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Master of Science Thesis

Rain jackets

Creation of a procedure to evaluate the conditions of
second-hand and end-of-life products



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Abstract

This study focused on developing a protocol to evaluate the viability of 256 second-hand and end-of-life rain jackets. The methodology comprised four distinct stages: visual inspection, ISO 4920:2012 Spray Testing, climate chamber rain simulation, and hydrostatic pressure testing (Suter Test). Initial visual scoring (scale 1–5) proved limited, as superficial inspection failed to detect latent structural failures. Similarly, the Spray Test was deemed insufficient for comprehensive evaluation, as its short exposure duration did not accurately reflect real-world environmental stress, limiting its utility to DWR assessment only. In contrast, the rain simulation, conducted at a flow rate of 2,700 ml/min for 30 minutes with garments mounted at a 45° angle, provided the most significant insights into garment integrity, despite its logistical complexity. The final hydrostatic test (700 and 2100 mmH₂O), preceded by a treatment with isopropyl alcohol, served primarily to analyse specific critical factors rather than overall condition. Statistical analysis confirmed a correlation between visual scores and rain test performance; however, the rain test remained essential for identifying defects invisible to the naked eye. The study concludes that while visual and spray tests offer limited data, a comprehensive rain simulation is critical for accurate validation. Further research is necessary to refine a testing matrix that addresses all variables inherent to end-of-life textiles.

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1 Introduction

One of the most pressing global issues in recent years has been the development of a more sustainable economic model, aimed at minimising environmental degradation resulting from both natural resource extraction and pollution from consumer products. Among the various industries contributing to this challenge, the apparel sector is notably significant. While it constitutes a vital component of the global economy, it also imposes a disproportionately substantial ecological footprint. The extensive utilisation of resources such as water, raw materials, and energy in manufacturing processes is a matter of concern. Technical garments, including rain jackets, exemplify this issue. Although their overall production volume is comparatively lower than that of mass-market clothing, the complexity of specialised materials necessary to meet performance standards frequently complicates recycling efforts and exacerbates waste management challenges.

In response to these concerns, the current project was developed to identify and analyse the main factors contributing to the degradation of such garments. By addressing these factors, the research aims to suggest strategies to extend the functional lifespan of rain jackets, thereby reducing their environmental impact. To achieve this, the project focused on creating a lab procedure that allows to systematically examining and testing the various physical and technical properties of rain jackets, while also evaluating the degree of wear and decline observed in both second-hand and end-of-life products.

The performance characteristics of rain jackets can vary depending on the specific needs of consumers and resellers. Different intended uses may require assessing various properties, reflecting each stakeholder's functional priorities. There is currently no standardised testing method for second-hand and end-of-life rain jackets. Therefore, a key aim of the project is to develop a series of evaluative tests to establish a reliable framework that enables both companies and consumers to detect defects and potential issues in products systematically.

To accurately identify and analyse potential issues in a rain jacket, it is essential to first comprehend the key features that characterise such a garment. Rain jackets are not constructed uniformly; rather, their design and materials exhibit significant variation influenced by factors such as the manufacturer, the target price range, the availability of specific materials, and the primary intended function of the jacket. Consequently, a comprehensive understanding of these elements is imperative before investigating potential failure mechanisms or performance concerns. Therefore,

the following chapter aims to provide the foundational knowledge necessary to understand and interpret the subsequent analysis.

1.1 Waterproof breathable jacket structure

The primary function of a waterproof-breathable jacket is to prevent external water ingress while permitting internal moisture, such as sweat and condensation, to escape. This dual capability is vital for maintaining thermal comfort and averting moisture accumulation within the jacket, which could otherwise impair performance and comfort. To achieve this, the jacket is constructed from multiple layers of various materials, each specifically designed to serve a distinct purpose, as illustrated in *Figure 1*. Some layers are essential and universally incorporated into such jackets, while others are optional, depending on the desired level of performance, comfort and durability.

