

"DEVELOPMENT IN FLAME RETARDANT MATTRESS COVER FABRIC USING CIRCULAR KNITTING TECHNOLOGY"

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By

Priyam Arth Patel

(Reg. no.: FoTE/1073)

Under the Guidance of

Dr. Aadhar Mandot



Department of Textile Engineering,
Faculty of Technology & Engineering,
The Maharaja Sayajirao University of Baroda,
Vadodara – 390001, Gujarat, India

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1.0 Introduction

Textiles constitute an integral component of modern living environments, finding extensive applications in domestic, commercial, industrial, and transportation sectors. Products such as mattresses, upholstered furniture, carpets, curtains, and interior furnishings are predominantly composed of textile materials, many of which are inherently combustible. With increasing global urbanisation and the rising use of synthetic polymers in household products, the risk associated with textile-related fires has grown considerably in recent decades [1], [2]. Consequently, fire safety has emerged as a critical performance requirement in contemporary textile engineering and product design.

Among various textile end uses, mattresses and upholstered furniture represent one of the most significant sources of residential fire hazards. The widespread incorporation of polyurethane foam (PU), polyester fabrics, and other highly flammable components in bedding systems has been directly linked to rapid fire growth, intense heat release, and excessive smoke generation during fire incidents [3], [4]. Statistical studies have consistently shown that a large proportion of domestic fire fatalities originate from the ignition of bedding and furniture materials [5]. These concerns have intensified the need for effective flame-retardant (FR) textile systems capable of delaying ignition, limiting flame spread, and reducing heat release in real fire scenarios.

In response to these safety concerns, stringent flammability regulations and performance standards have been introduced across the world. Standards such as BS 7177, BS 5852, ISO 12952, EN 597, and California TB 117 impose mandatory fire safety requirements for mattresses, upholstery, and interior textiles [6], [7]. Compliance with these regulations necessitates the incorporation of flame-retardant materials and technologies into textile products. As a result, the development of reliable, durable, and user-friendly FR textiles has become a major focus of research and industrial innovation.

Traditionally, flame retardancy in textiles has been achieved through two principal approaches: application of chemical flame-retardant finishes and utilisation of inherently flame-resistant fibres [8], [9]. Chemical finishing methods involve the topical application of phosphorus-, nitrogen-, halogen-, or mineral-based compounds onto conventional textile substrates such as cotton or

polyester. Although these treatments are relatively economical and easy to apply, they often suffer from significant drawbacks, including poor durability to laundering, environmental and health concerns, release of toxic by-products, and deterioration of fabric handle and comfort properties [10], [11]. Growing regulatory restrictions on hazardous chemicals have further limited the long-term viability of many conventional FR finishing systems.

An alternative and increasingly preferred approach is the use of inherently flame-retardant fibres such as aramids, modacrylics, melamine, polybenzimidazole (PBI), FR viscose, and other high-performance fibres [12], [13]. These fibres possess intrinsic thermal stability and do not rely on external chemical treatments for flame resistance. Fabrics produced from such fibres offer durable protection, excellent thermal performance, and superior resistance to repeated laundering and wear. However, the widespread adoption of inherently FR fibres is often constrained by higher raw material costs, processing difficulties, limited availability, and, in some cases, reduced comfort and flexibility [14].

These technological and economic trade-offs have encouraged researchers to explore more balanced and integrated solutions for flame-retardant textiles. Recent trends have shifted towards fibre-blending strategies, hybrid yarn systems, and structural fabric engineering approaches that combine the advantages of different materials and technologies [15], [16]. By strategically developing a blend which combines fire retardant and charring components at the fibre, yarn or fabric stage, it is possible to achieve synergistic improvements in flame resistance, mechanical strength, and comfort performance. However, the effectiveness of such hybrid systems depends greatly on the chosen fabric manufacturing technology and structural design.

Circular knitting technology has emerged as a highly versatile and efficient manufacturing route for functional textiles. Unlike weaving, which interlaces yarns in rigid orthogonal patterns, circular knitting forms fabrics through interconnected loops that provide inherent stretch and flexibility [17]. This looped architecture results in fabrics that are more comfortable, breathable, and adaptable to body contours and product geometries. For applications such as mattress covers and fire-blocking layers, these attributes are extremely valuable, as they allow protective fabrics to perform effectively without compromising user comfort.

In addition to comfort advantages, circular knitting offers significant technical and economic benefits. The technology enables high production speeds, seamless or tubular fabric formation, and precise control over structural parameters such as loop length, stitch density, fabric thickness, and areal density (GSM) [18]. These parameters strongly influence thermal insulation, porosity, and heat transfer characteristics of fabrics, which are critical factors governing flame-retardant performance. Consequently, circular knitting provides an ideal platform for engineering advanced FR textiles through systematic manipulation of fabric architecture.

Despite these advantages, the development of flame-retardant fabrics using circular knitting technology presents several technical challenges. Knitted structures are inherently more open and porous than woven fabrics, which can facilitate greater oxygen availability and faster flame spread under certain conditions [19]. The flexible looped geometry may also lead to dimensional instability and increased heat transfer when exposed to high temperatures. Therefore, achieving reliable fire performance in knitted fabrics requires careful selection of fibre types, yarn structures, and knitting parameters.

Recent research has demonstrated the potential of modacrylic-based blends, FR viscose, and hybrid fibre systems for producing effective flame-retardant knitted fabrics [20], [21]. Modacrylic fibres exhibit excellent char-forming behaviour and self-extinguishing characteristics, while FR viscose contributes improved comfort and moisture management. The incorporation of non-combustible glass fibres can further enhance thermal resistance and act as a physical barrier to flame propagation [22]. These fabrics operate through multiple flame-retardant mechanisms, including condensed-phase char formation, gas-phase radical quenching, and reduction of heat and mass transfer.

However, the integration of high-performance fibres such as glass into circular knitting processes introduces significant processing difficulties. Glass fibres are brittle, have low bending flexibility, and are prone to filament breakage during knitting operations [23]. Successful incorporation of such fibres requires machine modifications, specialised yarn feeding systems, and optimisation of knitting parameters. Moreover, the interaction between hybrid yarn compositions and knitted fabric structures remains insufficiently understood from a scientific perspective.

Although considerable progress has been made in the fields of flame-retardant fibres and chemical finishing, there exists a clear research gap in the integrated development of flame-retardant fabrics specifically engineered through circular knitting technology. Most existing studies focus either on fibre-level flame-retardant properties or on woven FR textiles. Limited systematic research has been conducted to establish quantitative relationships between knitting parameters, fabric structural characteristics, comfort properties, and standardised fire-performance metrics [24], [25].

Furthermore, comparative evaluations between hybrid knitted FR fabrics and conventionally FR-treated cotton fabrics are scarce in the literature. Such comparisons are essential for assessing the true technical and commercial viability of knitted FR solutions for mattress cover applications. There is also a need to investigate how variations in GSM, stitch structure, and fibre blend composition influence key performance attributes such as air permeability, thermal resistance, tensile strength, and flammability behaviour.

The present research is undertaken to address these gaps by developing and systematically evaluating flame-retardant fabrics produced using circular knitting technology. The study focuses on the design and fabrication of hybrid knitted fabrics incorporating modacrylic, FR viscose, and glass fibres, along with appropriate structural optimisation. Machine modifications and process adaptations are implemented to enable the successful knitting of brittle high-performance fibres on industrial circular knitting machines. Comprehensive experimental investigations are carried out to evaluate the structural, mechanical, comfort, and fire-performance characteristics of the developed fabrics. Standardised testing methods are employed to assess parameters such as GSM, thickness, air permeability, tensile strength, thermal behaviour, limiting oxygen index (LOI), and flammability performance. The results are compared with those of conventional FR-treated cotton fabrics to establish the relative advantages and limitations of the proposed approach.

The broader objective of this thesis is to contribute to the development of safer, more durable, and environmentally responsible flame-retardant textiles for mattress and protective applications. By emphasising inherently FR and hybrid fibre systems, the research seeks to reduce dependence on chemical flame-retardant finishes and promote sustainable material solutions. The study aims to

establish a scientifically grounded structure-property-performance framework that can guide future development of knitted FR fabrics in both academic and industrial contexts.

The remainder of the thesis is structured as follows:

- **Chapter 2** presents a comprehensive literature review covering textile fibres, combustion fundamentals, flame-retardant mechanisms, high-performance fibres, and previous research on flame-retardant knitted fabrics.
- **Chapter 3** details the materials, experimental methodologies, machine modifications, fabric development procedures, and testing techniques employed in the research.
- **Chapter 4** discusses the results and analysis related to physical properties, mechanical performance, comfort characteristics, and flammability behaviour of the developed fabrics.
- **Chapter 5** summarises the major findings, draws conclusions from the research, and provides recommendations for future investigations in the field.

Through this structured approach, the thesis aims to advance the understanding and practical implementation of flame-retardant fabrics produced via circular knitting technology, thereby contributing to improved fire safety in textile applications.

Gap Analysis

Flame-retardant (FR) mattress cover fabrics play a crucial role in preventing fire propagation in residential and institutional environments. Despite increasing awareness of fire safety standards and regulations, commercially available FR mattress cover fabrics face several technical, economic, and manufacturing limitations. These constraints highlight the need for a simplified, scalable, and cost-effective manufacturing approach using circular knitting technology. The following are the limitations of existing flame-retardant mattress cover fabrics:

- **Core-Sheath Spun Yarn-Based FR Knitted Fabrics:** Although effective in flame resistance with the incorporation of inherently FR fibres, these yarns increase manufacturing complexity, processing difficulty, and production cost. The requirement of specialised spinning processes limits scalability and universal accessibility.

- **Woven Flame-Retardant Fabrics:** They exhibit lower elasticity, reduced breathability, and inferior comfort compared to knitted structures. For mattress cover applications, where flexibility and conformability are essential, woven constructions may compromise tactile comfort and moisture management.
- **Surface-Finished Flame-Retardant Fabrics:** These finishes may suffer from durability issues, reduced wash resistance, and potential environmental and health concerns. Repeated finishing treatments increase processing stages, cost, and ecological impact.
- **Limited Utilisation of Circular Knitting Technology for Glass Fibre:** Circular knitting machines are extensively used in apparel manufacturing but remain underutilised for technical yarns like glass fibre. There is insufficient research on modifying and optimising circular knitting machines to process technical and flame-retardant yarns effectively.

Apart from these technical limitations, a significant challenge lies in the affordability of flame-retardant mattress cover fabrics. High production costs and complex manufacturing processes restrict their widespread adoption, particularly in cost-sensitive markets. Therefore, there is a clear need to develop a simplified, economically viable, and scalable manufacturing method utilising circular knitting technology to make fire-retardant mattress covers universally accessible.

Aim & Objectives of the Study

The primary aim of this research is to develop a flame-retardant mattress cover fabric using circular knitting technology through a simplified, cost-effective, and scalable manufacturing approach, ensuring enhanced fire safety, comfort, and universal accessibility.

The specific objectives of the study are:

- Minimise reliance on complex core-spun yarn systems by exploring simpler yarn constructions that are easier to manufacture and process. Therefore, to develop flame-retardant knitted fabrics using suitable blends of inherently flame-retardant fibres such as Modacrylic, FR viscose, and Glass fibres to achieve optimal flame resistance and comfort properties.
- Modify and optimise circular knitting machines to efficiently process glass fibre yarn and flame-retardant yarns for mattress cover applications.

- Evaluate mechanical properties, flammability characteristics, and physical properties of the developed fabrics and conduct comparative studies between developed inherently flame-retardant knitted fabrics and surface-finished FR knitted fabrics.
- Perform open-flame mattress model testing to establish structure-performance relationships under real-life fire simulation conditions.

This study aims to contribute toward enhancing domestic fire safety by developing a technically sound, comfortable, and economically accessible flame-retardant mattress cover fabric using circular knitting technology.

2. Brief Research Methodology

The present study has been carried out to develop a flame-retardant mattress cover fabric suitable for applications such as Hometech and Protech. An effort has been made to provide a cost-effective solution that can eliminate the existing tedious and costly core-sheath spinning system for producing a suitable yarn. This requires selecting suitable raw materials and manufacturing techniques for effectiveness, affordability, and ease of availability. The experimental framework of this study involves the procurement of fire-retardant yarns and chemicals, required modifications in a circular knitting machine for running high-performance yarns, and thereby developing a flame-retardant mattress cover knitted fabric. The procured yarns have been characterised using FTIR, XRD, DSC, and TGA, along with their linear density and tensile characteristics. Further, the prepared fabrics have been analysed for their structural, mechanical, and comfort-related properties while assessing their performance against flame. **Figure 1** shows the comprehensive graphical workflow of the study.

