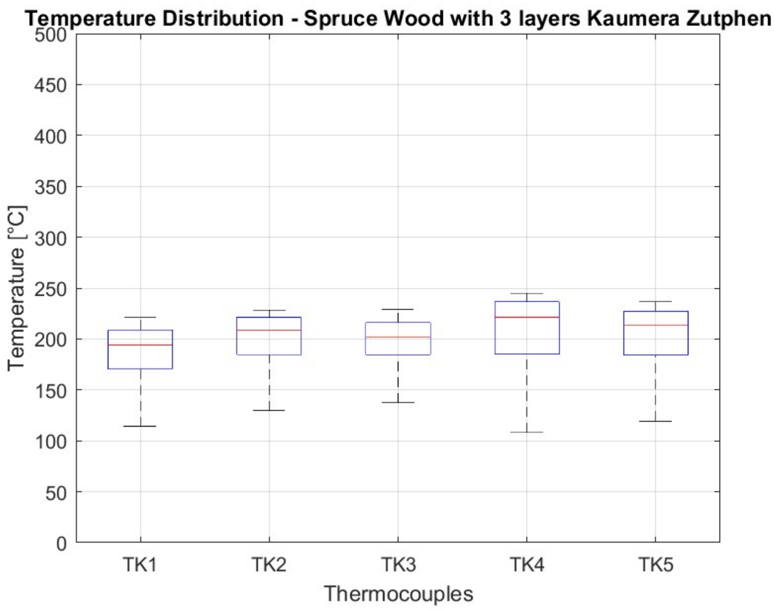
KAUMERA ZUTPHEN, 1 LAYER



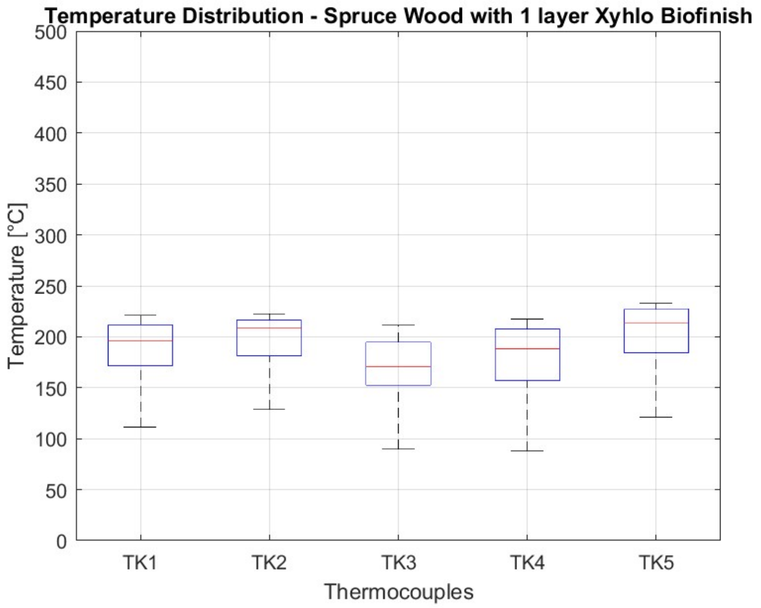
Kaumera Zutphen, 2 layers



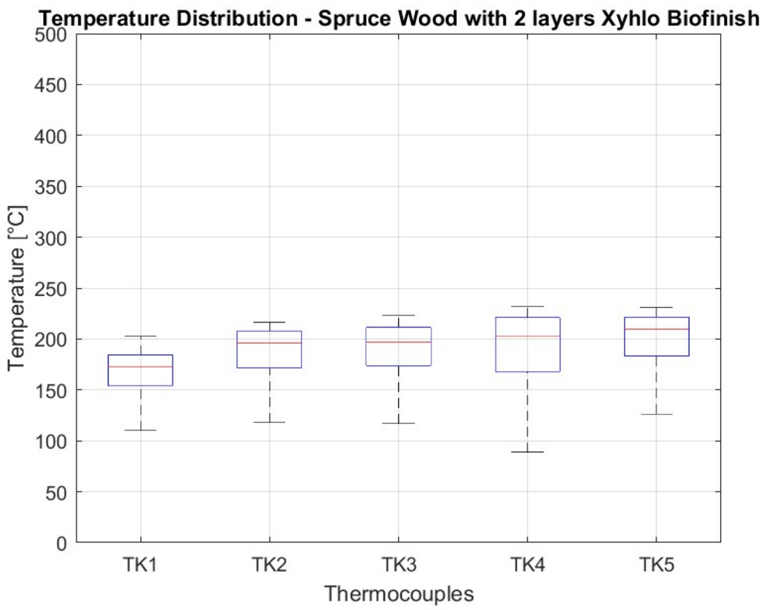
Kaumera Zutphen, 3 layers



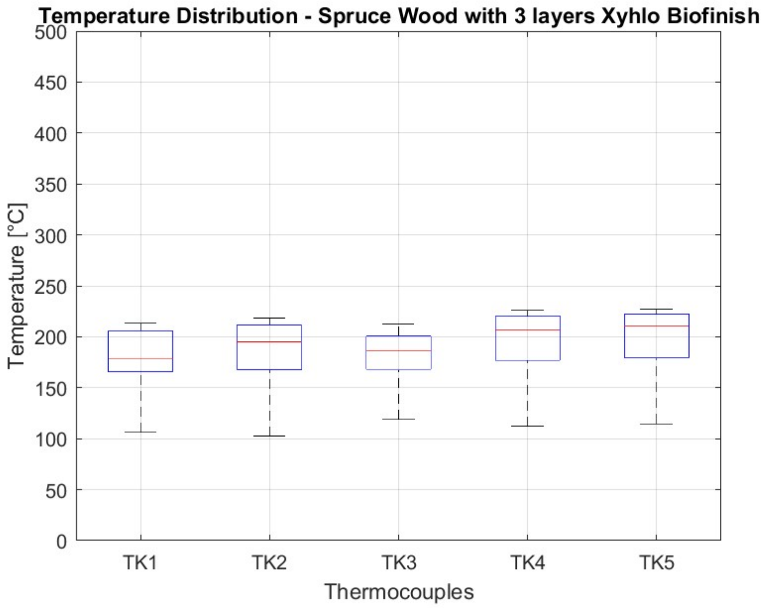
Xyhlo Biofinish, 1 layer



Xyhlo Biofinish, 2 layers

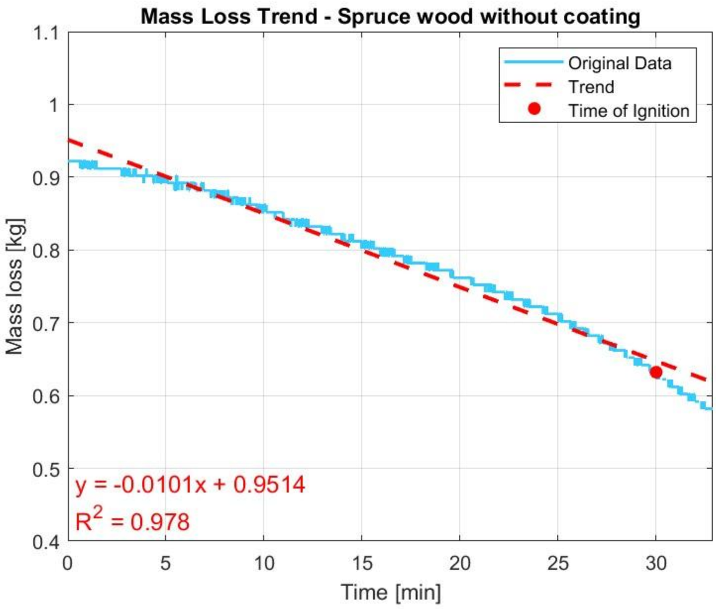


XYHLO BIOFINISH, 3 LAYERS

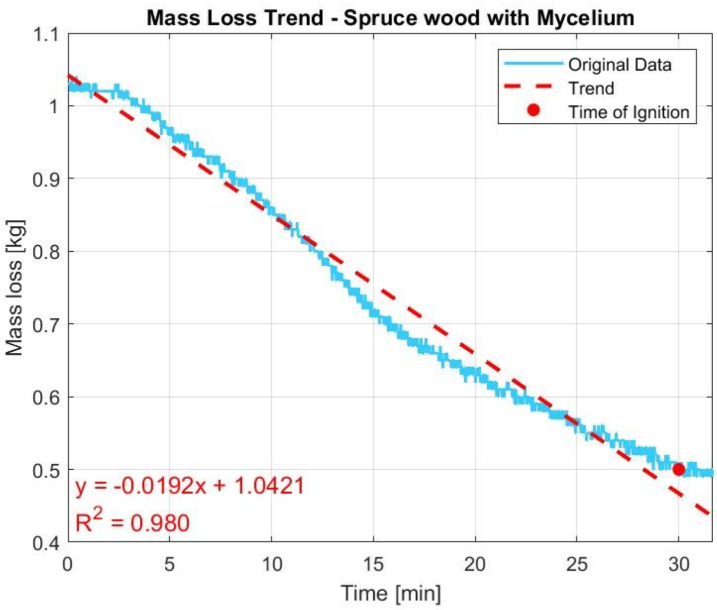


A4. Mass Loss with Linear Trendline over Entire Test Duration and Ignition Point – Radiant panel tests