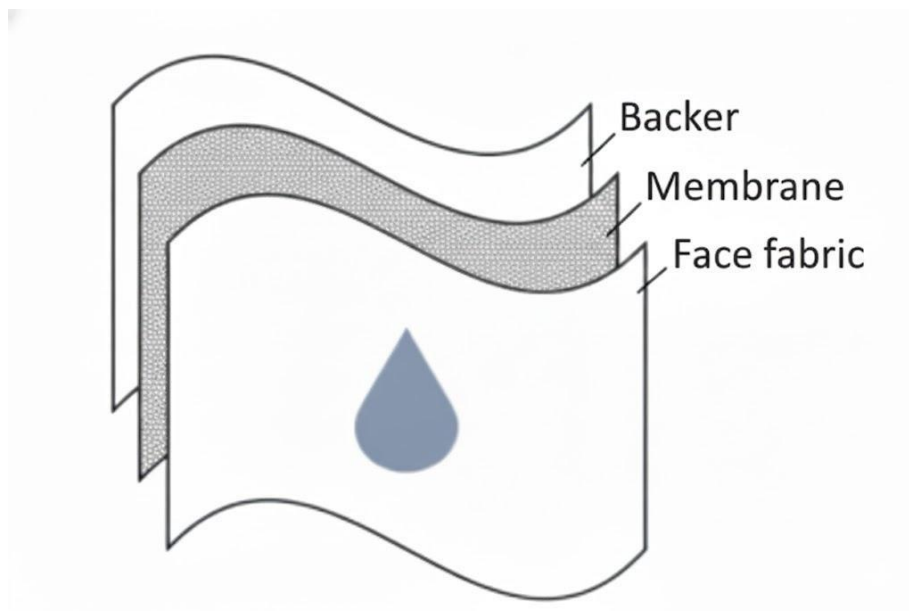


Figure 1 - General construction of a rain jacket [1]

The two fundamental and indispensable layers are as follows:

- **Outer shell.** As the outermost layer of the garment, this component assumes a vital role in establishing the jacket's external performance attributes. The durable waterrepellent (DWR) coating is applied to this layer, serving as the primary barrier against water penetration by causing water to bead and slide off the surface. In addition to its hydrophobic function, the outer shell provides mechanical resistance to external stresses, such as abrasion, scratches, and punctures that may occur during use in demanding environments. Consequently, it is

imperative that the material selected for this layer possesses adequate tensile strength and elasticity to endure mechanical deformation (e.g., stretching) without failure, thereby guaranteeing the long-term durability and integrity of the garment.

- **Membrane laminate.** Positioned immediately beneath the outer shell, this layer is affixed using adhesive. Its primary function is to serve as the main waterproof and breathable barrier, preventing water ingress into the garment's interior once the DWR treatment has been surpassed, while concurrently enabling water vapour to diffuse from the inside to the outside. Various membranes are available, composed of different materials and employing a range of technologies (such as microporous or monolithic structures), all of which serve the same fundamental purpose. It is noteworthy that, due to its thin nature, which renders it susceptible to punctures, tears, and abrasions, the membrane provides only functional protection rather than mechanical strength, thereby increasing its vulnerability to damage.

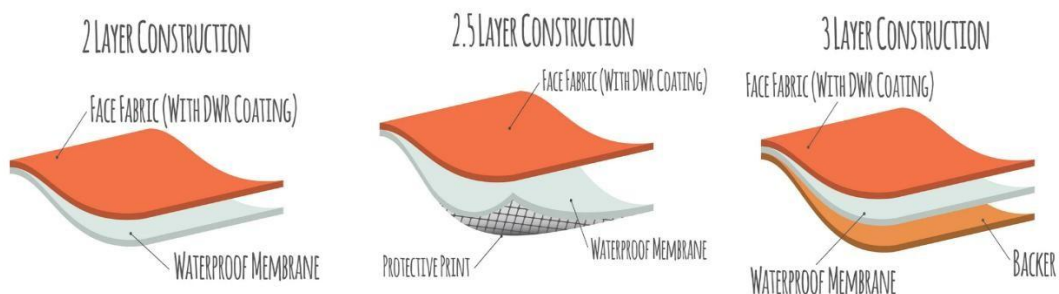
A primary concern regarding direct contact between the wearer and the membrane pertains to potential degradation caused by chemical residues, such as skincare products or perspiration, as well as incidental mechanical damage during use. Such damage can precipitate rapid and direct failure of the membrane, thereby substantially compromising the jacket's durability. Furthermore, the possibility of the membrane adhering to the skin—particularly during physical activity—may diminish comfort and lead to wearer dissatisfaction. To mitigate these issues, additional optional layers are frequently incorporated on the innermost side of the garment.