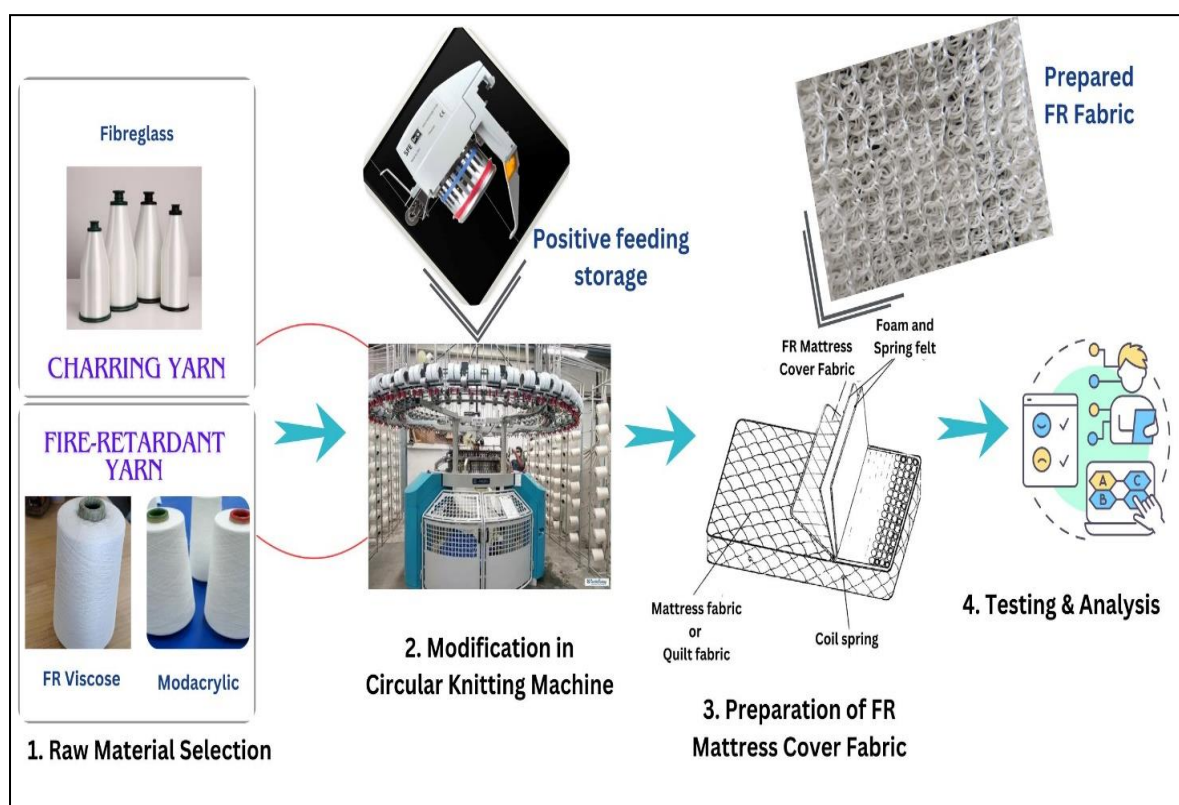


Figure 1: Graphical workflow of the study

Materials

The design of a flame-retardant (FR) mattress cover demands a rigorous balance among inherent fire resistance, mechanical integrity, comfort, and compatibility with the circular-

knitting process. All materials were selected based on their specific roles in the study and purchased from commercial suppliers. **Table 1** represents the procurement details for various materials, including yarns and chemicals.

Table 1: Procurement details of different materials

Product	Manufacturer
100% Modacrylic Yarn	Hind Synthetics Ltd., Kolkata, West Bengal - 700020, India
100% S-Glass fibre Yarn	Vetrotex Textiles India Ltd., Hyderabad, Telangana - 509325, India
100% FR Viscose Yarn	Grasim Industries Ltd., Birlagram, Madhya Pradesh - 456331, India
100% Cotton Yarn	Ramkrushna Cotspin Pvt. Ltd., Dhangadhra, Gujarat - 363310, India
FR Chemical REF-114	Rudra Enterprise, Surat, Gujarat – 395004, India

3.0.1 Modacrylic Yarn

Modacrylic yarn was selected for its inherent flame-retardant properties and balanced mechanical performance, making it suitable for fire-retardant mattress cover applications. It is an acrylonitrile-based copolymer containing flame-retardant comonomers such as vinyl chloride or vinylidene chloride, with acrylonitrile as the polymer backbone.



Figure 2: Modacrylic yarn

According to supplier specifications, the fibre exhibits self-extinguishing behaviour without the need for additional finishes. Upon exposure to flame, it forms a coherent char residue,

which effectively impedes heat transfer and prevents molten dripping. These properties make modacrylic yarn an excellent component for developing flame-retardant knitted cover fabric for mattresses. The selected modacrylic yarn is shown in **Figure 2**, and its specifications are given in **Table 2**.

Table 2: Yarn specifications

Yarn type	Count (Ne)	LOI (%)	Moisture regain (%)
Modacrylic yarn	30's	28-32	<2
FR Viscose	30's	28-30	11
S-Glass fibre yarn	48's	-	0
Cotton yarn	30's	18-19	6-8

FR-Viscose

FR-viscose yarn was selected for its regenerated cellulosic structure modified with 10% wt phosphorus-based flame-retardant additives, making it suitable for use in fire-retardant mattress cover fabrics. This modification provides flame retardancy while retaining the characteristic softness and moisture-management properties of conventional viscose. The fibre exhibits excellent evaporative cooling and thermoregulation, desirable features in mattress cover applications. This yarn is ideal for combining with glass fibres to maintain long-term fire protection without sacrificing comfort. The selected FR-viscose yarn is shown in **Figure 3**, and its specifications are given in **Table 2**.



Figure 3: FR viscose yarn

Glass Fibres

S-glass yarn was selected for its exceptional non-combustibility and superior mechanical performance, making it a suitable reinforcement component in the development of flame-retardant knitted cover fabric for mattresses. The fibre maintains its structural integrity without softening, serving as an effective barrier to flame penetration and heat transfer within composite fabric assemblies. Although S-glass demonstrates outstanding thermal and mechanical characteristics, its inherent stiffness and low elongation ($< 3\%$) present processing challenges during high-speed circular knitting. The selected S-glass yarn is shown in **Figure 4**, and its specifications are given in **Table 2**. Each yarn comprises 34 filaments of $\sim 9\ \mu\text{m}$ diameter, finished with a 0.8 wt% silane-based sizing (3-aminopropyltriethoxysilane) to enhance fibre cohesion and reduce abrasion during knitting.



Figure 4: Glass fibre yarn

Cotton Yarn

Cotton yarn was selected for its natural softness, breathability, and moisture management properties, providing enhanced comfort and thermophysiological balance in knitted cover fabrics for mattresses. It is a widely used natural fibre due to its tactile comfort, processability, and favourable mechanical behaviour. For interlock-knitted covers used in mattresses, cotton ensures a stable microclimate during prolonged body contact owing to its optimal moisture regain and air permeability. Although inherently combustible, the chemical compatibility makes it suitable for the application of flame-retardant (FR) agents to achieve improved fire performance. To comply with fire safety standards (BS 7177, ISO 12952), cotton fabrics are

treated with FR finishes that promote char formation and reduce flame spread while retaining comfort and aesthetics. The selected cotton yarn is shown in **Figure 5**, and its specifications are given in **Table 2**.



Figure 5: Cotton yarn

FR Chemical REF-114

Fire-retardant chemical REF-114, as shown in **Figure 6**, was used for application on the cotton fabric to attain fire-retardancy. It is a phosphorus-based flame-retardant formulation that promotes protective char formation upon thermal exposure, thereby suppressing combustible volatiles and inhibiting flame spread.

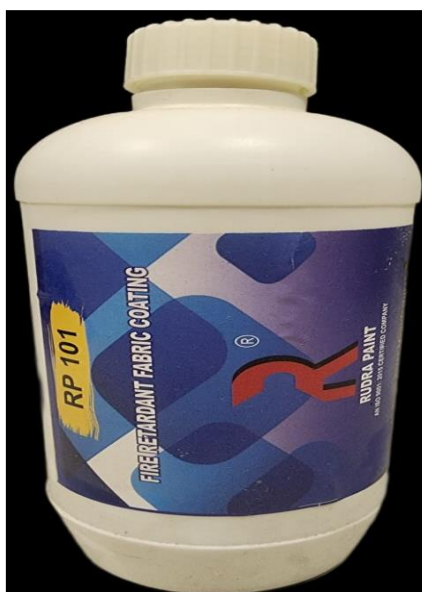


Figure 6: FR coating chemical REF-114

Rationale for Combining Two Yarns

The manufacturing of mattress fabric requires two components: one being inherently fire-retardant and the other having a firm structure. There is no single yarn that can simultaneously satisfy the spectrum of requirements for mattress covers. Modacrylic and FR-viscose yarns are inherently flame-resistant and have a pleasant handle but lack firmness and absolute non-combustibility. The glass fibre yarn provides an unparalleled firm structure & thermal barrier but lacks in drapeability and flexibility. FR-treated cotton enhances comfort and cost-effectiveness but exhibits limited durability and low LOI.

From the economic point of view, using these two yarns in combination (Charring & Fire-retardant) together on the knitting machine is beneficial compared to the commercially available core-sheath structure of yarn for the same purpose. Hence, different yarn combinations were selected in such a way that they would not hamper the knitting process, satisfying the requirement for the development of FR mattress cover fabric, as well as being economical. So, during the preparation of knitted fabric, glass fibre yarn was combined with modacrylic and FR viscose yarn, respectively.

Machine Modifications and Process Methodology

The production of flame-retardant mattress cover fabrics using interlock circular knitting requires a highly controlled integration of fibre engineering, machine adaptation, and process optimisation. Technical yarns such as modacrylic, FR-viscose, and glass fibre possess divergent mechanical behaviours that are incompatible with conventional circular knitting operations without targeted machine interventions. In particular, the brittle and low-elongation nature of glass fibre yarn complicates loop formation, leading to filament fracture, yarn breakage, and inconsistent stitch formation when processed on standard high-speed knitting machines. To address these challenges, systematic modifications were implemented on a Mayer & Cie OV 3.2 interlock circular knitting machine (30" diameter, 22 gauge, 84 feeders) as shown in **Figure 7** to enable the simultaneous knitting of a ring-spun modacrylic/FR-viscose yarn (30's Ne) and a glass fibre yarn (110 denier; 48's Ne). These alterations facilitated a simultaneous feeding mechanism, controlled yarn-path geometry, and customised cam settings strategies, thereby ensuring stable loop formation and the production of fabrics at three distinct areal densities. The subsections below provide the details related to machine modification as well as operational parameters, process-loss minimisation measures, and quality assurance protocols followed throughout the experimental work.

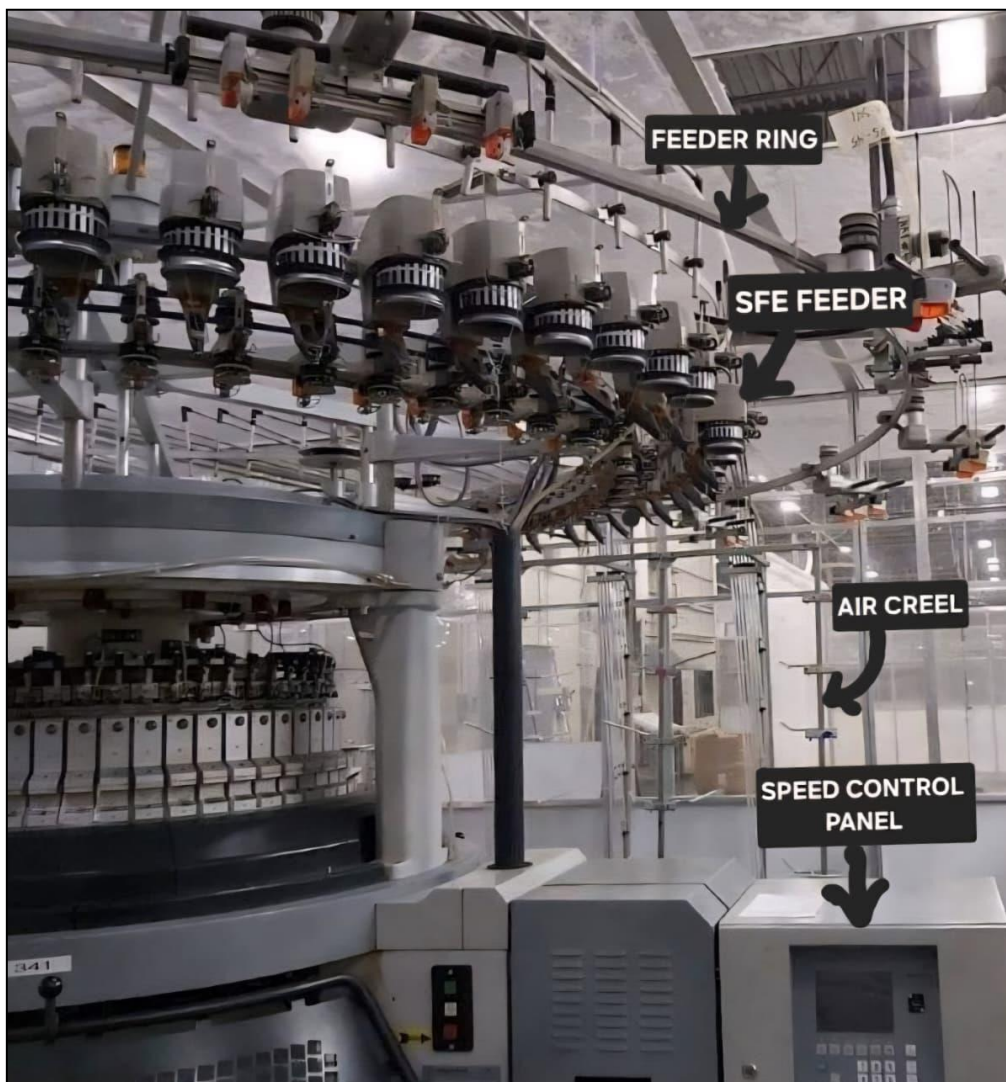


Figure 7: Modification on Mayer & Cie circular knitting machine

Rationale of Machine Modification for Combined Feeding

Glass fibre yarn, although exhibiting excellent thermal stability and non-combustibility, is intrinsically brittle and cannot withstand sharp bending or high-tension fluctuations within the knitting zone. Conversely, modacrylic and FR-viscose yarns exhibit softness, higher elongation, and improved flexibility, facilitating smooth loop formation. To exploit the advantages of both components while avoiding the limitations of the core-sheath spinning method, which would add cost and require additional spinning stages, a simultaneous feeding strategy was adopted. In this configuration, both yarns are delivered to the same needle, ensuring co-participation in loop formation. This design not only embeds the glass fibre yarn within every interlock loop and enhances char-forming integrity under fire exposure, but also reduces the cost in comparison with available core-sheath structures. Successful implementation demanded substantial machine alterations, such as:

- Establishing a low-tension yarn-path architecture to protect the brittle glass fibre yarn during in-feed and loop formation.
 - Installing independent positive feeders for ring-spun and glass fibre yarn, each calibrated to its specific tensile behaviour.
 - Revising cam profiles and stitch-length settings to reduce filament bending stress.
 - Adjusting needle-clearance geometry to avoid snagging and ensure clean loop takeover.
- These changes collectively enabled stable combined-yarn knitting without compromising material integrity or production efficiency.