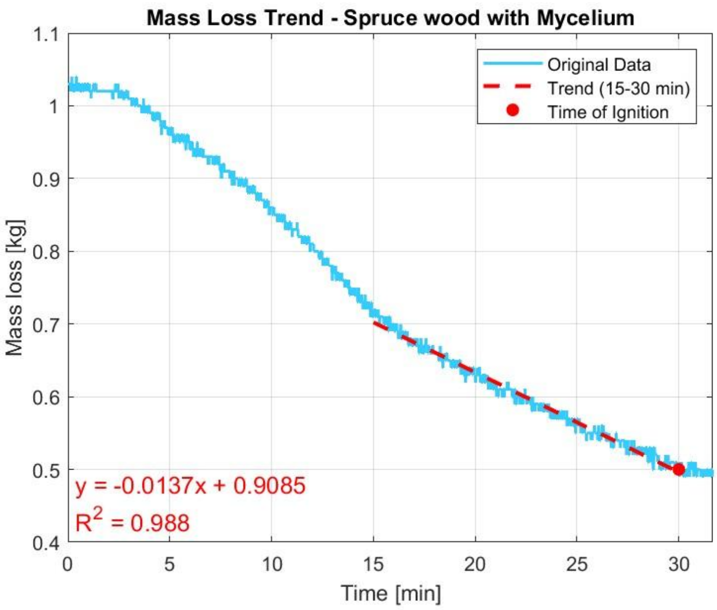
Uncoated spruce wood



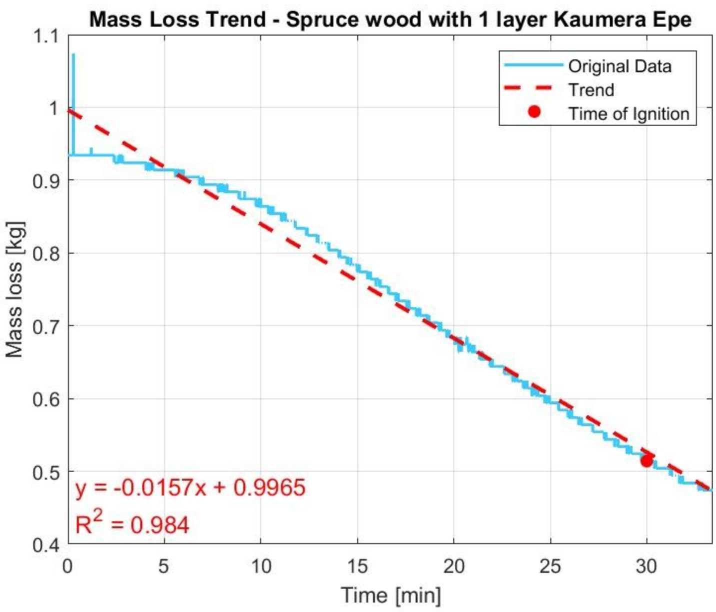
Mycelium



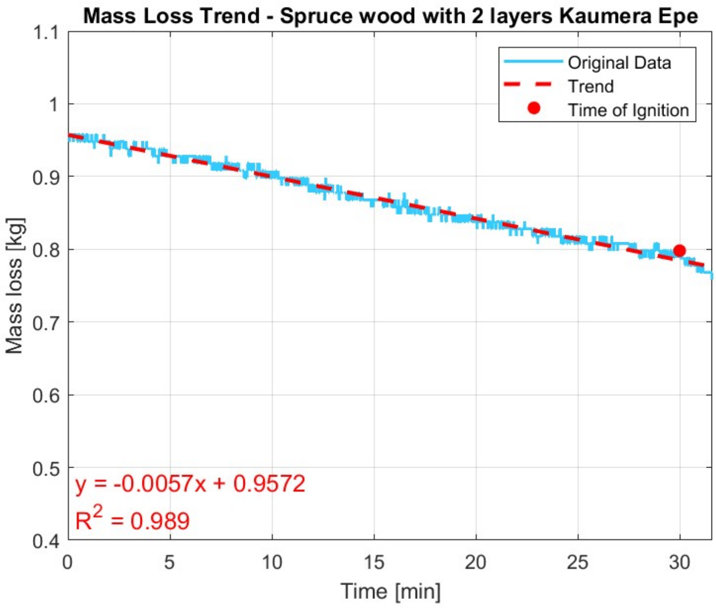
MYCELIUM (15-30 MINUTES)