- **Inner shell.** This layer is directly attached to the membrane and mainly functions as a protective barrier against mechanical or chemical damage. Additionally, it improves skin comfort by reducing friction and prevents the membrane from adhering to the wearer's body.
- **Liner.** The liner primarily performs the same protective and comfort functions as the inner shell; however, it differs in its attachment method, as it hangs loosely within the jacket and is connected at several contact points to the membrane. It is frequently constructed as a mesh structure with relatively large openings or gaps, which enhance breathability and facilitate the effective transportation of internal moisture away from the body.
- **Coating.** In certain cases, manufacturers choose not to apply a distinct textile layer over the membrane. Instead, they employ a coating composed of a different material that is applied directly to the membrane. This methodology provides comparable advantages in protection

and comfort while minimising weight and bulk, thereby rendering it appropriate for lightweight designs or minimalist applications.

By integrating the various types of layers described earlier, manufacturers are able to develop rain jackets with diverse structural configurations. These configurations can be generally categorised into four primary groups, as illustrated in *Figure 2*, based on the quantity of layers employed and the bonding method utilised.

- **2-layer (2L).** Jackets of this nature are constructed solely with an outer shell laminated to a membrane. This design renders them lightweight; however, the absence of a protective layer over the membrane renders them susceptible to damage. Consequently, this technology is the least utilised within the industry.
- **2-layer with liner (2+L).** This configuration represents a variation of the two-layer setup whereby the outer shell is directly bonded to the membrane, with a separate liner subsequently stitched onto the membrane. This technology is among the most widely adopted in the industry, as it provides an effective balance between cost, protection, breathability, and comfort. The only drawback is that these jackets tend to be heavier than alternative options.
- **2-layer printed (2.5L).** This design incorporates a traditional two-layer configuration, with an additional material printed directly onto the membrane to improve tactile comfort against the skin. Although this printed layer may appear as a simple coating, it is generally thicker and often exhibits a consistent, identifiable pattern on its surface.
- **3-layer (3L).** This is the most sophisticated and intricate configuration, comprising three distinct layers: the outer shell, the membrane, and an inner shell. The inner shell is adhered to the membrane, offering enhanced durability and comfort, thereby rendering this technology appropriate for high-performance applications.



1.2 Membranes

Membranes are critical components in the design and functionality of technical garments, particularly protective jackets. Their primary function is to prevent liquid water from permeating while facilitating the transmission of water vapour, thereby ensuring waterproofness and breathability. The effectiveness of a membrane is contingent upon its material composition and manufacturing process, both of which collectively influence its mechanical, thermal, and chemical stability. Presently, the dominant technologies within the field of functional textiles are hydrophilic non-porous membranes and hydrophobic microporous membranes, as elaborated in the publication by Y. Chang and F. Liu [2].

- **Hydrophilic Non-Porous Membranes**

Hydrophilic non-porous membranes rely on their continuous, pore-free structure to prevent the transmission of liquid water. The absence of pores not only ensures waterproofing but also reduces the likelihood of dust, dirt, and other particulates becoming embedded within the material. *Figure 3* shows how the moisture vapour permeability in these membranes is achieved not through open channels but via molecular diffusion. Hydrophilic functional groups facilitate this process within the polymer chains, which can bind and transport water molecules across the membrane when driven by a temperature gradient and a humidity differential between the internal and external environments. Simultaneously, the hydrophobic segment within the polymer structure further enhances water resistance by repelling liquid water molecules. The combined effects of high membrane tension, chemical functionality, and material integrity collectively account for the overall barrier properties of this system.

Polyurethane (PU) constitutes the most extensively utilised material within this category of membranes. Its widespread adoption is attributable to its favourable balance of mechanical strength, chemical resistance, thermal stability, and relatively straightforward processing. Nevertheless, despite these advantages, PU-based membranes also exhibit limitations, including comparatively low intrinsic hydrophobicity and limited water vapour transmission rates. These disadvantages can adversely affect comfort during prolonged usage.

Nonetheless, PU remains the predominant material in hydrophilic non-porous membrane technologies owing to its versatility and cost-effectiveness [2].