Modifications in Yarn Feeding System

A simultaneous introduction of the ring-spun and glass fibre yarns to the same needle was enabled by installing independent Memminger IRO SFE positive feeders instead of a basic Memminger IRO MPF-L positive feeder at each active feeder station (**Figure 8**). Each feeder was calibrated to the specific mechanical response of its respective yarn. FR yarns were processed at 2.7-3 gf tension, whereas the glass fibre yarn was delivered under a carefully controlled 4-4.2 gf to prevent filament fracture.

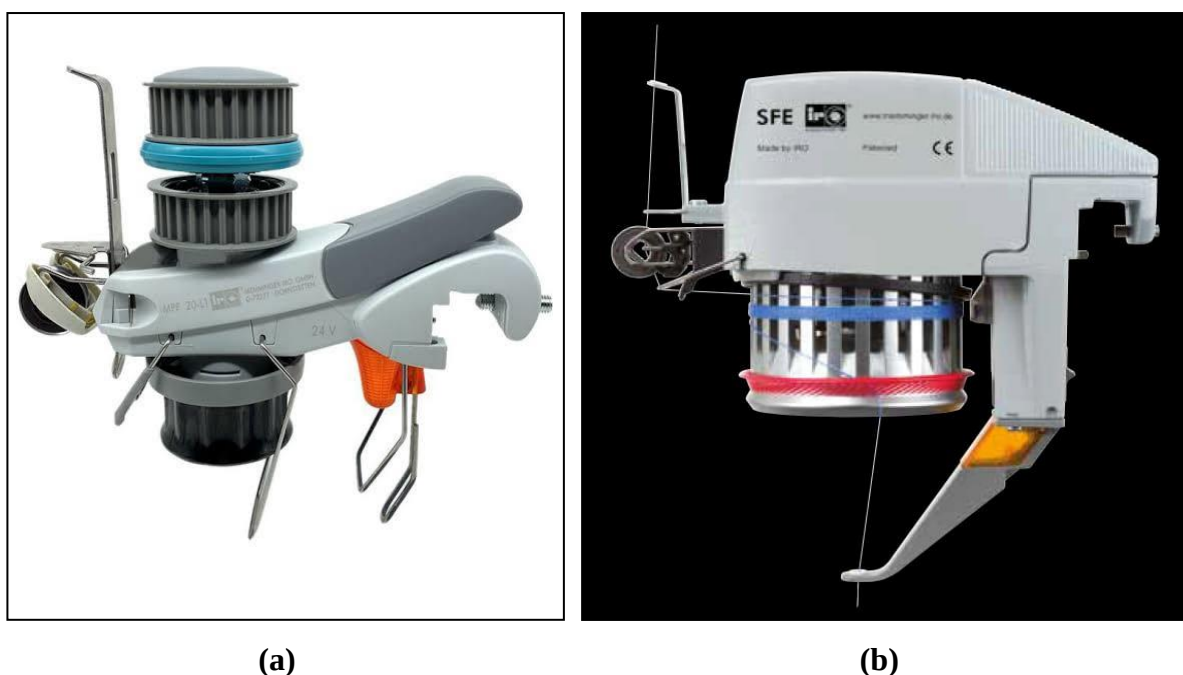


Figure 8: Memminger IRO positive feeder (a) MPF-L model and (b) SFE model

Both yarns are entered into the common knitting feeder and presented simultaneously at the needle hook. The SFE feeders were modified to operate with minimal storage rounds to reduce curvature stress on the glass fibre yarn. Moreover, the yarn-guide assemblies were repositioned

to establish straighter and shallower yarn-path angles, thereby eliminating sharp directional changes and unnecessary friction points. Ceramic eyelets and low-friction guide components were introduced along the yarn pathway to maintain a smooth, fracture-resistant yarn flow.

Modifications in Cam System

Alterations to the cam system were required to create a relaxed loop-formation environment suitable for brittle filament handling. The machine was equipped with a modified alternate knit-miss cam sequence on both cylinder and dial as shown in **Figure 9**, enabling a gentler knitting path and reducing the bending radius imposed on the glass filament during loop formation. This adjustment significantly diminished filament stress at the moment of needle penetration and during loop takeover.

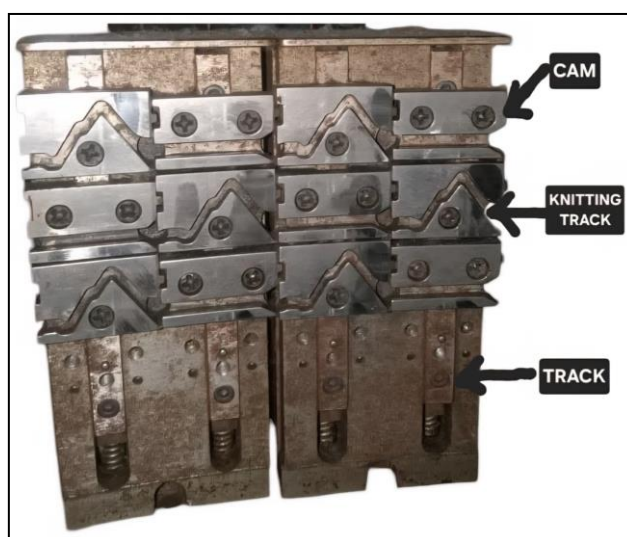


Figure 9: Circular knitting machine cam shell with cam arrangement

In addition, the cam depths and stitch-length control settings were recalibrated to achieve a more relaxed loop geometry. These adjustments required mechanical repositioning of the cam, alteration of cam profile engagement, and coordinated feed wheel alignment. Modified presser settings were incorporated to reduce drag on the stiff filament during loop placement.

Needle Height Adjustments

To accommodate the reduced flexibility of the glass fibre yarn, the machine needles were set to operate in a full-clear configuration. This adjustment increased the vertical clearance available during loop formation, thereby preventing snagging, excessive drag, and accidental fibre splitting. Full-clear needle settings enlarged the loop-takeover window, enabling the stiff glass fibre yarn to complete loop formation without obstructive interactions with adjacent yarns

or machine elements. Furthermore, needles with the smoothest hook profiles only were selected for operation, and the needle replacement frequency was increased to avoid micro-burr formation that could damage the glass fibre yarn. The dial and cylinder needle tracks were inspected and lubricated more frequently to ensure smooth mechanical motion at the reduced speeds required for hybrid yarn knitting.

Process Parameters and Machine Operation

Knitting was conducted on the Mayer & Cie OV 3.2 interlock machine, with operational speeds in the range of 18-22 RPM. The speed was adjusted to protect yarn integrity and produce errorless knitted fabric with Modacrylic or FR Viscose ring-spun yarn and glass fibre yarn, both having very different yarn properties.

Production trials were conducted to establish this optimal speed that balanced throughput with an acceptable filament-breakage rate of < 1 break/1000 m. Each run commenced with a trial swatch to confirm stitch settings, GSM, and the absence of defects. Upon validation, continuous lengths sufficient for all subsequent tests were produced.

Minimising Process Loss and Yield Optimisation

To minimise the process loss and to optimise the yield, the following strategies were deployed:

- Utilisation of low-yarn-storage Memminger IRO SFE feeders and straight, minimal-bend in-feed yarn paths with air creel to alleviate induced stresses on glass filaments.
- Conducting real-time monitoring of yarn breakage via integrated machine sensors and scheduled visual inspections. The production was halted when breakage counts exceeded predefined thresholds to permit corrective actions (tension recalibration, re-feeding and needle replacement).
- Employing uniform yarn packages having conical tubes with consistent winding profiles and replacing bobbins before reductions in package diameter to reduce erratic unwind behaviour.

Quality Control, Sampling Plan and Data Collection

Quality assurance encompassed both online and offline protocols:

- Online measures: Continuous feeder-tension surveillance with alarm set points; pneumatic sensors for detecting repeated needle failures; logging of machine RPM; automated yarn-break event counts (**Figure 10**).



Figure 10: Indicator lights for online measurement

- Offline measures: Systematic sampling of knitted fabric for visual defects (missed stitches, floats); gravimetric determination of GSM according to standardised protocol and tactile evaluation of fabric hand by trained assessors.

Fabric Preparation

The fabric samples were prepared by knitting two yarns simultaneously on an interlock circular knitting machine. The interlock structure was selected for its dimensional stability, reversability, and bulk, which are essential for mattress covers that demand both comfort and mechanical resilience.

Table 3: Sample variations and coding

Sample code	Yarn combinations	Areal density (g/m ²)
M220	Modacrylic & glass fibre yarn	220
M240	Modacrylic & glass fibre yarn	240
M260	Modacrylic & glass fibre yarn	260
V220	FR Viscose & glass fibre yarn	220
V240	FR Viscose & glass fibre yarn	240
V260	FR Viscose & glass fibre yarn	260
C220	100% cotton yarn	220
C240	100% cotton yarn	240
C260	100% cotton yarn	260

Different samples were prepared by varying different yarn combinations and fabric areal densities to have their best performance. **Table 3** shows the sample variations and their related coding.

Development of FR Fabric

The modacrylic ring-spun and glass fibre yarns were arranged in the air creel such that they were alternatively delivered to the Memminger IRO SFE positive feeders. Yarn paths were engineered with gentle guide angles, reduced wrap-around rollers, and minimal storage turns to reduce curvature-induced filament stress. The Memminger IRO SFE positive feeders were calibrated alternatively for staple-yarn and glass fibre yarn tension behaviour. The yarns were simultaneously presented to the needles in full clear arrangement, and they were further knitted into a fabric. Modacrylic glass fibre knit fabric in 220, 240 and 260 g/m² is demonstrated in **Figure 11 (a), (b) and (c)** respectively.

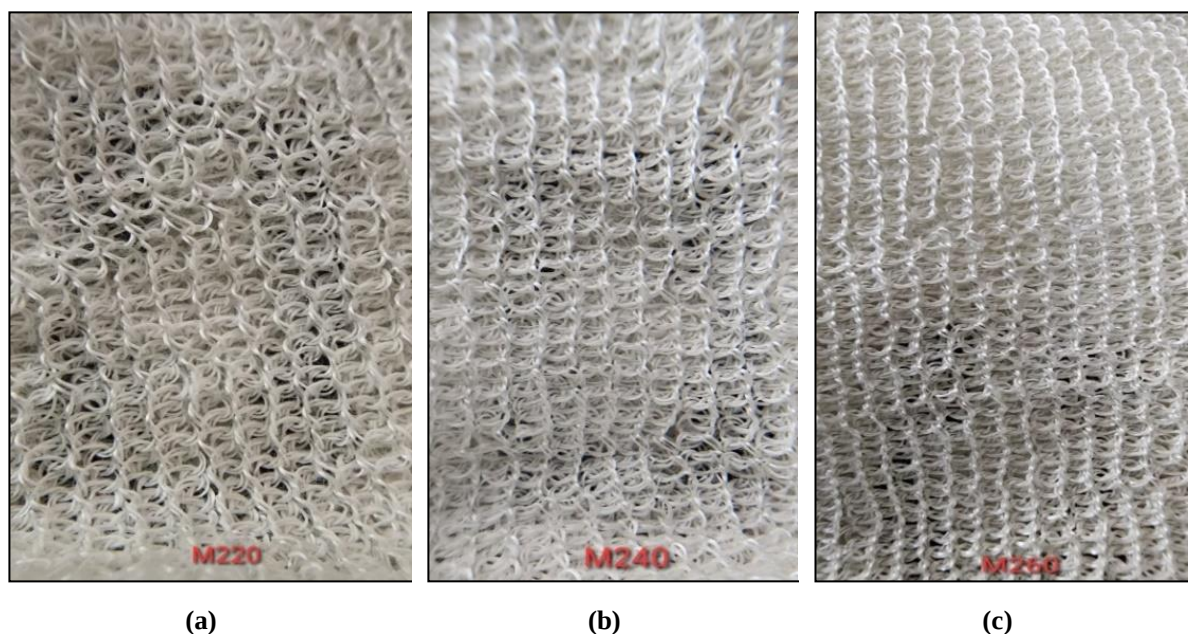


Figure 11 Modacrylic Glassfibre Knit fabric (a) 220 g/m², (b) 240 g/m² and (c) 260 g/m²

Fabric density variants in 220, 240, 260 g/m² were achieved by adjusting stitch-length settings during knitting. Samples were labelled as M220, M240, and M260 as shown in **Table 3.3**. Also, glass fibre yarn and ring spun FR yarns were fed to the same knitting feeder from their separately calibrated SFE feeder. FR Viscose glassfibre knit fabric in 220, 240 and 260 g/m² are demonstrated in **Figure 12 (a), (b) and (c)** respectively. Samples were labelled as V220, V240, and V260 as shown in **Table 3**.

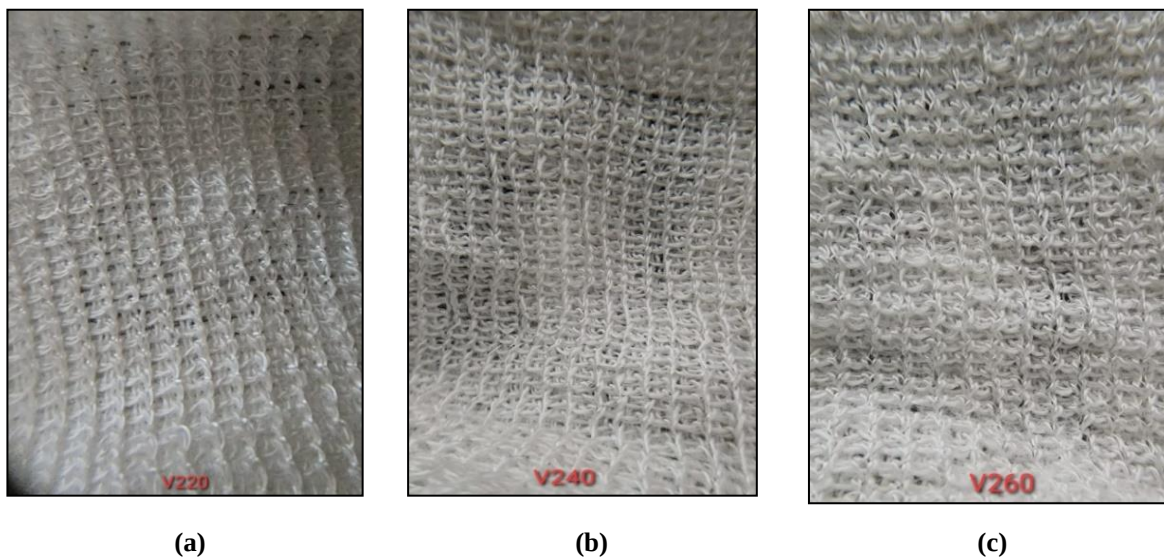


Figure 12 FR Viscose Glassfibre Knit fabric (a) 220 g/m², (b) 240 g/m² and (c) 260 g/m²

Development of 100% cotton fabric

The 100% cotton fabric was prepared by knitting ring-spun cotton yarn on an interlock circular knitting machine. Fabric density variants in 220, 240, 260 g/m² were achieved by adjusting stitch-length settings during knitting. Those fabrics are pictorially represented in **Figure 13 (a), (b) and (c)**. Samples were labelled as C220, C240, and C260 as shown in **Table 3**.