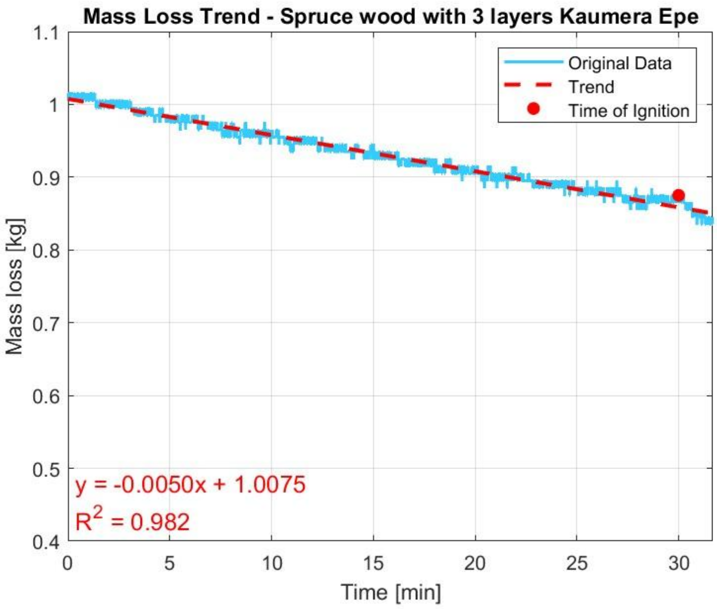
KAUMERA EPE, 1 LAYER



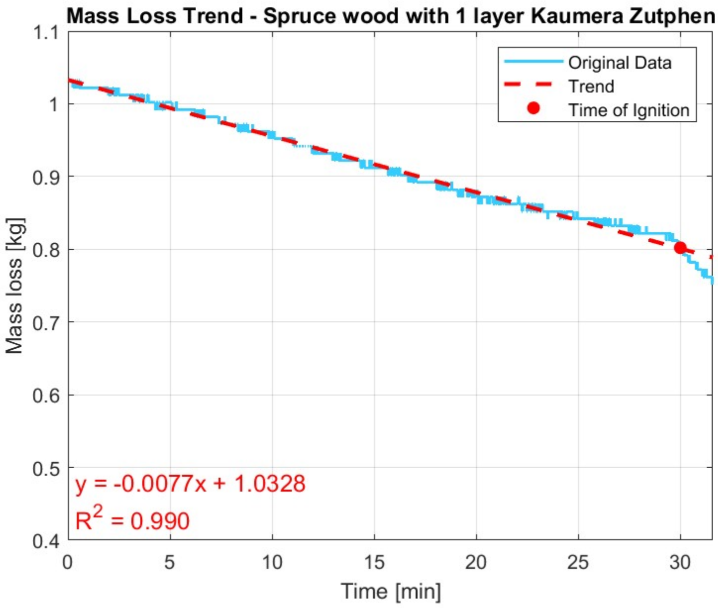
KAUMERA EPE, 2 LAYERS



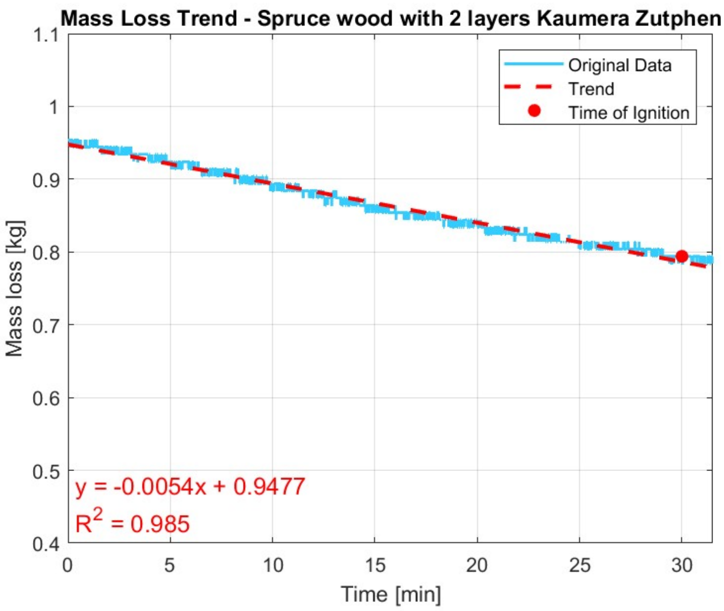
KAUMERA EPE, 3 LAYERS



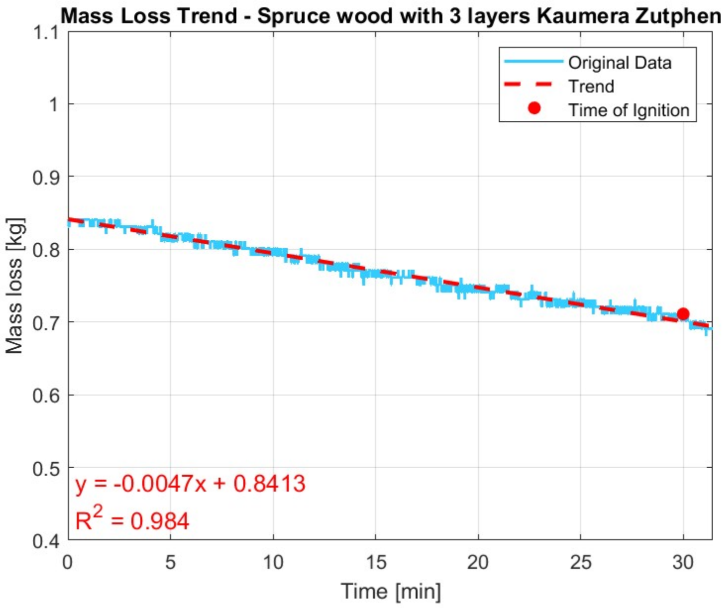
KAUMERA ZUTPHEN, 1 LAYER



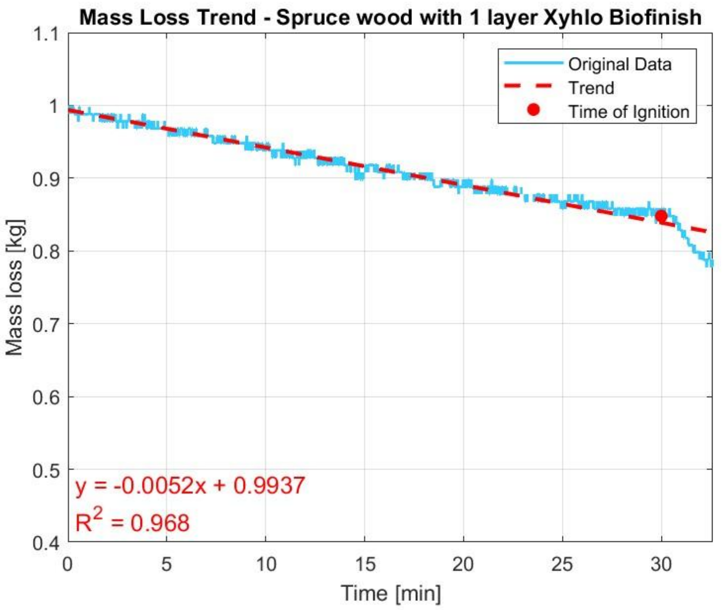
KAUMERA ZUTPHEN, 2 LAYERS



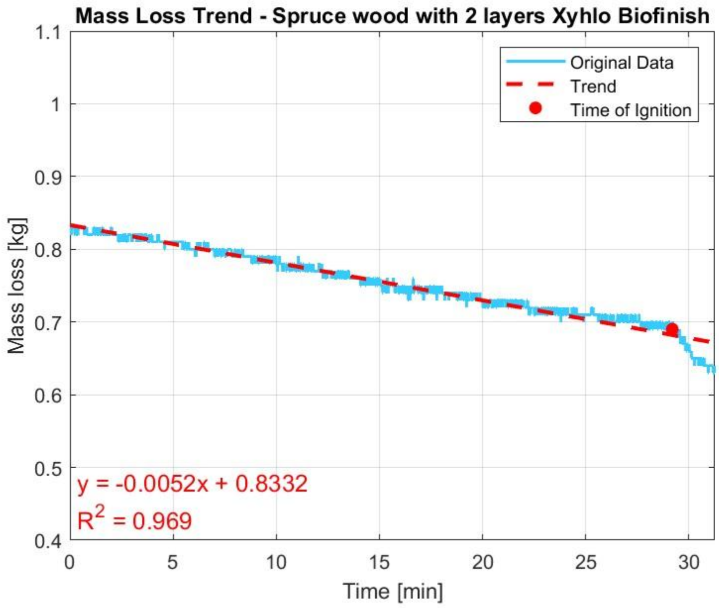
Kaumera Zutphen, 3 layers



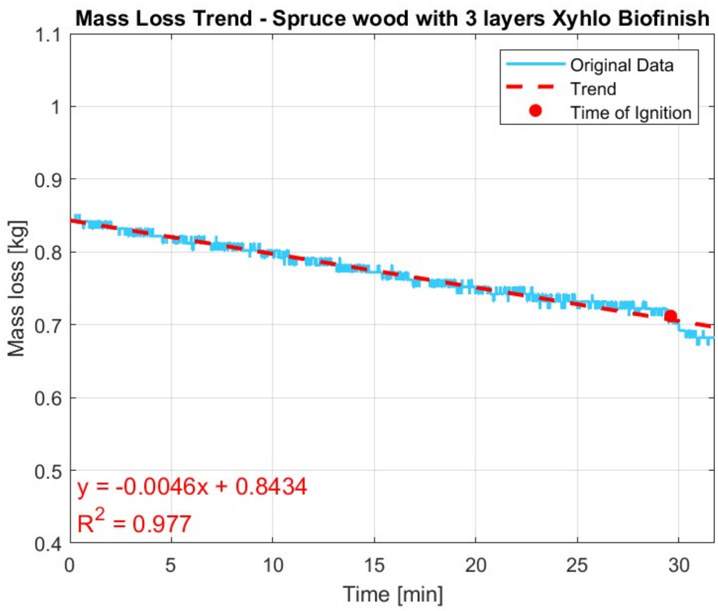
Xyhlo Biofinish, 1 layer



XYHLO BIOFINISH, 2 LAYERS

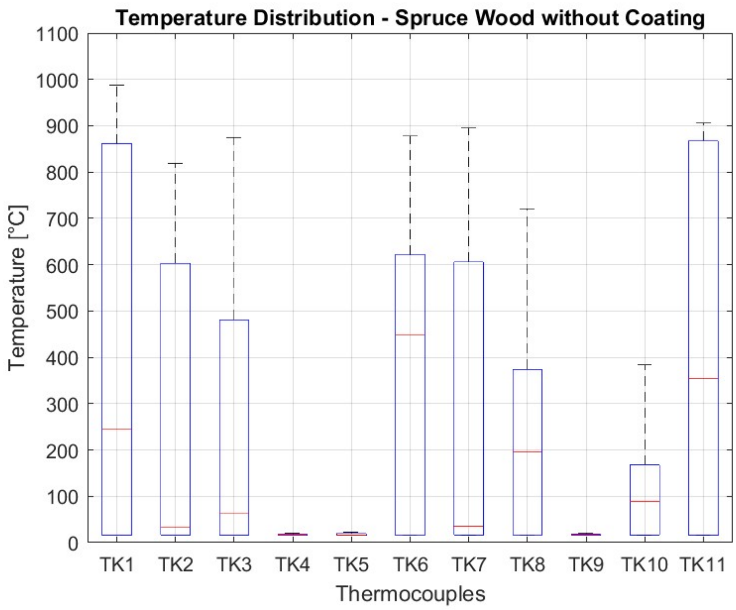


XYHLO BIOFINISH, 3 LAYERS

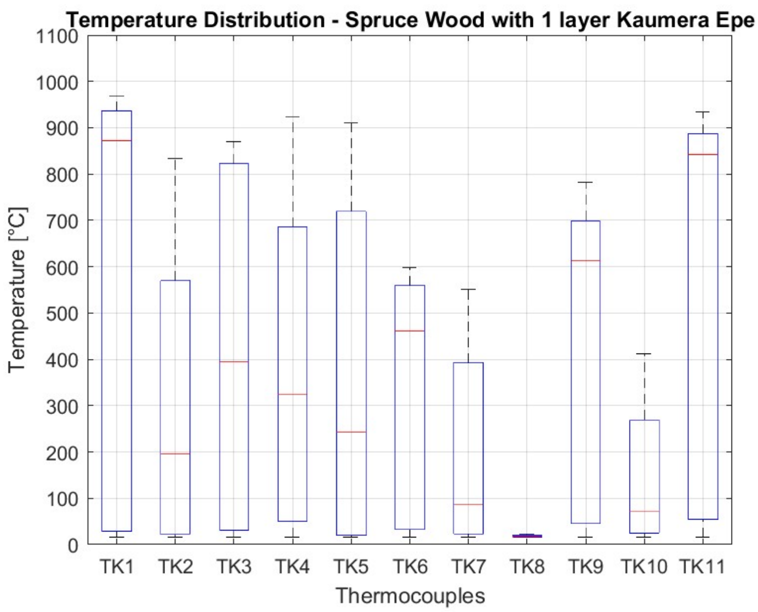


A5. Boxplots of Measured Temperatures for different Thermocouple Positions – Line burner tests