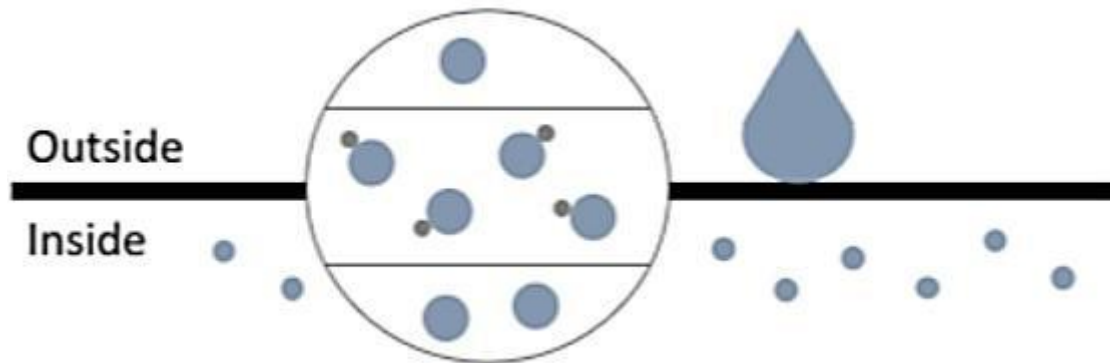


Figure 3 – Hydrophilic non-porous membrane [1]

- **Hydrophobic Microporous Membranes**

Hydrophobic microporous membranes, in contrast, achieve waterproofness through a different mechanism. Their surfaces are enriched with low-surface-energy chemical groups such as $-CF_2$, $-CF_3$, and $-CH_3$, which impart hydrophobicity and effectively block the passage of liquid water, as shown in *Figure 4*. Internally, these membranes exhibit a sponge-like morphology composed of an interconnected network of micropores. These pores provide pathways for the diffusion of water vapour molecules, thereby enabling breathability. The pore size is carefully controlled: sufficiently small to prevent water droplets from penetrating, yet large enough to allow vapour molecules to pass through. Despite these advantages, microporous membranes are inherently vulnerable to the accumulation of dust and fine particles within the pore network. This contamination can progressively diminish vapour permeability and compromise long-term user comfort. To counteract this limitation, microporous membranes are often incorporated into multilayer composite systems, thereby protecting the pore structure and extending the functional lifespan of the garment.

The earliest and most widely used material for microporous membranes was polytetrafluoroethylene (PTFE), first developed by Gore-Tex™. PTFE gained widespread recognition for its excellent waterproofness, high vapour permeability, and outstanding chemical and thermal stability. However, increasing regulatory scrutiny regarding the environmental persistence and ecological impact of fluorinated polymers [3] has prompted

a shift toward alternative materials. In recent years, expanded polyethylene (ePE) has emerged as a substitute. While ePE exhibits performance characteristics broadly comparable to those of PTFE, it suffers from lower chemical stability and, consequently, a reduced service life. This trade-off highlights the ongoing challenge of balancing environmental sustainability with technical performance in the development of advanced textile membranes.



Figure 4 - Hydrophilic porous membrane [1]

1.3 Inner and outer layer

1.3.1 Face fabric

To ensure the efficacy of technical membranes, it is imperative to shield them from environmental hazards such as abrasion, punctures, or other forms of mechanical stress. Accordingly, garments generally incorporate an external protective layer known as the face fabric, which fulfils both structural and functional purposes.

From a structural standpoint, the face fabric is typically fabricated from synthetic fibres such as polyamide (PA) or polyester (PES), selected for their superior resistance to abrasion and scratching. These fibres are generally woven in a plain weave pattern, as illustrated in *Figure 5*, a configuration that minimises the gaps between threads, thereby enhancing both durability and protective capacity. The strength of this layer ensures that the underlying membrane remains intact and continues to perform its designated function throughout the garment's lifespan.