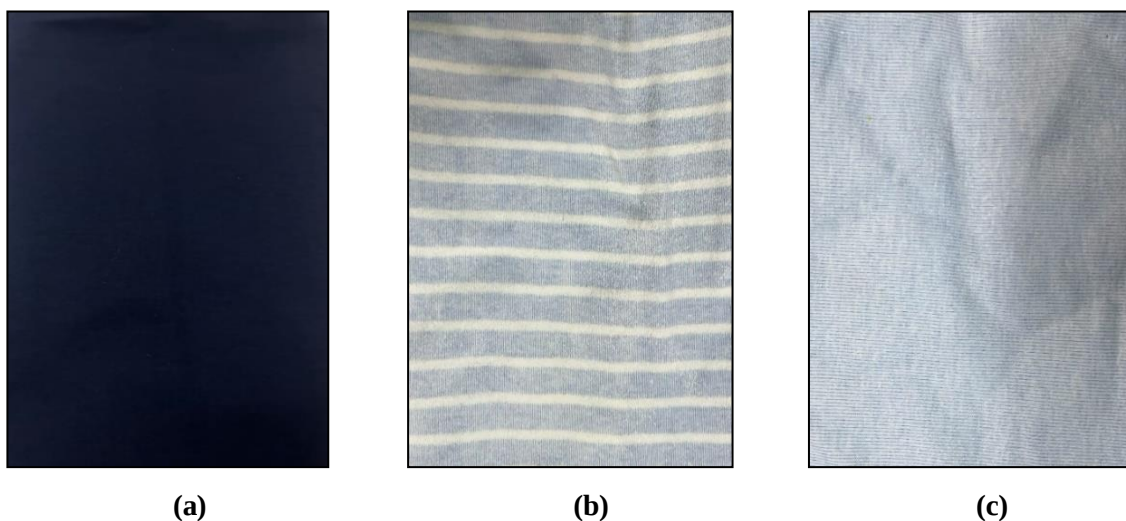


Figure 13 Cotton FR Coated fabric (a) 220 g/m², (b) 240 g/m² and (c) 260 g/m²

Flame-Retardant Treatment Process

A flame-retardant finish was applied to a prepared 100% cotton fabric. This was done to compare the properties of inherently developed flame-retardant fabric variants with the chemically coated cotton fabric. The application of FR chemical involves the use of a pressurised spray system that atomises REF-114 chemical using compressed air and uniformly

deposits the formulation on both fabric surfaces as shown in **Figure 14**. This method was preferred to get a uniform spread, reducing chemical wastage, and enhancing process control. Treated specimens were subsequently cured at ambient conditions (25 ± 2 °C) for 24 h, facilitating chemical fixation without imposing thermal stress. The targeted add-on was 15-18 % by weight, in accordance with the manufacturer's recommendations for optimal FR efficacy.



Figure 14: Spray coating of FR chemical

Prototype Mattress Manufacturing

Miniature mattress samples, measuring 30 cm x 30 cm x 15 cm, were developed. The prepared foam mattress consists of a layer of PU foam and memory foam, which are highly flammable, being composed of a petrochemical product of polyurethane (**Figure 15**).

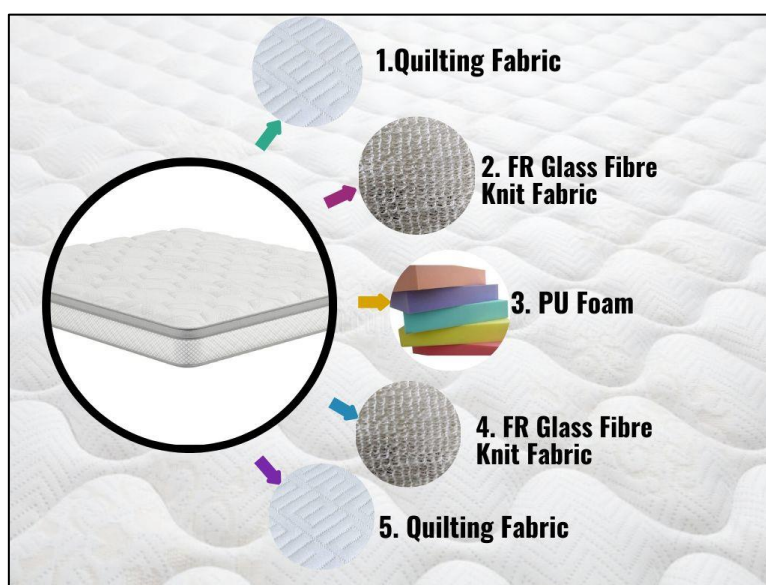


Figure 15: Description of Mattress layers

It was completely encapsulated by FR yarns (Modacrylic and FR Viscose) and glass knit fabric variants. It is further covered by quilting/ticking fabric for the aesthetic requirement and comfort of the user. These mattresses were further subjected to flame-retardant tests.

Testing Methods, Standards, and Procedures

According to the ASTM D1776 standard, all the samples were conditioned at R.H. (%) of $65 \pm 2\%$ and temperature of $25 \pm 2^\circ\text{C}$ for 4 hours. The sample testing was carried out under standard laboratory conditions.

3.0 Key Findings

In the present research, a comprehensive suite of evaluation methods was employed to assess both the raw material performance and the functional properties of knitted fabrics produced from combined yarn. At the yarn level, three distinct categories of yarns, i.e. 48's Ne S-glass, 30's Ne Modacrylic, and 30's Ne FR Viscose, were subjected to detailed analysis. Characterisation of the yarns procured was conducted using different techniques, including Fourier Transform Infrared Spectroscopy (FTIR), X-ray Diffraction (XRD), Differential Scanning Calorimetry (DSC), and Thermo Gravimetric Analysis (TGA). Mechanical attributes such as yarn count and load-elongation behaviour were determined to establish their suitability for circular knitting operations.

Based on this, different fabric samples were prepared, and the variants were systematically evaluated for structural, mechanical, comfort, and flame-retardant properties. Furthermore, to simulate real-world applications, selected samples were fabricated into mini-mattress prototypes and were evaluated for their performance at the Wool Research Association (WRA) for large-scale flammability behaviour under open flame exposure. For better representation of different properties, sample coding was performed, and the details are shown in **Table 4**.

Table 4: Fabric sample coding

Sr. No.	Knitted Fabric Combinations	GSM	Sample Code
1	Glassfibre Modacrylic	220	M220
2	Glassfibre Modacrylic	240	M240
3	Glassfibre Modacrylic	260	M260
4	Glassfibre FR Viscose	220	V220
5	Glassfibre FR Viscose	240	V240
6	Glassfibre FR Viscose	260	V260
7	FR Treated Cotton	220	C220
8	FR Treated Cotton	240	C240
9	FR Treated Cotton	260	C260

The results presented here provide not only an empirical basis for assessing the performance of the selected fibres and fabrics but also a critical discussion of how structural modifications, fibre hybridisation, and GSM variations influence the balance between flame resistance, mechanical durability, and user comfort. This integrated approach establishes a scientific

framework for advancing the design of FR mattress cover fabrics manufactured using circular knitting technology, with direct implications for industrial-scale production and compliance with international fire safety standards.

Characterisation of Functional Yarns

Characterisation of functional yarns evaluates their specialised properties to ensure performance in the desired application. Functional yarns require testing to confirm consistency during spinning, weaving, and use.

Fourier Transform Infrared (FT-IR) Spectroscopy Analysis

It identifies substances by detecting how molecules absorb infrared light, revealing their unique chemical bonds and functional groups, making it crucial for material identification, quality control, and contamination detection. Fourier Transform Infrared (FT-IR) Spectroscopy analysis identifies molecular structures and chemical compositions in functional yarns. This technique reveals functional groups, crystallinity, and modifications essential for verifying yarn performance.

FTIR Spectra of Modacrylic Fibre

FTIR spectroscopy confirmed the characteristic chemical structure of modacrylic fibre as an acrylonitrile-based copolymer. The prominent absorption peak at 2244 cm^{-1} verified the presence of nitrile ($\text{C}\equiv\text{N}$) groups, representing the primary structural component of the polymer backbone. Peaks at 2922 cm^{-1} corresponded to aliphatic C–H stretching, while the bands in the range of $711\text{--}519\text{ cm}^{-1}$ indicated C–Cl stretching, confirming the incorporation of chlorinated comonomers such as vinylidene chloride. Minor absorption bands observed at 3414 cm^{-1} (OH), 1736 cm^{-1} (C=O), and $1111\text{--}1027\text{ cm}^{-1}$ (C-O-C) were attributed to moisture presence, surface oxidation, or processing-related additives.

FTIR Analysis of Fire-Retardant Viscose Fibre

FTIR spectroscopy confirmed the cellulose-based structure of fire-retardant (FR) viscose fibre along with the successful incorporation of phosphorus-containing flame-retardant functionalities. The broad absorption band around 3401 cm^{-1} corresponds to O–H stretching, reflecting extensive hydrogen bonding within the cellulose matrix. Peaks in the range of $2994\text{--}2894\text{ cm}^{-1}$ indicate aliphatic C–H stretching, while bands between $1159\text{--}1015\text{ cm}^{-1}$ and at $999\text{--}928\text{ cm}^{-1}$ confirm C–O–C stretching and β -glycosidic linkages characteristic of regenerated cellulose. Additional absorption bands in the lower wavenumber region ($\approx 965\text{--}$

604 cm^{-1}) are attributed to P=O and P–O–C vibrations, verifying the presence of phosphorus-based flame-retardant groups. Minor peaks associated with moisture and oxidation were also observed.

FTIR Analysis of Glass Fibre

FTIR spectroscopy confirmed the characteristic alumino-silicate structure of S-glass fibre along with the presence of silane-based surface modification. The broad band at $\sim 3433 \text{ cm}^{-1}$ corresponds to surface hydroxyl (–OH) groups and adsorbed moisture, which serve as active sites for silane coupling. Weak peaks in the range of 2957–2850 cm^{-1} and at 1464 cm^{-1} are attributed to C–H stretching and bending vibrations, indicating the presence of organofunctional silane coating. Strong absorption bands between 1225–1035 cm^{-1} correspond to Si–O–Si and Si–O–C stretching, confirming the silicate network and covalent bonding between the silane layer and the glass surface. Additional bands in the lower wavenumber region ($\approx 719\text{--}414 \text{ cm}^{-1}$) are associated with Si–O–Si and Si–O–Al bending vibrations, characteristic of alumino-silicate glass.

X-ray Diffraction (XRD) Analysis

X-ray Diffraction (XRD) analysis determines the crystalline structure, phase composition, and degree of crystallinity in functional yarns. This technique reveals how atomic arrangements affect mechanical strength, thermal stability, and performance in applications like composites or smart textiles

X-ray Diffraction (XRD) Analysis of Glass Fibre

X-ray diffraction (XRD) analysis revealed the predominantly amorphous nature of the glass fibre having alumino-silicate structure with localized ordering, contributing to its high mechanical strength and thermal stability. A broad diffraction halo centred at $\sim 27^\circ$ (2θ) within the $15\text{--}30^\circ$ range confirms the disordered arrangement of silica-based network structures typical of glassy materials. The absence of sharp diffraction peaks at higher angles further supports the lack of long-range crystalline order. However, the asymmetric profile and finite intensity of the main halo indicate the presence of limited short-range ordering or partially crystalline regions formed during fibre processing. Quantitative analysis using the area method yielded a crystallinity index of approximately 46.5%, suggesting moderate structural organization within an otherwise amorphous matrix.

X-ray Diffraction (XRD) Analysis of Modacrylic Fibre

X-ray diffraction (XRD) analysis of modacrylic fibre revealed a predominantly amorphous structure with dispersed semi-crystalline regions. The diffraction pattern exhibited a broad

halo centred at $\sim 17^\circ$ (2θ), representing amorphous domains and short-range molecular ordering, along with a moderate peak near 23° (2θ) corresponding to partially ordered crystalline regions. Weak features between $26\text{--}32^\circ$ (2θ) further indicated the presence of small, imperfect crystallites arising from disrupted chain packing. Quantitative evaluation using the area method yielded a crystallinity index of approximately 37.1%, confirming the dominance of amorphous phases due to copolymerization and chemical modification of the acrylic backbone.

X-ray Diffraction (XRD) Analysis of FR Viscose Fibre

X-ray diffraction (XRD) analysis of fire-retardant (FR) viscose fibre revealed a semi-crystalline structure characteristic of regenerated cellulose. Distinct diffraction peaks at $\sim 11^\circ$ and $\sim 21^\circ$ (2θ) correspond to the (1-10) and (110)/(020) planes of cellulose II, confirming the regenerated nature of the fibre. The presence of broad halos, particularly in the $18\text{--}24^\circ$ region, indicates a significant amorphous fraction resulting from fibre regeneration and flame-retardant modification. Minor peaks between $25\text{--}30^\circ$ (2θ) suggest limited short-range ordering within the polymer chains. Quantitative analysis using the area method yielded a crystallinity index of approximately 48.5%, indicating a balanced distribution of crystalline and amorphous phases.

Differential Scanning Calorimetry (DSC)

Differential Scanning Calorimetry (DSC) analysis measures heat flow changes in functional yarns as temperature varies, identifying thermal transitions like melting, glass transition, and crystallization. This reveals how yarns respond to heat, critical for performance in textiles under processing or end-use conditions. Here, Differential Scanning Calorimetry is performed to measure the heat flow changes in functional yarns as temperature varies, providing critical insights into thermal behavior and material properties essential for quality assurance and product development.