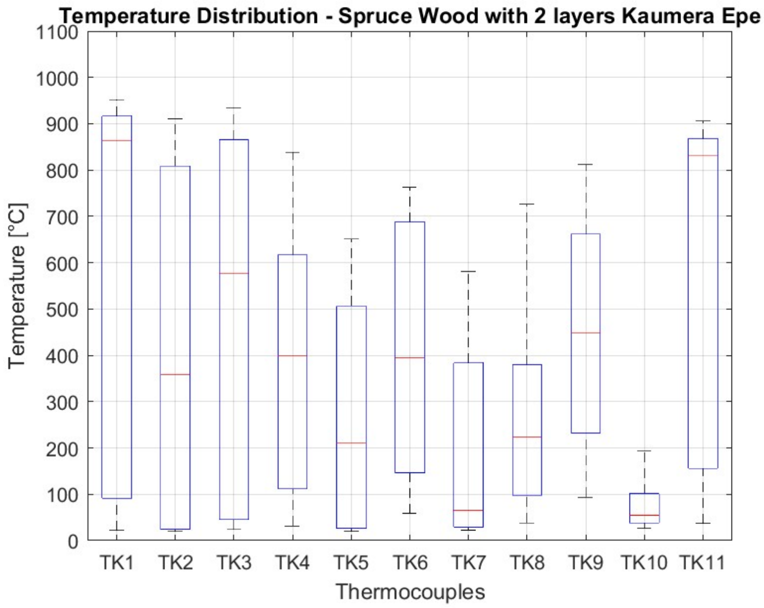
Uncoated spruce wood



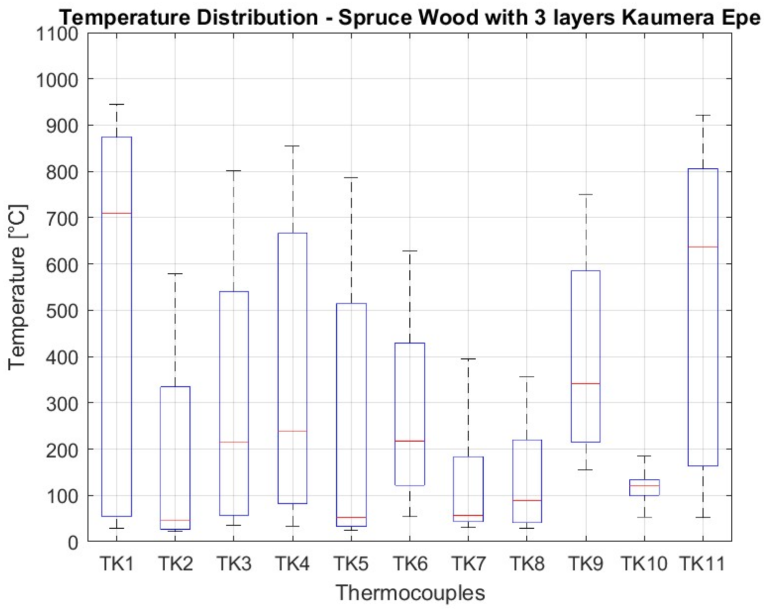
Kaumera Epe, 1 layer



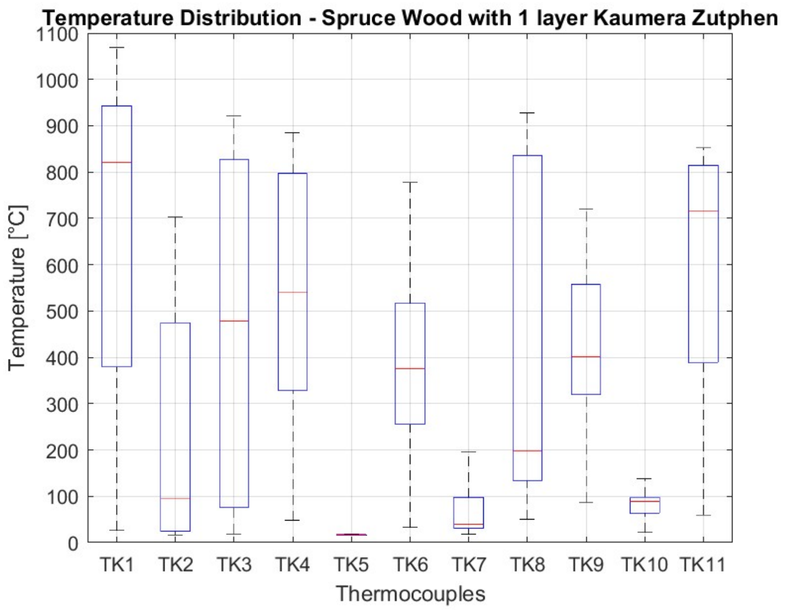
Kaumera Epe, 2 layers



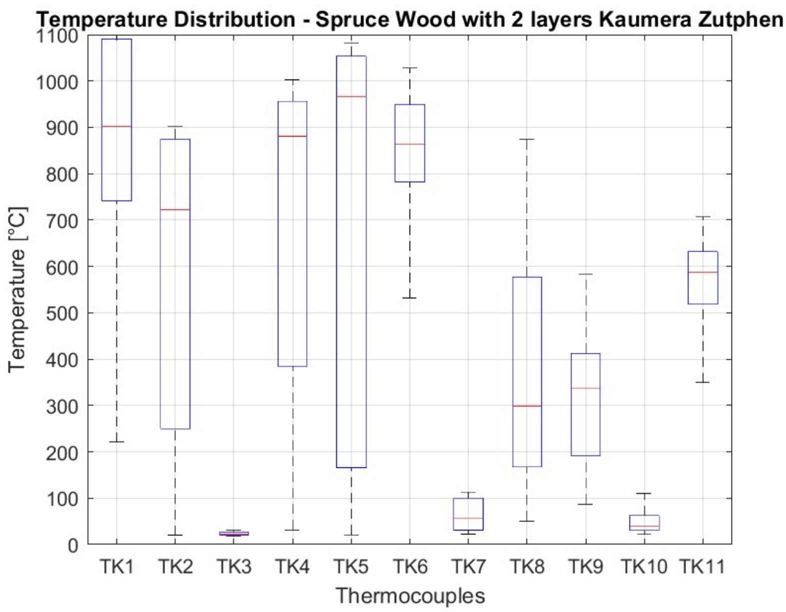
Kaumera Epe, 3 layers



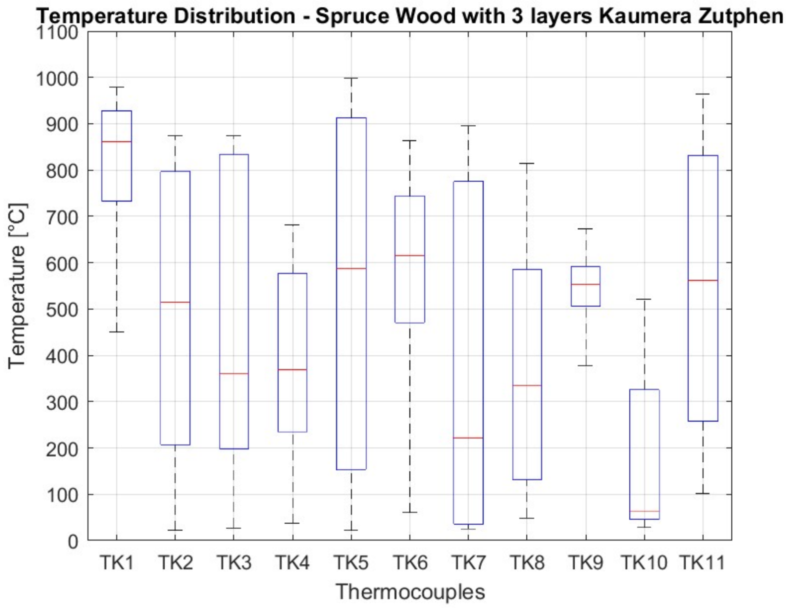
KAUMERA ZUTPHEN, 1 LAYER



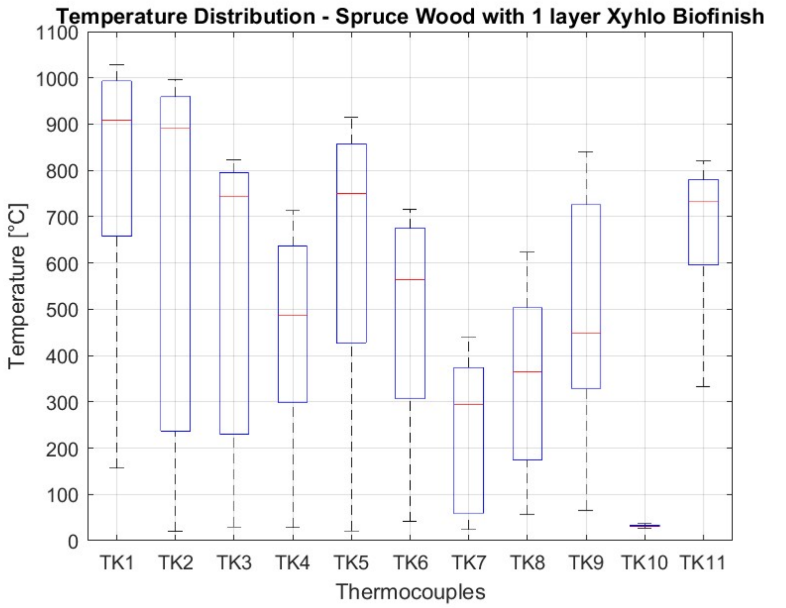