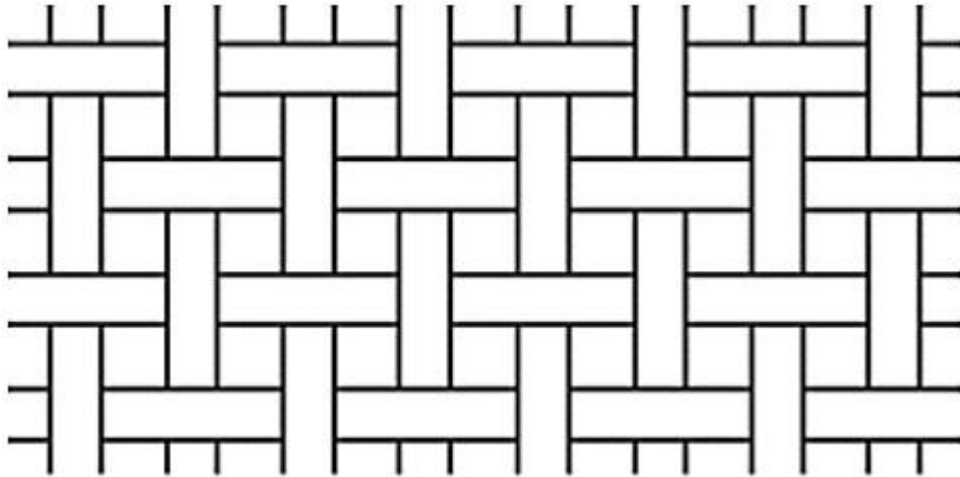


Figure 5 - Plain weave pattern [1]

Functionally, the face fabric also serves as the foundation for the application of a Durable Water Repellent (DWR) finish. This coating, composed of hydrophobic molecules, forms a continuous surface layer that provides an initial line of defence against moisture [1]. The hydrophobic characteristics of the DWR induce a beading effect, whereby water droplets roll off the jacket's surface rather than penetrate the material, as shown in the schematic in *Figure 6*. Historically, the most effective DWR treatments were based on per- and polyfluoroalkyl substances (PFAS), a class of fluorinated carbon chains renowned for their exceptional chemical stability and outstanding water-repellent performance. Nevertheless, this same stability renders PFAS environmentally problematic, as they are not readily biodegradable and tend to persist in ecosystems for extended periods. Consequently, the European Union and other international regulatory entities have commenced restricting or banning the use of fluorinated compounds

[3].

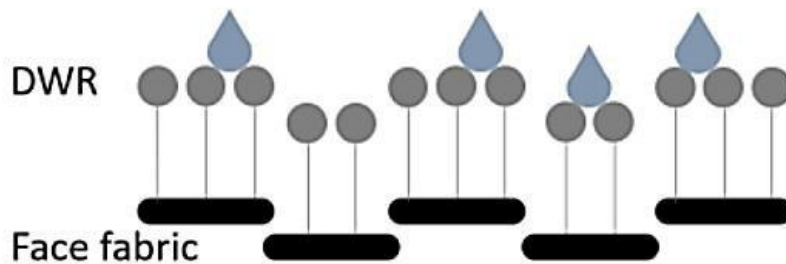


Figure 6 - Effect of DWR layer on the fabric [1]

As a result, manufacturers have progressively transitioned to alternative, non-fluorinated DWR chemistries. While these newer treatments are more environmentally sustainable, they tend to be less chemically stable than PFAS-based coatings. As a consequence, their water-repellent properties diminish more rapidly, necessitating more frequent reapplication to sustain performance. This trade-off epitomises a central challenge in the design of technical garments: balancing environmental responsibility with long-term functionality and durability.

1.3.2 Backing

The innermost layer of a technical garment, commonly referred to as the *backing*, is typically constructed from the same synthetic materials used in the outer shell, such as polyamide (PA) or polyester (PES). While it provides a degree of protection to the membrane from the interior side, its primary purpose lies in enhancing wearer comfort. As previously noted, when the membrane is placed in direct contact with the skin, it can generate an unpleasant tactile sensation, often described as clammy or sticky, particularly under conditions of perspiration. To mitigate this, manufacturers incorporate the backing layer as a protective interface, thereby improving the garment's overall wearability.

In terms of construction, the fibres of the backing layer are generally knitted rather than woven, most commonly employing a circular knit pattern, as Figure 7 shows. This structure differs from the plain weave of the face fabric and is deliberately chosen to maximise softness, flexibility, and breathability. The knitted configuration not only contributes to comfort but also aids in managing moisture by allowing a degree of air circulation and facilitating the wicking of perspiration away from the skin. As such, the backing layer performs a dual function: it safeguards the membrane against internal mechanical stress while simultaneously enhancing the physiological comfort of the wearer [1].