Differential Scanning Calorimetry (DSC) Analysis of FR Viscose Fibre

Differential Scanning Calorimetry (DSC) analysis of fire-retardant (FR) viscose fibre revealed distinct thermal transitions associated with moisture loss, structural relaxation, and thermal degradation. An initial broad endothermic peak between $\sim 50\text{--}80^\circ\text{C}$ corresponds to the evaporation of absorbed moisture. This is followed by a gradual heat flow change up to $\sim 220^\circ\text{C}$, indicating polymer relaxation and pre-degradation behaviour. A prominent exothermic peak at $\sim 250\text{--}260^\circ\text{C}$ marks the onset of cellulose backbone decomposition, indicating the primary degradation stage. Beyond this region, further thermal breakdown

occurs due to secondary decomposition processes. FR viscose fibre exhibits thermal stability up to approximately 220°C, beyond which rapid degradation occurs. This behaviour reflects its semi-crystalline structure and supports its suitability for moderate heat-resistant applications.

Differential Scanning Calorimetry (DSC) Analysis of Modacrylic Fibre

Differential Scanning Calorimetry (DSC) analysis of modacrylic fibre revealed thermal behaviour characteristic of an amorphous copolymer. An initial broad endothermic peak at ~50–70°C corresponds to moisture desorption, reflecting the hygroscopic nature of the fibre. A relatively stable baseline between ~120 - 210°C indicates amorphous chain relaxation without significant thermal transitions, confirming the absence of a distinct melting point. A sharp transition observed around ~230 - 240°C marks the onset of thermal degradation, associated with dehydrochlorination of the polymer. This early-stage decomposition contributes to the inherent flame-retardant behaviour of modacrylic fibres through the release of HCl, which suppresses combustion. Modacrylic fibre exhibits thermal stability up to ~210°C, with controlled degradation mechanisms that enhance its flame-retardant performance.

Differential Scanning Calorimetry (DSC) Analysis of Glass Fibre

Differential Scanning Calorimetry (DSC) analysis of glass fibre demonstrated exceptional thermal stability across the temperature range of 30 - 300°C, with minimal variation in heat flow and no distinct thermal transitions. This behaviour reflects the inorganic, amorphous silicate structure of glass fibre, which lacks polymeric phase transitions or degradation mechanisms. Minor thermal variations observed at lower temperatures (~30 - 150°C) are attributed to the decomposition and volatilization of organic sizing agents applied during fibre processing. Beyond this, the absence of significant thermal events confirms that the glass phase remains thermally stable within the studied range. The DSC results validate the inherent thermal inertness and high-temperature resistance of glass fibre, making it highly suitable as a reinforcement material in flame-retardant and high-performance textile systems.

Thermogravimetric Analysis

Thermogravimetric Analysis is conducted to measure mass loss in functional yarns as temperature increases, determining thermal decomposition temperatures, stability, and material composition, critical for assessing performance in heat-exposed applications and quality control

Thermogravimetric Analysis (TGA) of FR Viscose Fibre

Thermogravimetric analysis (TGA) of fire-retardant (FR) viscose fibre demonstrated multi-stage thermal degradation behaviour characteristic of modified cellulosic materials. An initial minor mass loss ($\sim 3\%$) below 100°C corresponds to moisture evaporation. The primary decomposition stage occurs between $\sim 230 - 270^\circ\text{C}$, which is lower than that of conventional viscose, indicating acid-catalysed dehydration induced by phosphorus-based flame-retardant additives. A secondary degradation phase between $\sim 370 - 420^\circ\text{C}$ is associated with char stabilization and residue formation. Notably, the fibre exhibited a high char yield of approximately 20% at elevated temperatures, significantly greater than that of untreated viscose. The reduced decomposition temperature combined with enhanced char formation confirms an intumescent flame-retardant mechanism, where early-stage degradation promotes the formation of a protective carbonaceous layer, thereby improving fire resistance.

Thermogravimetric Analysis (TGA) of Modacrylic Fibre

Thermogravimetric analysis (TGA) of modacrylic fibre exhibited a characteristic two-stage degradation profile, confirming its modified acrylic composition. The first decomposition stage ($\sim 220 - 300^\circ\text{C}$) is associated with dehydrochlorination and the release of non-flammable gases (e.g., HCl), resulting in an initial mass loss of approximately 30%. This is followed by an exothermic peak around $\sim 250\text{--}260^\circ\text{C}$, attributed to cyclization of nitrile groups, which stabilizes the polymer structure. The second degradation stage ($\sim 300 - 450^\circ\text{C}$) corresponds to the breakdown of the polymer backbone, with an additional mass loss of $\sim 33\%$. Despite this, a high char residue of approximately 35–40% is retained at elevated temperatures. The multi-stage degradation mechanism comprising gas-phase flame inhibition and solid-phase char formation confirms the superior flame-retardant performance of modacrylic fibre.

Thermogravimetric Analysis (TGA) of Glass Fibre

Thermogravimetric analysis (TGA) of glass fibre demonstrated exceptional thermal stability, characteristic of its inorganic silicate composition. A minor initial mass loss below $\sim 100^\circ\text{C}$ is attributed to surface moisture evaporation. The subsequent gradual weight reduction up to $\sim 300^\circ\text{C}$ corresponds to the decomposition and oxidation of organic sizing or binder materials applied during fibre processing. A broad exothermic event around $\sim 300^\circ\text{C}$ further indicates the combustion of these organic coatings. Beyond this stage, no significant degradation is observed, and the material retains approximately 85 - 90% of its original mass at elevated

temperatures. The high residual mass (~87%) confirms the predominantly inorganic nature of glass fibre with excellent thermal resistance.

Yarn Characterization

Tensile Behaviour of Yarns

The mechanical behaviour of constituent yarns plays a critical role in determining the performance of knitted flame-retardant mattress cover fabrics, as loop deformation, load distribution, and structural stability depend largely on yarn tensile characteristics. In this study, the tensile properties of four yarn types, glass fibre, modacrylic, flame-retardant (FR) viscose, and cotton, were evaluated according to ASTM D2256. Key parameters analysed included maximum load, extension at maximum load, tenacity (g/den), and percentage strain.

Glass fibre (110 denier) exhibited the highest tenacity (~5.81 g/den) and maximum load, but very low elongation (~3%), reflecting its rigid inorganic structure. This high strength and minimal extensibility make glass fibre an effective reinforcement component that enhances structural stability and thermal integrity in knitted fabrics.

Modacrylic yarn (190 denier) showed moderate tenacity (~1.01 g/den) but the highest elongation (~11%), indicating greater flexibility and deformation capacity. This property enables knitted loops to absorb mechanical stresses and improves fabric resilience under repeated compression.

FR viscose yarn (190 denier) demonstrated relatively low tenacity (~0.72 g/den) with moderate elongation (~4%), reflecting the limited chain mobility of its regenerated cellulosic structure modified with flame-retardant additives. Despite lower strength, its moderate extensibility contributes to improved comfort and fabric drape.

Cotton yarn (178 denier) exhibited higher tenacity (~1.45 g/den) than modacrylic and FR viscose with moderate elongation (~4.5%). This combination provides stable yarn feeding and reliable loop formation during circular knitting, although cotton lacks inherent flame resistance and requires additional treatment for fire-retardant applications.

Fabric Testing

Structural Analysis

Thread density measurements were carried out according to ASTM D3887 at ATIRA, Ahmedabad. Fabric structure was evaluated for three GSM levels 220, 240, and 260 g/m² across three fibre systems: Modacrylic–Glass fibre (M-series), FR Viscose–Glass fibre (V-series), and FR-treated Cotton (C-series). Thread density was assessed in terms of courses per

inch (CPI) and wales per inch (WPI).

Within the M-series fabrics, increasing GSM from 220 to 260 g/m² produced minimal structural variation, with CPI remaining nearly constant (28 - 27) and WPI showing only slight changes (12–15). In the V-series fabrics, CPI varied marginally (27 - 29) while WPI remained within the range of 13–16. In contrast, FR-treated cotton (C-series) fabrics exhibited significantly higher thread densities. CPI increased from 32 to 40 with increasing GSM, while WPI remained high (36 - 37), indicating a much denser and more compact loop structure compared to glass fibre-based fabrics.

Comparative analysis across fibre systems has shown that cotton fabrics consistently exhibit the highest thread densities, whereas the M-series and V-series fabrics display relatively lower and comparable values due to the stiffness of glass fibre components. The denser cotton structure is likely to reduce fabric porosity and air permeability, whereas the comparatively open glass fibre-based structures may enhance breathability and moisture transport. Consequently, the flammability behaviour of the fabrics must be interpreted not only in terms of fibre chemistry but also in relation to the structural geometry of the knitted fabric.

Mechanical Properties of Fabric

Bursting Strength (ASTM D3786)

Bursting strength represents the resistance of knitted fabrics to multidirectional rupture and is influenced by fibre characteristics, yarn structure, loop geometry, and fabric density. The tests were conducted according to ASTM D3786 at ATIRA, Ahmedabad.

Within individual fabric systems, bursting strength generally increased with GSM. In the Modacrylic–Glass fibre (M-series) fabrics, bursting strength increased from 110 PSI at 220 GSM to 155 PSI at 260 GSM. Similarly, FR Viscose–Glass fibre (V-series) fabrics showed an increase from 133.3 PSI to 178.3 PSI as GSM increased. In the FR-treated Cotton (C-series) fabrics, bursting strength increased from 216.7 PSI at 220 GSM to a maximum of 273.4 PSI at 240 GSM, followed by a slight decrease to 265 PSI at 260 GSM. This suggests the presence of an optimal structural compactness, beyond which excessive loop densification reduces the fabric's ability to distribute biaxial loads effectively.

Comparative analysis across fibre systems shows that FR-treated cotton fabrics consistently exhibit the highest bursting strength at equivalent GSM levels due to higher thread density, fibre extensibility, and stronger interloop friction. In contrast, glass fibre-based fabrics display relatively lower bursting strength because filament rigidity restricts loop deformation under multidirectional stress.

Fabric Tensile Strength (ASTM D5034-09)

Tensile strength is an important indicator of fabric durability and load-bearing capacity, reflecting the combined influence of fibre properties, loop structure, and fabric density. Tensile testing was performed using the ASTM D5034 at ATIRA, Ahmedabad. Tensile strength was evaluated in both course-wise and wale-wise directions for different fabric blends and GSM levels.

Within individual fabric systems, tensile strength generally increased with GSM up to an optimum level. In Modacrylic–Glass fibre (M-series) fabrics, strength increased from 46.7 N to 55.15 N (course-wise) and from 75.82 N to 100.17 N (wale-wise) as GSM increased from 220 to 240 g/m², followed by a slight decline at 260 g/m² due to increased loop compactness restricting yarn mobility. In FR Viscose–Glass fibre (V-series) fabrics, course-wise tensile strength steadily increased from 58.22 N to 75.19 N with increasing GSM, while wale-wise strength rose moderately from 108.22 N to 117.02 N. The flexible viscose component enables improved stress redistribution within the knitted structure. FR-treated Cotton (C-series) fabrics exhibited the highest tensile strength overall. Course-wise strength increased from 143.8 N at 220 g/m² to 223.2 N at 260 g/m², while wale-wise strength peaked at 412.2 N at 240 g/m² before slightly decreasing at 260 g/m², indicating an optimal loop compactness for effective load distribution.

Comparative analysis across fibre systems shows that FR-treated cotton fabrics consistently demonstrate the highest tensile strength due to greater fibre extensibility and stronger interloop cohesion, whereas glass fibrebased fabrics display lower tensile values due to filament rigidity. In all samples, tensile strength in the wale direction exceeds the course direction because of the continuous yarn alignment along the wale axis. Overall, the results highlight the combined influence of fibre composition and structural density on the anisotropic tensile performance of knitted fabrics.

Fabric Stretch and Recovery (ASTM D3107)

Stretch and recovery behaviour reflects the elastic response of knitted fabrics under deformation and is governed by fibre elasticity, loop structure, and fabric density. Different

fibre blends at GSM levels of 220, 240, and 260 g/m² are tested for fabric stretch and recovery using ASTM D 3107 method at ATIRA, Ahmedabad.

Within the Modacrylic–Glass fibre (M-series) fabrics, stretch increased significantly from 120.3% at 220 GSM to 280.1% at 240 GSM, followed by a slight reduction to 263.9% at 260 GSM due to increased loop compactness restricting yarn mobility. Recovery improved simultaneously from 69.0% to approximately 86.5%, indicating enhanced elastic resilience and loop interlocking within the knitted structure. In FR Viscose–Glass fibre (V-series) fabrics, stretch decreased from 290.2% at 220 GSM to 211.7% at 260 GSM, while recovery initially improved to about 87.9% at 240 GSM before declining to 63.9% at 260 GSM. The combination of viscose’s flexibility and glass fibre’s rigidity allows large reversible deformation but increasing fabric density gradually limits extensibility. For FR-treated Cotton (C-series) fabrics, stretch remained relatively stable between 109.5% and 114%, with a slight reduction at higher GSM. However, recovery decreased progressively from 63.9% to 55.6%, indicating reduced elastic rebound, likely due to structural compactness and the stiffening effect of flame-retardant finishing.

Comparative analysis across fibre systems shows that glass fibre–based blended fabrics i.e modacrylic and FR viscose exhibit substantially higher stretch and better recovery than FR-treated cotton fabrics. FR Viscose–glass fibre fabrics generally demonstrate the highest extensibility, while Modacrylic–glass fibre fabrics provide a balanced combination of stretch and dimensional recovery. In contrast, FR-treated cotton fabrics show limited elasticity and declining recovery due to the rigidity introduced by flame-retardant treatment.

Performance Evaluation for Comfort-Related Properties of Fabric

Air Permeability (ASTM D737)

Air permeability represents the rate of airflow through a fabric under a specified pressure difference and reflects the combined influence of fabric porosity, yarn packing, fibre morphology, and stitch structure. The tests were conducted at ATIRA, an NABL accredited facility based in Ahmedabad, Gujarat according to ASTM D737 using a pressure differential of 125 Pa over a 38 cm² test area.