KAUMERA ZUTPHEN, 2 LAYERS



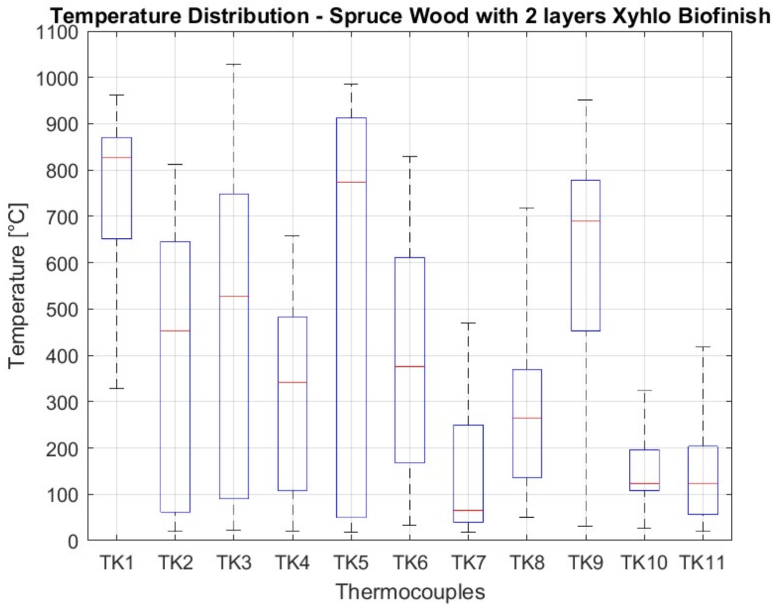
KAUMERA ZUTPHEN, 3 LAYERS



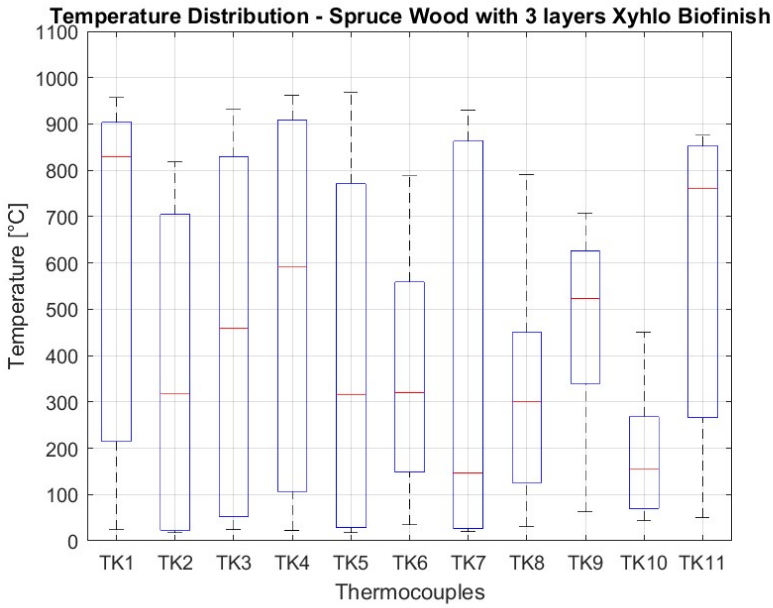
XYHLO BIOFINISH, 1 LAYER



Xyhlo Biofinish, 2 layers

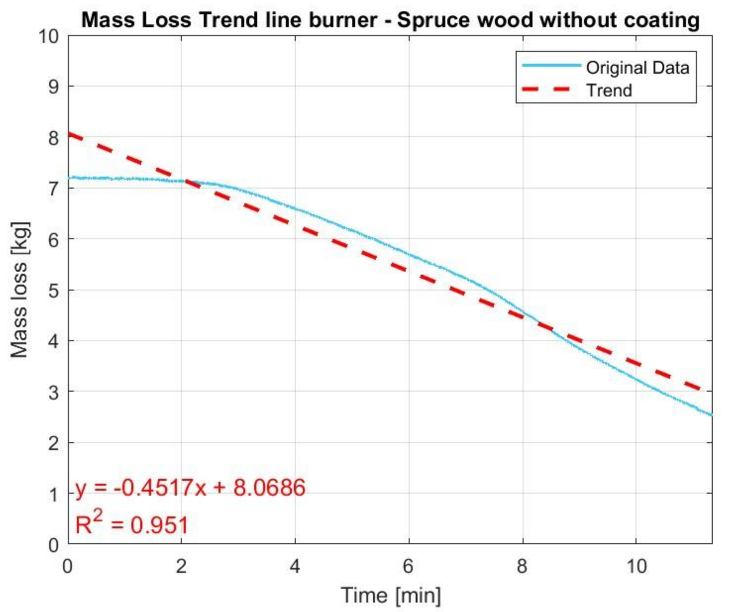


Xyhlo Biofinish, 3 layers

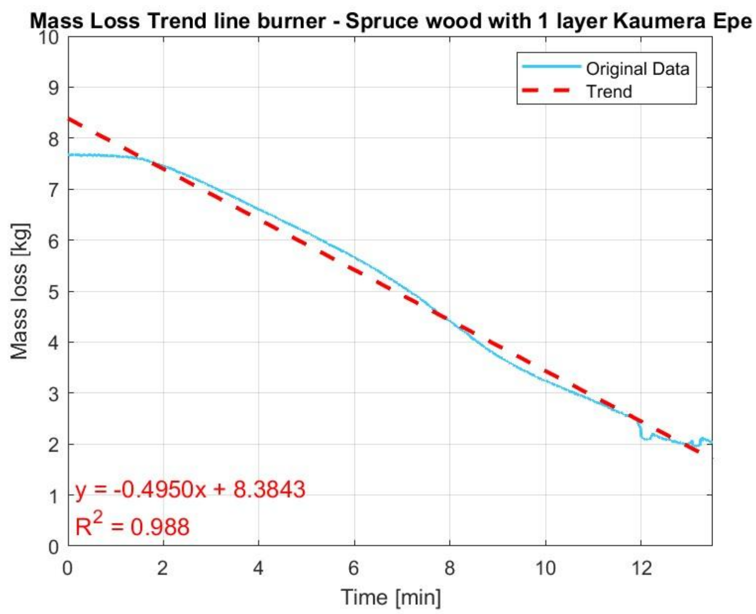


A6. Mass Loss with Linear Trendline over Entire Test Duration – Line burner tests