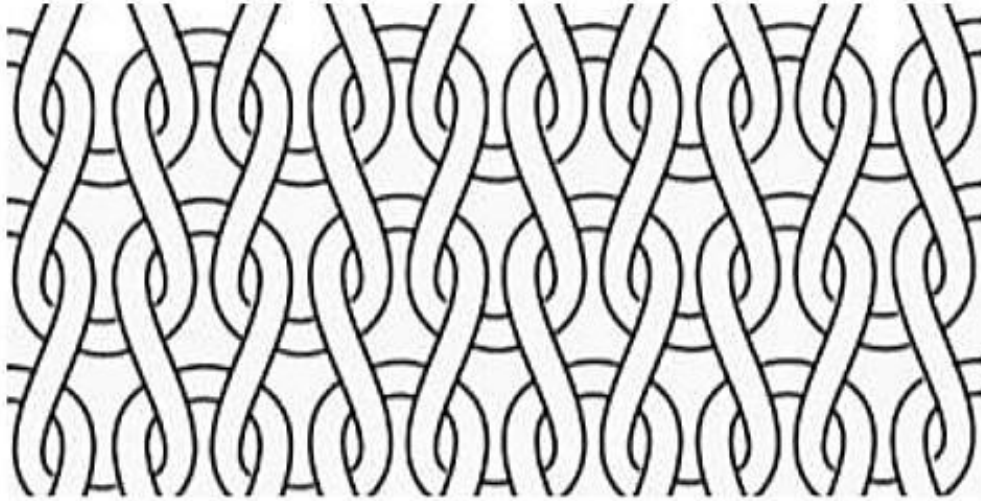


Figure 7 – Knitted pattern [1]

1.4 Waterproof and water-resistant

A persistent misconception within the discourse on technical garments concerns the interpretation and use of the term *waterproof*. In common parlance, consumers frequently describe jackets and other apparel as waterproof, yet this characterisation is often technically inaccurate. According to the Collins English Dictionary [4], *waterproof* is defined as “something which does not let water pass through it”. Although this definition appears straightforward, it is rarely applicable to garments, particularly those that have been worn or purchased secondhand. While certain jackets may achieve a degree of waterproofing when new (usually through a combination of fabric membranes and surface treatments), this property is exceedingly difficult, if not impossible, to recover once it has degraded. Even with specialised treatments, a jacket cannot regain true impermeability. At best, such interventions can restore *water resistance*, which refers to a garment’s capacity to temporarily withstand water penetration, though sustained or heavy exposure will eventually compromise the barrier.

This conceptual misunderstanding has significant implications for how consumers evaluate the performance and condition of their clothing. Many individuals mistakenly assume that when a jacket no longer repels water effectively, it has lost its functional capacity altogether. In reality, this decline is most often attributable to the deterioration of the garment’s surface treatment, typically a durable water repellent (DWR) finish, which can be reapplied to restore a level of *water repellency*. Such treatments enable water to bead and run off the surface, thereby delaying saturation, but they do

not reestablish complete waterproofing. The situation is further complicated by misleading commercial practices: certain aftercare products are marketed as *waterproof* despite their inability to deliver the performance implied by the term.

For these reasons, it is essential to emphasise the importance of terminological precision in both consumer understanding and industry communication. Consumers must be aware of the practical differences between *waterproof*, *water-resistant*, and *water-repellent* in order to make informed judgments about their garments' condition and functionality. At the same time, manufacturers and retailers bear responsibility for ensuring accurate product labelling and avoiding claims that misrepresent performance. Improved awareness and more transparent communication would mitigate widespread misinterpretation, prevent unnecessary consumer dissatisfaction, and promote more responsible use and care of technical garments.

2 Method used

Consequently, the primary goal of this project was to develop a new testing protocol capable of enabling a comprehensive analysis of the condition and functional performance of these garments.

The evaluation process was structured into four stages:

1. Visual inspection
2. Spray test
3. Rain test
4. Hydrostatic head press test

2.1 Visual inspection

The visual inspection constituted the initial and essential step in evaluating the condition of each jacket. Given the absence of any background information concerning prior usage or the users of the jackets, this preliminary assessment of the physical state of each garment was crucial in establishing a consistent baseline for subsequent evaluations.