Within individual fabric systems, Modacrylic–Glass fibre (M-series) fabrics showed a clear reduction in air permeability with increasing GSM, decreasing from 588.7 CFM at 220 g/m² to 374.5 CFM at 260 g/m² due to increased loop compactness and reduced pore volume as fabric mass increases. In FR Viscose–Glass fibre (V-series) fabrics, air permeability remained relatively stable across the GSM range approximately 347–376 CFM. The flexible

viscose component helps maintain microchannels for airflow, while the glass fibre reinforcement prevents excessive pore collapse, resulting in consistent breathability. For FR-treated Cotton (C-series) fabrics, air permeability values were significantly lower, ranging between 62 and 70 CFM with minimal variation across GSM levels. The durable flame-retardant finish likely forms a semi-occlusive layer on fibre surfaces, reducing inter-fibre gaps and limiting airflow regardless of structural variations.

Comparative analysis across fibre systems shows that glass fibre based fabrics exhibit substantially higher air permeability than FR-treated cotton fabrics. Modacrylic–glass fibre fabrics demonstrate the highest airflow at lower GSM levels, while viscose–glass fibre fabrics maintain relatively stable permeability across the weight range. In contrast, FR-treated cotton fabrics remain comparatively impermeable due to higher structural compactness and the restrictive effect of the flame-retardant finish.

Water Permeability (ASTM D4491)

Water permeability indicates the rate at which liquid water passes through a fabric under a specified hydrostatic pressure and provides insight into moisture management and protective performance. The tests were conducted according to ASTM D4491 at ATIRA, Ahmedabad using a hydrostatic head apparatus.

Within individual fabric systems, Modacrylic–Glass fibre (M-series) fabrics showed a gradual reduction in water permeability with increasing GSM, decreasing from 115.0 mm/s at 220 g/m² to 95.2 mm/s at 260 g/m². This reduction is attributed to loop densification and the consequent decrease in capillary channels available for liquid flow.

Similarly, FR Viscose–Glass fibre (V-series) fabrics exhibited a comparable downward trend, with permeability declining from 107.8 mm/s to 93.9 mm/s as GSM increased. The increased stitch compactness at higher fabric weights restricts pore volume and limits water flow through the fabric structure.

In contrast, FR-treated Cotton (C-series) fabrics displayed significantly lower permeability values ranging from approximately 14.3 to 17.8 mm/s, with minimal variation across GSM levels. Due to durable flame-retardant finish forming a semi-occlusive layer on fibre surfaces that partially blocks micro-pores and reduce capillary flow, thereby limits water passage through the fabric.

Comparative analysis across fibre systems reveals a consistent hierarchy in permeability, with glass fibre based fabrics i.e modacrylic–glass fibre and FR viscose–glass fibre exhibiting substantially higher water permeability than FR-treated cotton fabrics at equivalent GSM

levels. The open knitted structure of the glass fibre blends facilitates liquid transport through interconnected pore channels, whereas the flame-retardant coating on cotton restricts fluid movement.

Vertical Wicking Test (AATCC 197)

Vertical wicking evaluates the ability of a fabric to transport liquid through capillary action and is an important indicator of moisture management performance. The test was conducted according to AATCC Test Method 197 by recording the height of liquid rise in the fabric over a period of 30 minutes. Wicking height and the corresponding wicking rate were determined for two glass fibre-based knitted systems: Modacrylic–Glass fibre (M-series) and FR Viscose–Glass fibre (V-series), each produced at GSM levels of 220, 240, and 260 g/m².

Within the Modacrylic–Glass fibre (M-series) fabrics, capillary rise increased gradually with time. The M220 and M240 samples reached equilibrium heights of approximately 8 mm and 12 mm after 30 minutes, respectively. The M260 fabric exhibited a higher wicking height of about 15 mm with a delayed but sharper rise, indicating activation of additional capillary pathways at higher fabric density. In contrast, FR Viscose–Glass fibre (V-series) fabrics displayed significantly greater and faster wicking behaviour. The V220 and V240 samples achieved wicking heights of approximately 12 mm and 15 mm, respectively, while the V260 fabric showed a substantially higher rise of about 35 mm within the same duration. Correspondingly, the vertical wicking rate increased with GSM, reaching the highest value for V260. The enhanced performance is attributed to the hydrophilic nature and higher moisture regain of viscose fibres, which promotes stronger capillary driving forces.

Comparative analysis across fibre systems demonstrates that FR viscose glass fibre fabrics consistently outperform Modacrylic glass fibre fabrics at all GSM levels. The hydrophilic fibre matrix of viscose facilitates efficient liquid absorption and transport, whereas the relatively hydrophobic nature of modacrylic fibres limits capillary flow. In both blends, the glass fibre component primarily contributes to structural stability and pore continuity rather than moisture transport.

Flammability Performance of Fabrics

Vertical Flammability Test (IS 11871 Method A)

The vertical flammability test evaluates the resistance of fabrics to flame propagation under vertically oriented ignition conditions. The test was conducted according to IS 11871 Method A at ATIRA, Ahmedabad. Key parameters assessed included char length, after-flame time, and after-glow behaviour for different fibre blends and GSM levels.

Within the Modacrylic–Glass fibre (M-series) fabrics, char length decreased with increasing GSM, indicating improved flame resistance. The course-wise char length reduced from 23 mm at 220 g/m² to 13 mm at 260 g/m², while the wale-wise char length decreased from 20

mm to 16 mm. No after-flame or after-glow was observed, demonstrating immediate self-extinguishing behaviour. This enhanced performance is attributed to the inherent flame-retardant nature of modacrylic fibres and the structural stability provided by glass fibre reinforcement.

In contrast, FR Viscose–Glass fibre (V-series) fabrics exhibited increasing char length with increasing GSM. Course-wise char length increased from 55 mm at 220 g/m² to 81 mm at 260 g/m², while wale-wise values ranged between 59 mm and 83 mm. Although no after-flame or after-glow was recorded, the greater char length suggests that the cellulosic component of FR viscose contributes to higher thermal degradation once combustion initiates.

For FR-treated Cotton (C-series) fabrics, the flame propagated completely to the upper edge of the specimen, preventing measurement of char length. Instead, significant after-flame durations were recorded, increasing from approximately 37 - 45 s at 220 g/m² to 48 - 69 s at 260 g/m². The absence of after-glow indicates that burning ceased once flaming stopped; however, the results highlight the limited effectiveness of surface-applied flame-retardant treatments in preventing vertical flame spread.

Comparative analysis across fibre systems shows that Modacrylic glass fibre fabrics exhibit the highest flame resistance, characterised by minimal char length and rapid self-extinction. FR Viscose–Glass fibre fabrics demonstrate moderate performance, while FR-treated cotton fabrics display the poorest resistance to flame propagation.

45° Flammability Test (IS 11871 Method B)

The 45° flammability test evaluates ignition resistance and flame propagation under mild flame exposure conditions. The test was conducted according to IS 11871 Method B at ATIRA, Ahmedabad.

Across all fibre systems and GSM levels, no ignition was observed during the 15-second exposure, and no flame spread time, after-flame, or after-glow was recorded. This uniform behaviour indicates excellent resistance to small-flame exposure, with effective self-extinguishing characteristics upon removal of the ignition source.

Comparatively, all three fibre systems—Modacrylic glass fibre (M-series), FR Viscose glass fibre (V-series), and FR-treated Cotton (C-series) exhibit similar non-ignition performance at equivalent GSM levels. However, the underlying mechanisms differ: in M-series fabrics, flame resistance is governed by the inherent chemistry of modacrylic fibres; in V-series fabrics, it

arises from modified viscose structure combined with glass fibre reinforcement; while in C-series fabrics, ignition resistance is primarily due to the protective effect of surface-applied flame-retardant finishes.

Flammability Testing of Mattress Fabrics using WRA TM 2950

Full-scale flammability testing using WRA TM 2950 conducted at WRA, Mumbai demonstrated the critical role of flame-retardant (FR) knitted covers in mitigating fire propagation in mattress systems. Unlike laboratory-scale evaluations, the full-scale approach captured the interaction between fabric structure, fibre composition, and polyurethane foam substrate under open-flame conditions.

All FR-covered mattresses, irrespective of blend composition or areal density, successfully confined flame spread to the outer textile layer and prevented ignition of the underlying foam, in contrast to the non-FR control mattress, which exhibited sustained flaming for 680 s. This highlights the inherent fire vulnerability of uncovered polyurethane foam and the effectiveness of FR barriers.

Within the Modacrylic glass fibre (M-series) fabrics, flaming duration increased consistently with areal density (149 s at 220 g/m² to 720 s at 260 g/m²), indicating prolonged surface burning at higher mass without compromising structural integrity or causing after-glow. In contrast, FR Viscose glass fibre (V-series) fabrics exhibited a non-linear response, with an optimal performance at 240 g/m² (146 s), suggesting a balance between thermal insulation and char-forming efficiency.

Comparative analysis revealed that M-series fabrics performed better at lower GSM (220 g/m²), whereas V-series fabrics demonstrated superior fire resistance at higher GSM levels (240–260 g/m²). The results confirm that both fibre composition and fabric areal density critically influence flammability behaviour, with optimized FR knitted structures effectively enhancing fire safety in mattress applications.

Multiple Criteria Decision Making

This chapter covers further analysis of the developed fire-retardant fabrics using the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) tool. This multi-criteria decision-making (MCDM) technique was employed to examine and rank the fabrics based on various performance criteria. TOPSIS facilitated an objective evaluation, which helped identify the most effective and suitable fabric for architectural use [228].

Multiple criteria decision making (MCDM) is a branch of operations research that focuses on decision-making in scenarios where multiple, often conflicting criteria need to be evaluated.

Unlike single-criterion decision-making, MCDM involves analysing and prioritising various options based on several criteria that are important to the decision-maker. MCDM is widely used in various fields, including engineering, environmental management, business strategy, healthcare, and urban planning, where complex decisions involving multiple criteria are common [229].

The following are various objectives of using MCDM:

1. **Identify and clarify criteria:** Determine and clearly define all the criteria that are relevant to the decision-making process. This includes both quantitative and qualitative factors that impact the decision [229], [230].
2. **Evaluate alternatives:** Assess the different alternatives or options available in light of the defined criteria. This often involves gathering data, performing analyses, and understanding the trade-offs between criteria [229], [230].
3. **Prioritise criteria:** Assign weights or levels of importance to each criterion based on the decision-maker's values, preferences, or strategic goals [229], [230].
4. **Develop a decision model:** Create a structured model or framework that integrates all the criteria and their respective weights. This could involve various MCDM methods, such as the Analytic Hierarchy Process (AHP), Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), or Multi-Attribute Utility Theory (MAUT) [229], [230].
5. **Optimise decision-making:** Use the decision model to rank or score the alternatives and identify the best option(s) according to the prioritised criteria [229], [230].
6. **Support transparent and rational decision-making:** Ensure that the decision-making process is transparent, rational, and justifiable by providing a clear rationale for why certain alternatives were chosen over others [229], [230].
7. **Facilitate consensus building:** Help multiple stakeholders with different preferences and priorities reach a consensus by providing a structured approach to evaluate and compare alternatives [229], [230].

Selection Criteria and Weight Assignment for Standard Analysis

In a Multi-Criteria Decision-Making (MCDM) process, the selection of relevant criteria and their respective weightings plays a crucial role in accurately assessing the performance. The analysis focused on a total set of performance parameters, such as thread density (cpi & wpi), tensile strength (cpi & wpi), bursting strength, vertical flammability, air permeability, water permeability, fabric stretch and fabric recovery for which reliable data were obtained. Each selected criterion contributes uniquely to the overall performance of the fabric in fire-retardant mattress cover applications. The relative importance of each criterion was quantified by

assigning a weight, with the total sum normalised to 1. These weights were determined through a combination of literature review, commercial data available and based on application needs.

Table 5, shows the weightage of different properties considered for MCDM comparison. Almost all the properties evaluated during the experiment are considered here, except 45° flammability and open flame study of the sample mattresses, as the results are not quantifiable. The selected criteria reflect a balance between mechanical strength, comfort and flammability, ensuring the decision-making process aligns with real-world applications.

Table 5: Weightage of different properties for MCDM comparison (standard)

Property	Weightage
Thread density (cpi)	0.04
Thread density (wpi)	0.04
Tensile strength (cpi)	0.05
Tensile strength (wpi)	0.05
Bursting strength	0.08
Air permeability	0.11
Water permeability	0.05
Vertical flammability (cpi)	0.2
Vertical flammability (wpi)	0.2
Fabric stretch	0.1
Fabric recovery	0.08

Comparison of All Flame-Retardant Knitted Fabrics (Standard Analysis):

The overall performance scores (P_i), as illustrated in **Figure 16**, indicate a comprehensive multi-criteria selection outcome. Among all evaluated fabrics, Modacrylic-M240 emerged as the top-performing sample with the highest P_i value of 0.7565, securing Rank 1. This was closely followed by Modacrylic-M260 ($P_i = 0.7375$) and Modacrylic-M220 ($P_i = 0.7068$), ranking second and third, respectively. The dominance of the modacrylic series under mattress-application weightage is primarily attributed to their low vertical flammability values combined with balanced comfort and mechanical performance. Since flame resistance carried substantial cumulative weightage (0.40).