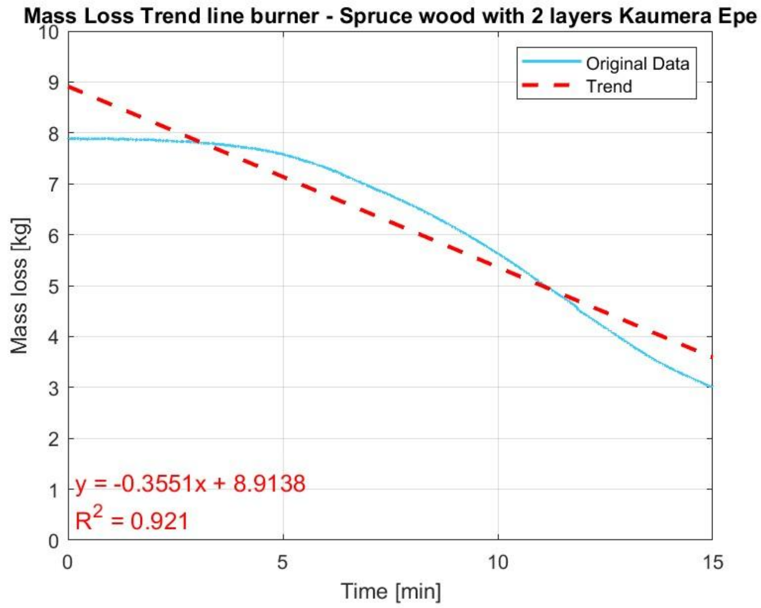
Uncoated spruce wood



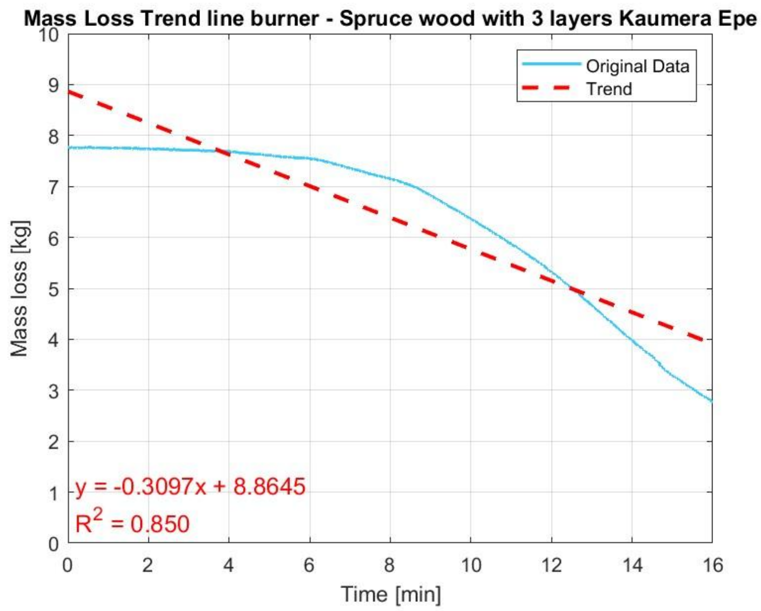
Kaumera Epe, 1 layer



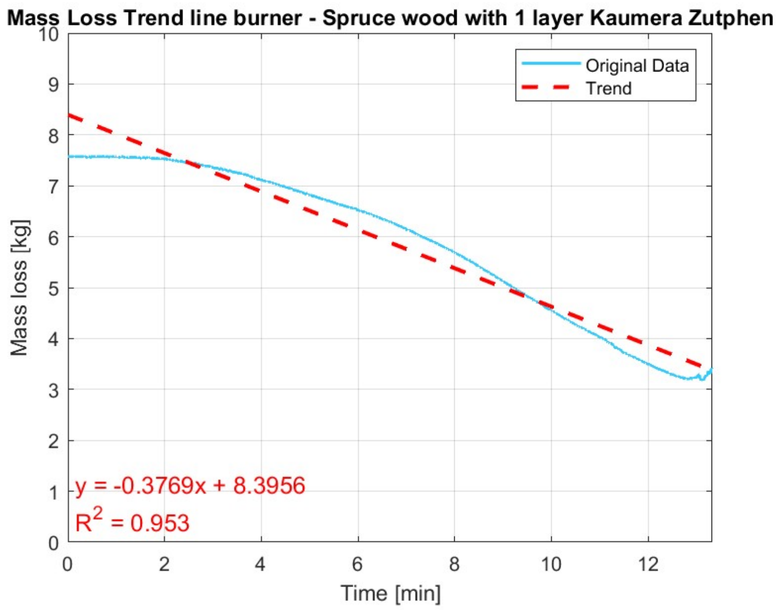
Kaumera Epe, 2 layers



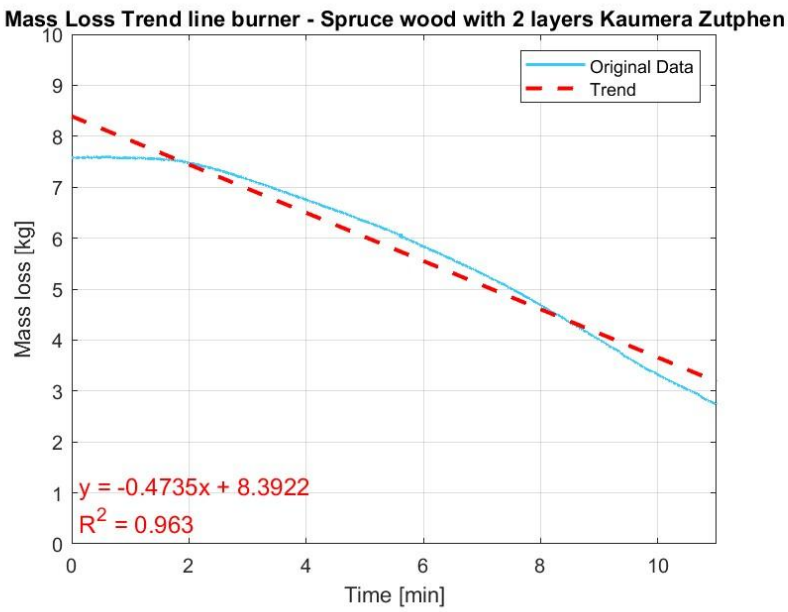
Kaumera Epe, 3 layers



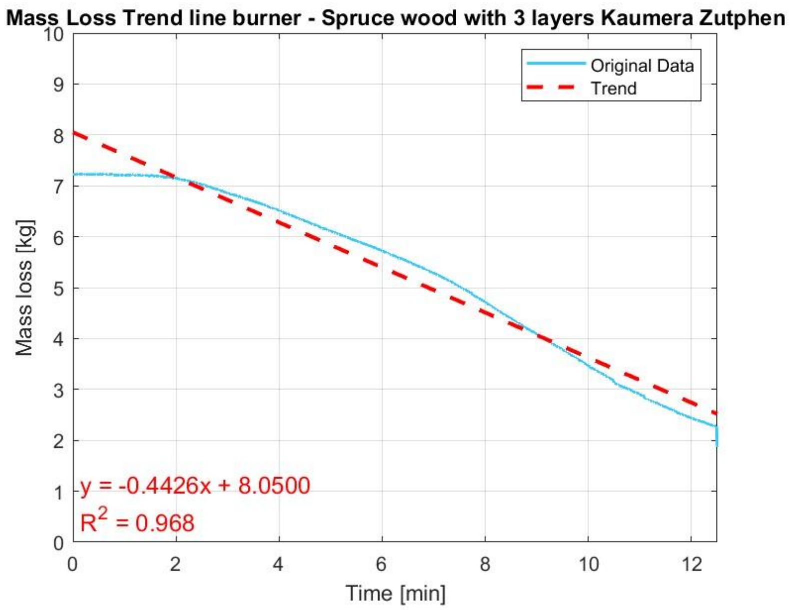
KAUMERA ZUTPHEN, 1 LAYER



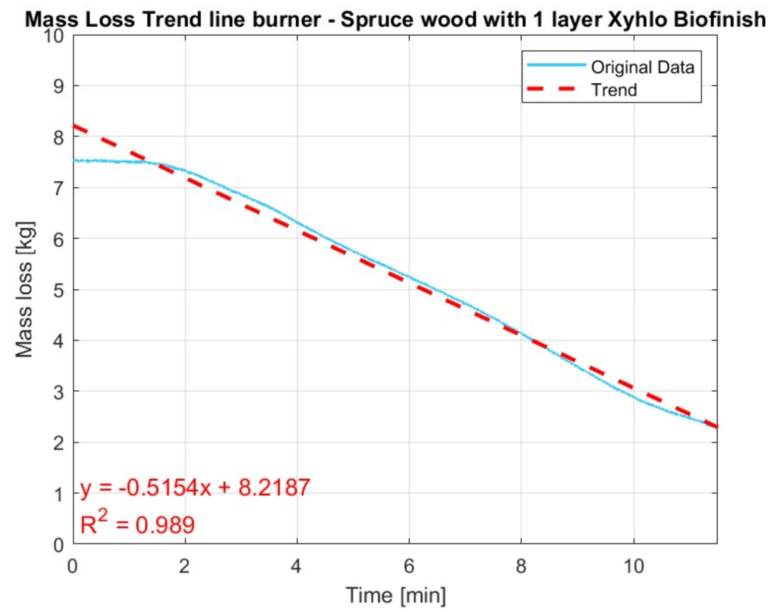