At the commencement of the inspection, general information was documented for each jacket examined. This encompassed details such as the manufacturer, the type of membrane technology employed, the colour, the size, and whether the jacket was designed for men or women. Initially, the year of manufacture was also intended to be included in the data collection. However, since this information could only be obtained from the label and not all labels contained it, the manufacturing year was subsequently excluded from the final list of recorded details.

The second stage of the evaluation focused on the construction typology of the jackets. Each product was examined and categorised into one of four structural groups based on its build:

- 2-layer (2L)
- 2-layer with liner (2L + L)
- 2-layer printed (2.5L)
- 3-layer (3L)

In addition to identifying the construction type, the material composition of each layer was documented. Depending on the construction, a jacket could consist of either two or three distinct layers. Jackets in the 2L, 2L+L, or 2.5L categories are generally composed of a face fabric and a

membrane, whereas 3L jackets also feature an additional inner backing layer. Another crucial aspect of construction considered during inspection was the presence and condition of seam tapes, which are applied over stitching lines to block water from seeping into the interior of the garment.

Following the general classification, a more detailed analysis of the jacket was carried out by dividing each part (face fabric, membrane, seams) into nine specific sections:

- Hood
- Neck
- Shoulders
- Upper back
- Lower back
- Underarms
- Arms
- Cuffs
- Front

In addition to these zones, the inspection included an evaluation of extra features such as zippers, press studs, cords, and Velcro fasteners. These components were further categorised according to their location on the jacket, as detailed below:

- **Velcro**
 - Cuffs
 - Central front
- **Press studs**
 - At the end of the main zipper
 - Along the central zipper area
- **Cords**
 - Bottom hem
 - Front of hood
 - Back of hood

- **Zippers**
 - Main central zipper
 - Armpit ventilation zippers
 - Pocket zippers

To promote consistency and reduce subjectivity in the evaluation, a 5-point rating scale was adopted. A brief qualitative description accompanied each score to guide the evaluation process:

1= Unusable or broken

2= Almost unusable

3 = Functioning but in suboptimal condition

4 = Good condition

5 = Almost as good as new

Whenever defects were identified in any of the jacket's zones or features, they were documented using the standardised custom sheet illustrated in *Figure 8*. Each defect was classified according to its nature. Although damages may arise from various types of wear, applications, or incidents, all observed issues were consolidated into the following eight categories.

- Hole
- Tear or Rip
- Stain
- Delamination
- Damage to trims
- Abrasion
- Non-functioning component
- Other forms of damage

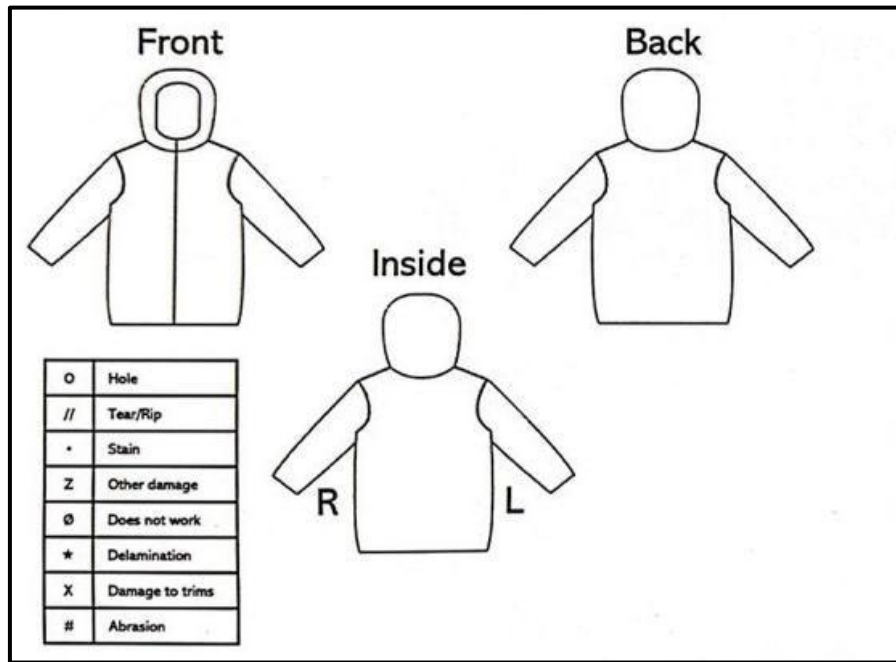


Figure 8 - Custom sheet

This classification enabled the identification of recurring issues in specific areas across multiple jackets, which in turn facilitated the recognition of potential patterns or common causes of wear and damage. Additionally, this information proved helpful in guiding subsequent testing stages, enabling careful selection of measurement locations and ensuring that pre-existing defects did not skew results.