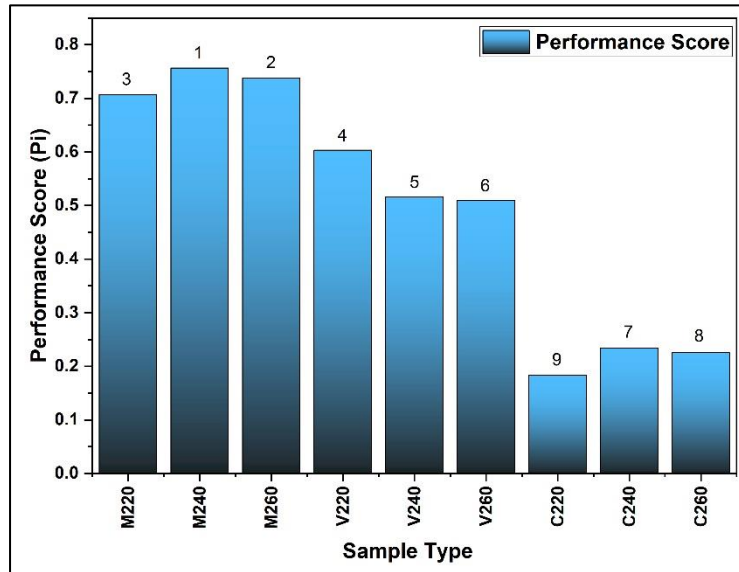


Figure 16: Comparison of prepared fabrics with mattress cover fabric application-based weightage

The FR viscose-based fabrics demonstrated moderate overall performance under these evaluation conditions. FR Viscose-V220 ($P_i = 0.6030$) ranked fourth, followed by FR Viscose-V240 ($P_i = 0.5161$) and FR Viscose-V260 ($P_i = 0.5094$), respectively.

In contrast, the FR cotton-based fabrics recorded the lowest performance scores in this scenario. FR Cotton-C240 ($P_i = 0.2347$), FR Cotton-C260 ($P_i = 0.2254$), and FR Cotton-C220 ($P_i = 0.1839$) ranked seventh, eighth, and ninth, respectively.

Criteria and Weight Assignment for Flammability Resistance as Priority

In this second option, these weights were determined keeping in mind the flammability aspect of the product. As the whole work is related to the development of flame-retardant mattress cover fabric, it was decided to keep maximum weightage on vertical flammability and less weightage on other parameters and check whether any change in the selection criteria is observed or not. **Table 6** shows the weightage of different properties considered for MCDM comparison related to flammability.

Table 6: Weightage of different properties for MCDM comparison (flammability)

Property	Weightage
Thread density (cpi)	0.02
Thread density (wpi)	0.02
Tensile strength (cpi)	0.02
Tensile strength (wpi)	0.02
Bursting strength	0.02
Air permeability	0.1

Water permeability	0.1
Vertical flammability (cpi)	0.3
Vertical flammability (wpi)	0.3
Fabric stretch	0.05
Fabric recovery	0.05

Comparison of All Flame-Retardant Knitted Fabrics (Flammability Resistance Priority)

The performance evaluation of all developed flame-retardant knitted fabric samples using the TOPSIS method, with flammability-related properties assigned the highest priority weightage (vertical flammability in course and wale directions = 0.30 each), revealed a distinctly different ranking pattern. The overall performance scores (P_i), as illustrated in **Figure 17**, indicate that fabrics with flammability parameters carried the maximum cumulative weightage (0.60).

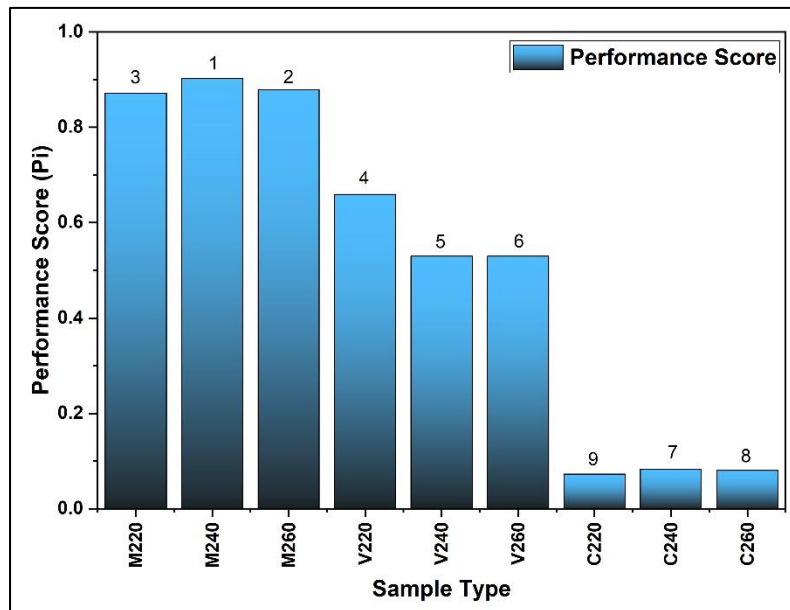


Figure 17: Comparison of prepared fabrics with flammability resistance as priority

Among all evaluated fabrics, Modacrylic-M240 emerged as the top-performing sample with the highest P_i value of 0.9033, securing Rank 1. This was followed by Modacrylic-M260 ($P_i = 0.8784$) and Modacrylic-M220 ($P_i = 0.8718$), ranking second and third, respectively. The dominance of the modacrylic series under flammability-priority conditions is primarily attributed to their inherently low vertical flammability values. Modacrylic-M260 exhibited the lowest flammability values (13 mm in course and 16 mm in wale direction), while M240 demonstrated a highly balanced overall performance. The FR viscose-based fabrics demonstrated moderate performance under these evaluation conditions. FR Viscose-V220 ($P_i = 0.6591$) ranked fourth, followed by FR Viscose-V240 ($P_i = 0.5298$) and FR Viscose-V260 ($P_i = 0.5295$), respectively. In contrast, the FR cotton-based fabrics recorded the lowest performance scores in this scenario.

FR Cotton-C240 ($P_i = 0.0831$), FR Cotton-C260 ($P_i = 0.0803$), and FR Cotton-C220 ($P_i = 0.0729$) ranked seventh, eighth, and ninth, respectively.

Criteria and Weight Assignment for Mechanical Property as Priority

In this third option, these weights were determined keeping in mind the Tensile aspect of the product. As the tensile characteristics are very important in any development work, it was decided to keep maximum weightage on tensile-related properties and less weightage on other parameters and check whether any change in the selection criteria is observed or not. **Table 7**, shows the weightage of different properties considered for MCDM comparison related to tensile properties.

Table 7: Weightage of different properties for MCDM comparison (Mechanical Property)

Property	Weightage
Thread density (cpi)	0.02
Thread density (wpi)	0.02
Tensile strength (cpi)	0.2
Tensile strength (wpi)	0.2
Bursting strength	0.2
Air permeability	0.05
Water permeability	0.05
Vertical flammability (cpi)	0.1
Vertical flammability (wpi)	0.1
Fabric stretch	0.03
Fabric recovery	0.03

Comparison of All Flame-Retardant Knitted Fabrics (Mechanical Property Priority)

The performance evaluation of all developed flame-retardant knitted fabric samples using the TOPSIS method, with mechanical properties assigned the highest priority weightage, revealed distinct variations in their overall rankings based on the performance score (P_i), as illustrated in **Figure 18**. Among all the evaluated fabrics, FR Cotton-C240 emerged as the top-performing sample with the highest P_i value of 0.6722. This was followed by FR Cotton-C260 ($P_i = 0.6499$) and FR Cotton-C220 ($P_i = 0.4526$), respectively.

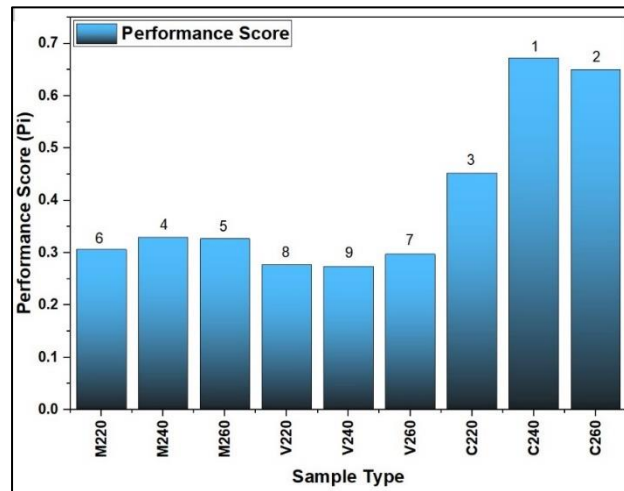


Figure 18: Comparison of prepared fabrics with mechanical property as priority

In contrast, the modacrylic-based fabrics exhibited moderate performance scores. Among them, Modacrylic-M240 ($P_i = 0.3301$) ranked fourth, followed by Modacrylic-M260 ($P_i = 0.3267$) and Modacrylic-M220 ($P_i = 0.3062$). Although modacrylic fabrics demonstrated acceptable flame-retardant characteristics and relatively good air permeability, their comparatively lower bursting and tensile strength values restricted their overall ranking when mechanical properties were given dominant importance. Nevertheless, the 240 GSM variant displayed improved structural–mechanical synergy, indicating that optimised fabric density positively contributes to cumulative performance. The lowest performance scores were recorded for the FR viscose-based fabrics. FR Viscose-V260 ($P_i = 0.2972$) ranked seventh, followed by FR Viscose-V220 ($P_i = 0.2775$) and FR Viscose-V240 ($P_i = 0.2738$), respectively.

Criteria and Weight Assignment for Comfort Property as Priority

In this fourth option, these weights were determined keeping in mind the comfort aspect of the product. In the development of mattress cover fabric, comfort plays an important role. The developed material has to be comfortable apart from other properties, hence it was decided to keep maximum weightage on comfort-related properties and less weightage on other parameters and check whether any change in the selection criteria is observed or not. **Table 8**, shows the weightage of different properties considered for MCDM comparison related to comfort properties.

Table 8: Weightage of different properties for MCDM comparison (Comfort)

Property	Weightage
Thread density (cpi)	0.02
Thread density (wpi)	0.02
Tensile strength (cpi)	0.02
Tensile strength (wpi)	0.02
Bursting strength	0.02
Air permeability	0.3
Water permeability	0.3
Vertical flammability (cpi)	0.1
Vertical flammability (wpi)	0.1
Fabric stretch	0.05
Fabric recovery	0.05

Comparison of All Flame-Retardant Knitted Fabrics (Comfort Property Priority)

The performance evaluation of all developed flame-retardant knitted fabric samples using the TOPSIS method, with comfort-related properties assigned the highest priority weightage (air permeability and water permeability = 0.30 each), revealed a distinctly different ranking pattern compared to the mechanically prioritised scenario. The overall performance scores (Pi), as illustrated in **Figure 19**, indicate a strong shift in preference toward fabrics exhibiting superior breathability and moisture management characteristics. Among all evaluated fabrics, Modacrylic-M220 emerged as the top-performing sample with the highest Pi value of 0.8917, securing Rank 1.

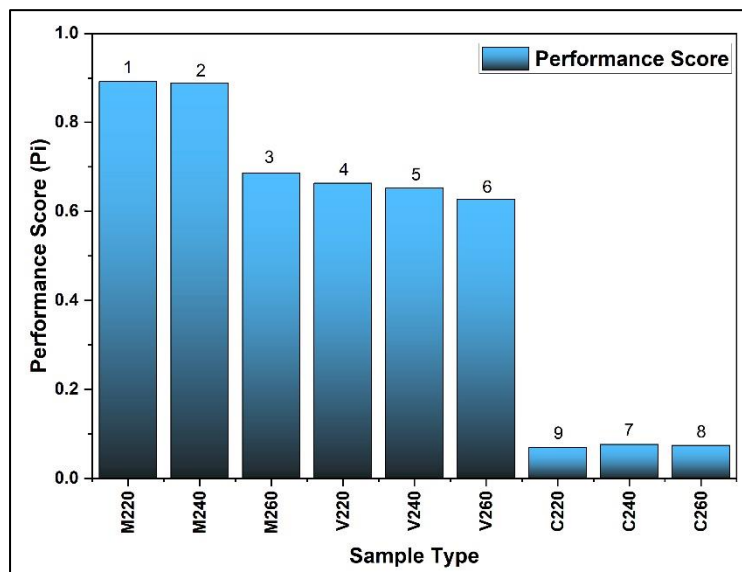


Figure 19 : Comparison of prepared fabrics with comfort property as priority

The FR viscose-based fabrics demonstrated moderate performance under these evaluation conditions. FR Viscose-V220 ($P_i = 0.6633$) ranked fourth, followed by FR Viscose-V240 ($P_i = 0.6526$) and FR Viscose-V260 ($P_i = 0.6274$), respectively. In contrast, the FR cotton-based fabrics recorded the lowest performance scores in this scenario. FR Cotton-C240 ($P_i = 0.0765$), FR Cotton-C260 ($P_i = 0.0744$), and FR Cotton-C220 ($P_i = 0.0691$) ranked seventh, eighth, and ninth, respectively.

4.0 Conclusion

The present research investigates the engineering, characterisation, and performance evaluation of flame-retardant (FR) knitted mattress cover fabrics developed using circular knitting technology. The study focuses on three representative material systems, viz., glassfibre modacrylic (M-series), glassfibre flame-retardant viscose (V-series), and flame-retardant treated cotton (C-series), each series producing three distinct areal densities (220, 240, and 260 g/m²). Through an extensive experimental database, Structural, Mechanical, Comfort-related, and Flammability-related evaluations were carried out, which define how fibre chemistry, fabric architecture, and mass per unit area collectively dictate the performance profile of knitted fabrics. This chapter consolidates the critical findings from preceding analyses and interprets the interdependencies among key material variables, and establishes an integrated scientific rationale for the observed trends. The outcomes are discussed in terms of yarn characterisation, mechanical durability of yarn and fabric, thermo-physiological comfort, and flame-retardant efficacy. The chapter also concludes with a forward-looking perspective on research extensions and technological advancements essential for realising next-generation FR knitted fabrics.

Glass fibre yarn's inherent brittleness, low elongation, and sensitivity to bending make it incompatible with standard high-speed circular knitting, often causing filament fracture, yarn breaks, and inconsistent loops. The systematic modifications to the Mayer & Cie OV 3.2 interlock circular knitting machine successfully overcame the challenges of knitting brittle glass fibre yarn alongside flexible modacrylic/FR-viscose yarns, enabling stable production of flame-retardant mattress cover fabrics at varied areal densities. The Memminger IRO SFE positive feeders with tailored tensions (2.7-3 gf for FR yarns, 4-4.2 gf for glass fibre), low-tension yarn paths with ceramic guides, revised cam profiles for gentler loop formation, full-clear needle settings, and reduced speeds (18-22 RPM), minimised filament breakage to under 1 break/1000 m while preserving yarn integrity and loop consistency. These adaptations not only bypassed costly core-sheath spinning but also optimised process efficiency through real-time monitoring, uniform yarn packages, and rigorous online/offline quality controls. Thus, Glass fibre can be

effectively knitted on modified circular machines by prioritising fragility protection through low-tension paths, customised cams/needles, and slowed speeds, achieving stable hybrid fabrics for applications like flame-retardant mattress covers.