KAUMERA ZUTPHEN, 2 LAYERS



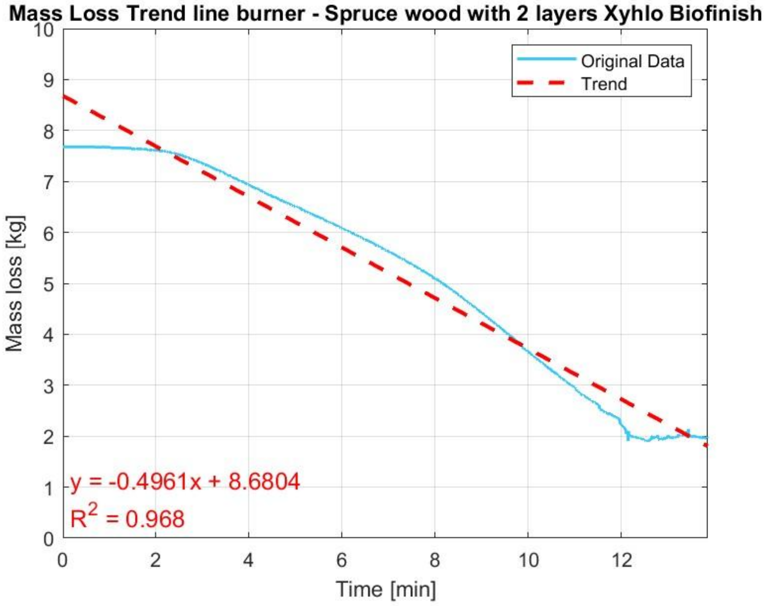
KAUMERA ZUTPHEN, 3 LAYERS



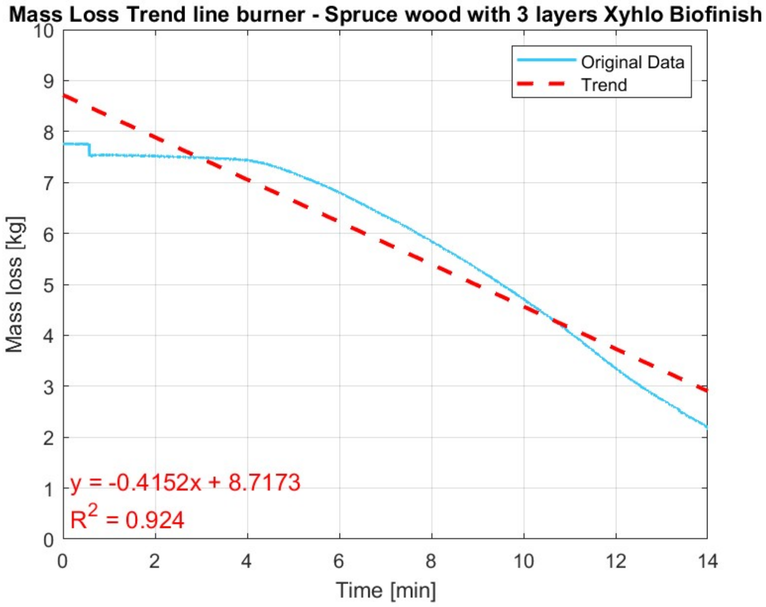
XYHLO BIOFINISH, 1 LAYER



XYHLO BIOFINISH, 2 LAYERS

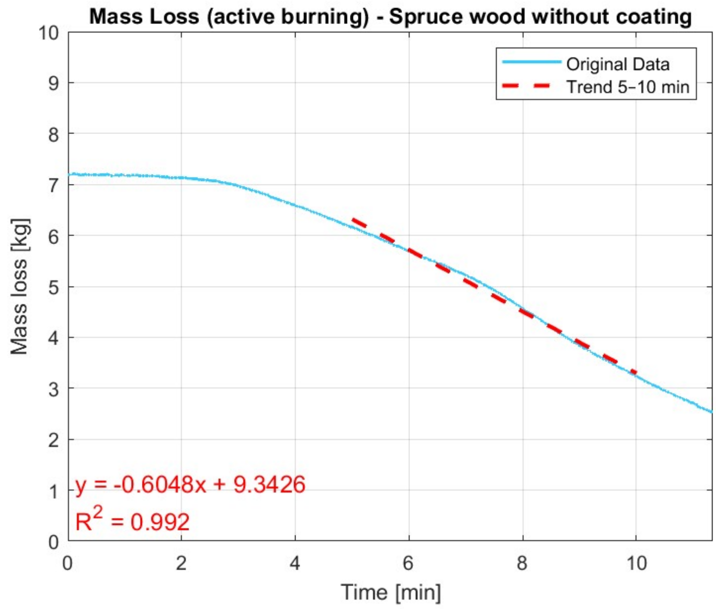


XYHLO BIOFINISH, 3 LAYERS

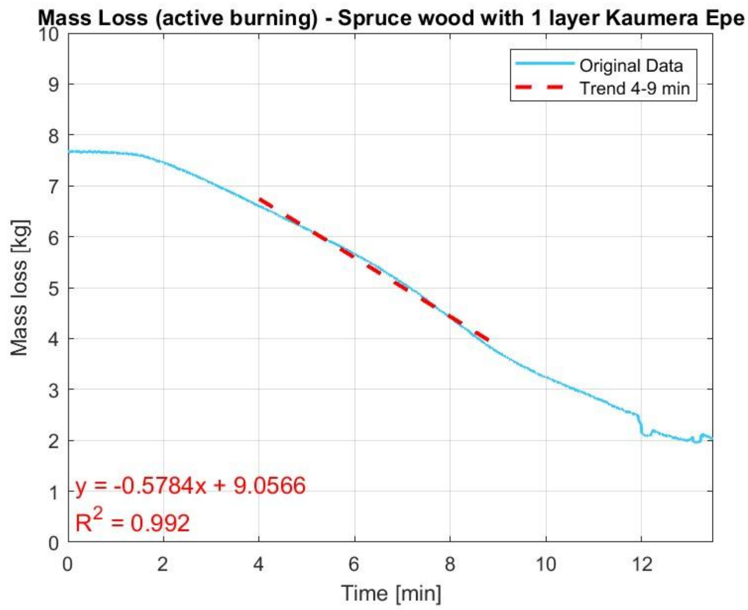


A7. Mass Loss with Linear Trendline during Active Burning Phase – Line burner tests

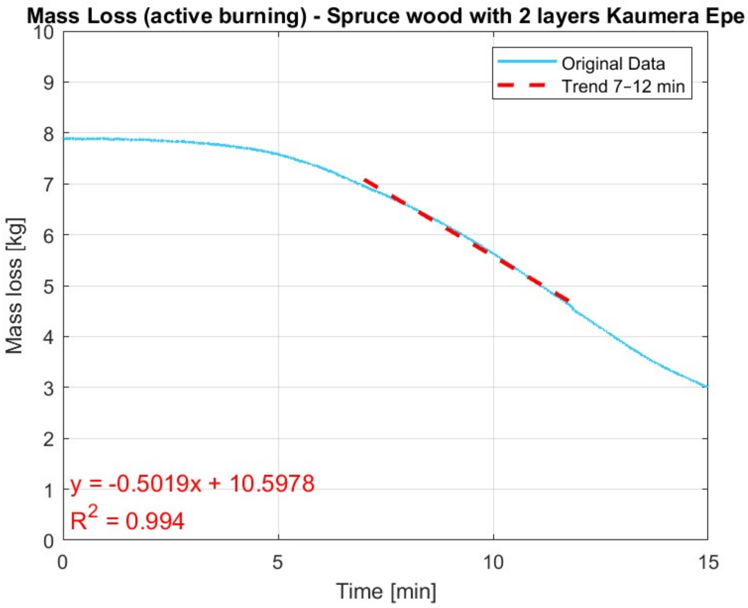
Uncoated spruce wood



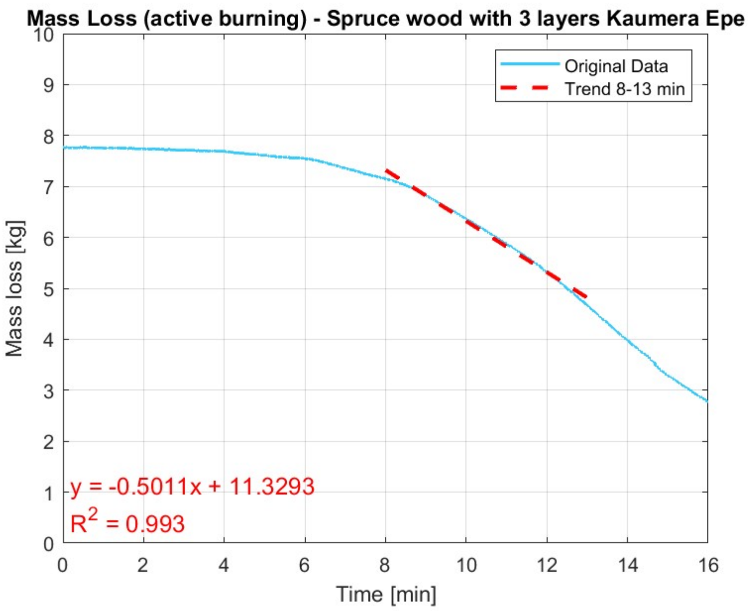
Kaumera Epe, 1 layer



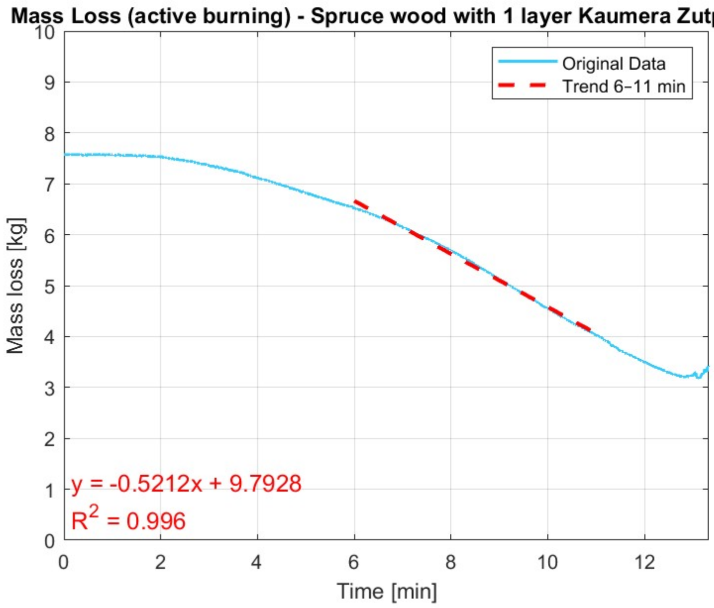
Kaumera Epe, 2 layers



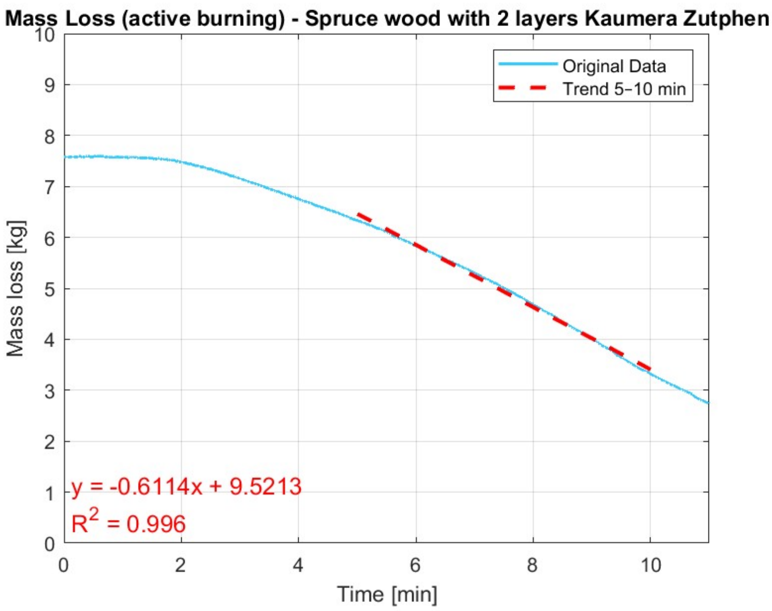
Kaumera Epe, 3 layers



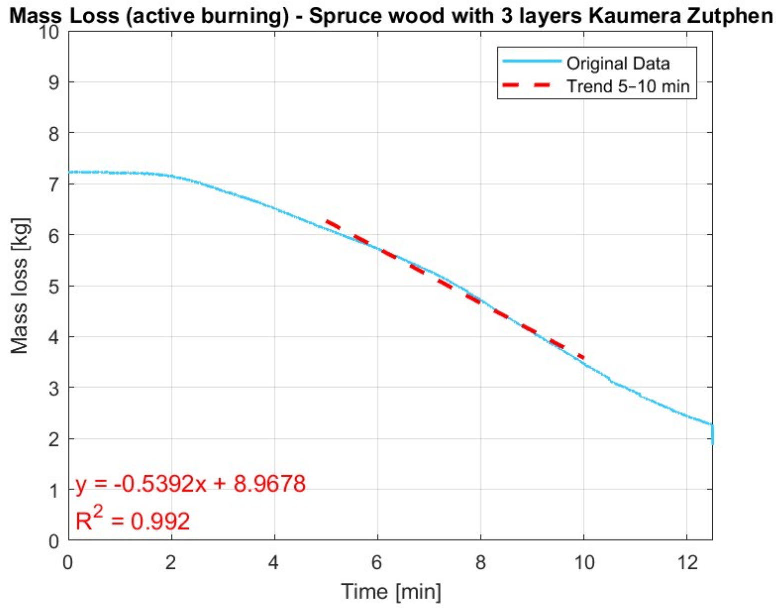
KAUMERA ZUTPHEN, 1 LAYER



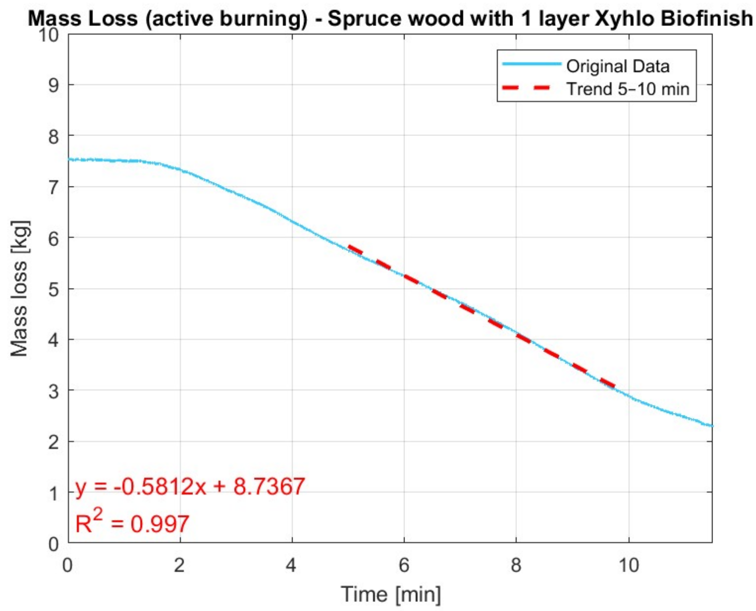
KAUMERA ZUTPHEN, 2 LAYERS



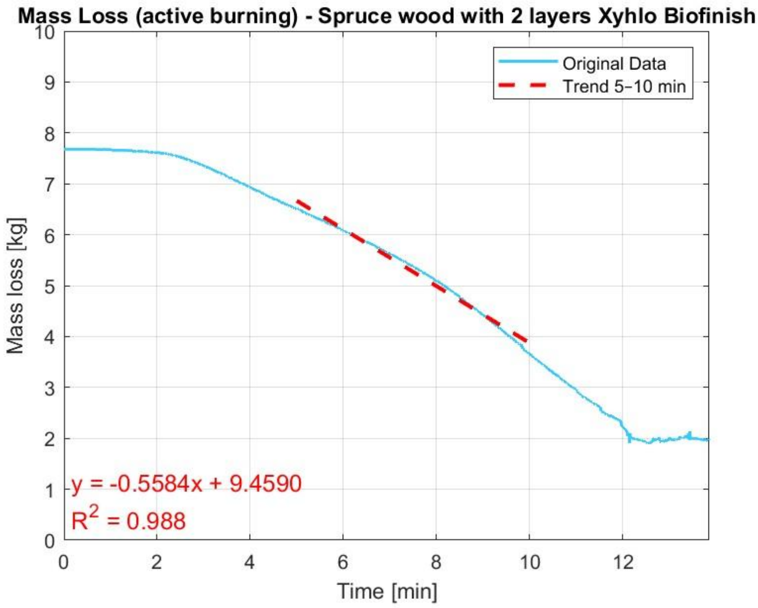
KAUMERA ZUTPHEN, 3 LAYERS



XYHLO BIOFINISH, 1 LAYER



Xyhlo Biofinish, 2 layers



Xyhlo Biofinish, 3 layers