The combined FT-IR, XRD, DSC, and TGA characterisation of the three functional yarns: modacrylic, flame-retardant (FR) viscose, and S-glass fibre confirms that each material has a distinct chemical and structural signature that supports its functional performance, particularly in flame retardancy, thermal stability, and mechanical integrity. For Modacrylic fibre, the FT-IR spectrum confirms an acrylonitrile–vinylidene chloride copolymer, with strong nitrile ($\text{C}\equiv\text{N}$) and $\text{C}-\text{Cl}$ stretching bands, plus minor $-\text{OH}$ and $\text{C}=\text{O}$ features indicating surface oxidation or processing-related modification. The XRD pattern shows a semi-crystalline, largely amorphous structure with a crystallinity index of 37.07%, consistent with disrupted chain packing due to comonomer incorporation, which enhances flexibility and softness. Thermal behaviour of the yarn was analysed by DSC & TGA, where DSC reveals no sharp melting, a stable baseline up to $\sim 210^\circ\text{C}$, and an exothermic degradation onset near $230\text{--}240^\circ\text{C}$, linked to dehydrochlorination that contributes to flame retardancy. TGA shows a two-stage decomposition with a total char yield of $\sim 37\%$, confirming that the chlorinated comonomers and nitrile cyclisation create a protective carbonaceous residue, making modacrylic highly flame-retardant. So, Modacrylic achieves flame retardancy through chlorine-driven gas phase inhibition and nitrile cyclisation, supported by a semi-amorphous structure that balances flexibility and protection.

In the case of flame-retardant viscose fibre, the FT-IR spectrum retains the cellulose II backbone ($\text{O}-\text{H}$, $\text{C}-\text{O}-\text{C}$, β -glycosidic linkages) but shows additional bands in the $\text{P}=\text{O}$, $\text{P}-\text{O}-\text{C}$, and $\text{P}-\text{O}-\text{H}$ regions, proving the incorporation of phosphorus-based flame-retardant additives into the viscose matrix. XRD indicates a semi-crystalline regenerated cellulose structure with a crystallinity index of 48.50%, balancing amorphous regions (for chemical accessibility and FR action) and crystalline domains (for mechanical integrity). The case of thermal behaviour, DSC shows moisture loss and glass transition below 100°C , followed by the onset of cellulose decomposition near $250\text{--}260^\circ\text{C}$, slightly higher than amorphous cellulose but lower than highly crystalline forms. The TGA reveals multi-stage degradation with a char yield of $\sim 20\%$, confirming that the FR additive promotes acid-catalysed dehydration and early char formation, acting as a thermal barrier and reducing flammability. So, FR viscose retains cellulose functionality while incorporating phosphorus-based additives that promote early dehydration and high char yield, enhancing fire resistance without sacrificing structural integrity.

The case of S-glass fibre, FT-IR spectrum reflects a silicate (Si–O–Si, Si–O–Al) network with additional bands from surface –OH and organofunctional silane sizing (C–H, Si–O–C), verifying successful surface modification that enhances matrix adhesion in composites. XRD shows a broad amorphous halo centred near $27.24^\circ 2\theta$, with a crystallinity index of $\sim 46.5\%$, indicating a predominantly amorphous alumino-silicate glass with short-range order, typical of high-strength S-glass. The case of thermal behaviour DSC displays minimal thermal events over 30–300 °C, with only slight changes due to organic sizing decomposition, confirming the exceptional thermal stability of the inorganic glass phase. TGA shows very low mass loss ($\sim 12.81\%$), corresponding to organic sizing/binder decomposition, while $\sim 87\%$ residue remains as thermally stable glass, making it ideal as a high-temperature reinforcement in composites. So, S-glass fibre behaves as a thermally inert, amorphous inorganic reinforcement, with surface sizing providing interfacial compatibility in hybrid textile systems, and negligible degradation up to at least 300 °C.

The tensile data show that yarn strength (tenacity) and strain behaviour differ markedly across the four yarn types, directly influencing their roles in knitted flame-retardant mattress covers. Glass fibre has by far the highest tenacity (5.81 g/den), making it the primary load-bearing, structural reinforcement in the fabric. It's very low strain ($\sim 3\%$) means it provides rigidity, dimensional stability, and a strong thermal barrier but contributes little to elasticity. Cotton follows in strength with 1.45 g/den, offering good load-bearing capacity and moderate strain ($\sim 4.5\%$), which supports mechanical durability and stable stitch formation in knitting, though it lacks inherent flame retardancy. Modacrylic has moderate tenacity (1.01 g/den) but the highest strain (10–12%), so it acts as the deformation-absorbing, resilient component that enhances loop extensibility, recovery, and comfort without sacrificing too much strength. Finally, FR viscose has the lowest tenacity (0.72 g/den) and relatively low strain ($\sim 4.1\%$), so it contributes mainly to comfort, drape, and moisture management, with flame-retardant functionality provided by chemical modification rather than mechanical strength. In the knitted mattress cover system, glass fibre dominates in strength and rigidity, cotton provides robust mechanical support, modacrylic delivers high extensibility and recovery, and FR viscose offers comfort-oriented, flame-retardant performance with limited strength. Together, their tensile characteristics are complementary, where glass will carry the main mechanical load, while modacrylic and FR viscose enhance flexibility, comfort, and fire-performance, enabling a balanced, durable, and functional fabric structure.

The structural and mechanical data show that fabric physical properties like thread density, bursting strength, tensile strength, and stretch–recovery are strongly governed by fibre system,

GSM, and loop architecture, with clear correlation between mechanical robustness, comfort, and flame-retardant performance.

FR-treated cotton (C-series) has the highest thread density (courses and wales per inch) at all GSM levels, producing a dense, compact loop structure that reduces porosity and air permeability, which can limit moisture transport but may suppress oxygen diffusion in fire.

The bursting strength increases with GSM for all series, but FR-treated cotton fabrics (C-series) consistently show the highest values (up to ~273 PSI at 240 GSM), indicating superior biaxial integrity due to dense loops and good fibre extensibility. Tensile strength is highest in C-series, especially in the wale direction, with a pronounced peak at 240 GSM, confirming an optimal compactness for load sharing; glass fibre-based fabrics show lower but adequate strength, with better performance in the walewise direction due to continuous yarn paths. It has limited stretch and declining recovery at higher GSM, as flame-retardant finishes and loop densification reduce molecular mobility and elastic rebound, compromising long-term dimensional stability.

In the case of Modacrylic-glassfibre (M-series) and FR viscose-glassfibre (V-series) fabrics, which are more open, with uncertain changes in CPI and WPI as GSM increases; this enhances breathability and moisture regulation but may allow greater convective heat transfer during flaming. Glass fibre-based blends (M and V series) exhibit lower bursting strength than cotton but still improve with GSM, reflecting their role as thermally stable reinforcements rather than primary load-carriers. Modacrylic-glassfibre (M-series) shows large stretch increases with GSM and high recovery (86–87%), making it very resilient under repeated compression and recovery cycles typical of mattress use. FR viscose-glassfibre (V-series) exhibits the highest stretch at lower GSM and excellent recovery, combining viscose's pliability with glass fibre's dimensional control to deliver superior elastomeric behaviour.

So finally, FR-treated cotton fabrics provide maximum mechanical strength and structural compactness, suitable where durability and dimensional stability are prioritized, but with reduced comfort and elastic recovery. Modacrylic-glassfibre and FR viscose-glassfibre blends offer a better balance of strength, elasticity, and recovery, along with enhanced thermal protection and flame-retardant performance, making them more suitable for comfort-oriented, flame-retardant mattress covers. Across all systems, 240 GSM emerges as a practical optimum, where loop compactness, strength, and elasticity are best balanced, while 260 GSM tends to over-compact the structure and slightly degrade stretch and recovery, especially in cotton-based fabrics.

In the case of comfort-related properties, air permeability, water permeability, and vertical wicking properties were tested and analysed. The case of air permeability property, Modacrylic–glass fibre (M-series) has the highest air permeability (up to ~589 CFM at 220 GSM), which drops with increasing GSM but remains much higher than cotton-based fabrics, indicating good airflow and cooling potential at lower weights. The FR viscose–glass fibre (V-series) shows moderate and relatively stable permeability across GSM, combining viscose’s flexibility with glass fibre’s pore stability to maintain consistent breathability even at higher areal densities. The FR-treated cotton (C-series) exhibits very low air permeability (~62–70 CFM), nearly independent of GSM, because the flame-retardant finish forms a semi-occlusive film that restricts airflow and reduces evaporative cooling.

In the case of water permeability and moisture transport analysis, M- and V-series fabrics allow relatively high water permeability (95–115 mm/s), which decreases slightly with GSM due to loop densification but remains far above cotton, supporting faster liquid passage and better moisture release. C-series fabrics show very low and nearly constant water permeability (~14–18 mm/s) because the FR finish blocks inter-fibre pores, effectively limiting liquid penetration and capillary transport, which may improve surface protection but reduces the fabric moisture movement. Whereas in the case of Vertical wicking and moisture management, FR viscose–glass fibre (V-series) displays significantly higher wicking heights and rates than modacrylic–glass fibre, especially at 260 GSM, due to viscose’s hydrophilicity and high moisture regain, which enhance capillary action and moisture spreading. Modacrylic–glass fibre (M-series) shows moderate wicking, with a noticeable increase at higher GSM, but still lower than the V-series because modacrylic is relatively hydrophobic and wicking is delayed until pores saturate. FR-treated cotton, while not tested in wicking here, is expected to have restricted wicking due to the same surface-film effect that reduces air and water permeability, limiting comfort under prolonged moisture exposure.

So finally, FR viscose–glass fibre and modacrylic–glass fibre knitted fabrics provide superior comfort in terms of breathability, moisture transport, and wicking, making them more suitable for sleep-oriented, flame-retardant mattress covers where heat and sweat management are critical. FR-treated cotton fabrics sacrifice comfort-related permeability and wicking for higher surface barrier and mechanical robustness, which may be acceptable where maximum strength and limited air/water passage are prioritised over thermo-physiological comfort. Across GSM levels, 220–240 g/m² generally offers the best compromise between comfort (air and water permeability, wicking) and structural integrity, while 260 g/m² tends to reduce airflow and moisture mobility, particularly in cotton-based constructions

Finally, the flammability data show that all three FR-knit systems exhibit good flame-retardant performance. Still, modacrylic–glass fibre (M-series) provides the best vertical flame resistance, while FR viscose–glass fibre (V-series) offers a better balance of barrier efficiency and burning-time control in mattress tests. FR-treated cotton (C-series) relies on surface-dependent protection with limited char barrier formation.

The Vertical flammability of Modacrylic–glass fibre fabrics shows the shortest char lengths (down to 13–16 mm at 260 GSM) and no after-flame or after-glow, indicating strong self-extinguishing behaviour due to Modacrylic’s halogen-based flame-retardant chemistry and glass fibre’s inert skeleton. The FR viscose–glass fibre fabrics exhibit longer char lengths that increase with GSM (up to ~80 mm), reflecting higher combustible mass and more extensive pyrolysis, even though they still self-extinguish without after-flame or after-glow. The FR-treated cotton fabrics show no measurable char length because the flame reaches the top edge in all cases, with after-flame times increasing with GSM (37 to 69 seconds), indicating that topical FR treatment alone does not create an effective internal char barrier.

The 45° flammability for all three systems (M-series, V-series, C-series) shows no ignition and no flame spread during the 15-second exposure, confirming that all FR-knit covers provide excellent resistance to small-flame attack and low surface flammability. This uniform non-ignition behaviour reflects effective heat shielding, low volatile release, and self-extinguishing mechanisms, with modacrylic relying on inherent chemistry, FR viscose on integrated chemical modification, and FR cotton on surface-char formation.

In the case of a full-scale mattress test, Modacrylic–glass fibre-covered mattresses show increasing flaming duration with GSM (149-720 s) but no core ignition or after-glow, indicating that heavier covers prolong visible flaming while still preventing foam ignition, thanks to glass fibre-stabilised char and modacrylic’s flame-suppression. FR viscose–glass fibre-covered mattresses display a non-linear trend: flaming duration is longest at 220 GSM (658 s), drops sharply at 240 GSM (146 s), and rises again at 260 GSM (416 s), suggesting optimal barrier efficiency at 240 GSM, where compactness and char-forming capacity best limit flame duration. The non-FR control mattress (NC) burns continuously for 680 s, confirming that the FR covers successfully confine flaming to the textile layer and prevent substrate ignition, regardless of blend.

The holistic convergence of materials characterisation (FTIR, XRD, DSC, TGA), yarn mechanics, loop architecture control, comfort engineering, and multi-scale flammability assessment positions this study as a comprehensive contribution to fire-safe sleep systems and

protective interior textiles. Beyond product development, the findings reinforce the importance of engineered hybridisation, combining inorganic reinforcement with inherent or chemically modified flame-retardant fibres to achieve durable, resilient, and thermally protective knitted structures. The outcomes directly support evolving global fire safety regulations, sustainable product design strategies, and performance-driven textile innovation, thereby strengthening the academic relevance and industrial applicability of advanced flame-retardant architectural and interior fabric systems.

5.0 Future Scope of Study / Recommendations

While the current study has successfully performed the modification of the circular knitting machine to run technical yarns and successfully carried out the development of flame-retardant mattress cover fabrics on it, there are still many areas that can be explored and worked out:

- The further study can be extended by the development of advanced fire modelling, like Fire Dynamics Simulator (FDS), Pyrolysis model, etc., which can help us study the behaviour of fabrics and stages of improvement.
- The study can be extended by carrying out the manufacturing of glass fibre with other high-performance technical yarns like m-aramids, p-aramids, etc., which have excellent strength properties as well as flame retardancy in order to explore the use of fabric in the defence sector.
- Further study should be carried out to analyse the process parameters that affect the running of technical yarns on the circular knitting machine and measures to maintain it.

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