2.2 Spray test

The spray test constitutes a standardised methodology employed to assess the water repellency of textile materials, especially those designated for outdoor or performance purposes, in accordance with ISO 4920:2012. The procedure entails positioning a fabric specimen at a 45-degree angle and exposing it to a controlled spray of 250 ml of distilled water from a nozzle maintained at a fixed height of 15 cm, as illustrated in *Figure 9*. With a test duration of 30 seconds, the spray head's flow rate is calibrated at 500 ml per minute. To maintain uniform tension across the fabric surface during the test, the specimen is traditionally secured using a metal ring. However, since the fabric samples utilised in this study were not cut from the jackets in order to preserve their integrity for subsequent testing, a custom plastic ring was designed and manufactured via 3D printing technology. This ring

features smoother edges to prevent fabric damage and is equipped with an adjustable screw mechanism to accommodate variations in fabric thickness.



Figure 9 -Spray test machine [5]

The primary objective is to assess the efficacy of the fabric's resistance to wetting under simulated rainfall conditions. Following the spray cycle, the surface wetness is visually compared to a standardised photographic scale, and a numerical rating from 0 (indicating full wetting) to 100 (indicating no wetting) is assigned to the sample. The photographic scale is accompanied by descriptions for each value, as illustrated in *Figure 10*, facilitating a more objective evaluation of the results.

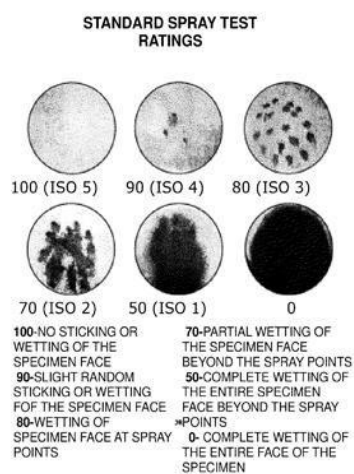


Figure 10 - Spray test photographic scale from ISO 4920:2012

This assessment is essential for evaluating the efficacy of water-repellent finishes or surface treatments applied to textiles. Fabrics exhibiting optimal performance typically demonstrate minimal or no wetting, with water droplets forming beads and rolling off the surface. Conversely, samples with inferior performance absorb moisture, resulting in visible darkening and surface saturation. The spray test presents several advantages: it is non-destructive, allowing for additional testing under various conditions; it necessitates minimal equipment; and it provides rapid results, making it suitable for routine quality control and research applications. Furthermore, it serves as a valuable indicator of fabric durability and functional performance, especially in technical textiles and outdoor apparel.

Each jacket was subjected to testing in no fewer than four separate regions, carefully chosen to represent the entire surface area. Beyond these conventional assessment zones, any visible or suspected imperfections that could potentially influence the efficacy of the durable water repellent (DWR) treatment were also included in the evaluation. The assessment of each section was carried out utilising a standardised scoring system. To improve the precision of the results, intermediate scores were incorporated at five-point intervals within the scale, facilitating a more nuanced and detailed analysis of DWR performance across different sections of the garment. This methodology was corroborated by the research conducted by P.

J. Hill [6].

2.3 Rain test

The primary objective of the rain test was to subject the jackets to environmental conditions that closely resemble real-world scenarios. This objective facilitated the assessment of how all known defects impacted the overall performance of the samples. Furthermore, it assisted in identifying any new issues that might emerge under realistic stress conditions. It is noteworthy that not all failures in end-of-life jackets can be detected exclusively through visual inspection or simple spray tests. Micro holes, being invisible to the naked eye, and the spray test, which offers only a preliminary evaluation of the DWR condition, underscore the necessity for a more precise testing method to achieve a comprehensive assessment.

The experimental procedure was conducted with the wind tunnel inside the Sports Tech Research Centre at MIUN, shown in *Figure 11*, which can also function as a climate chamber.

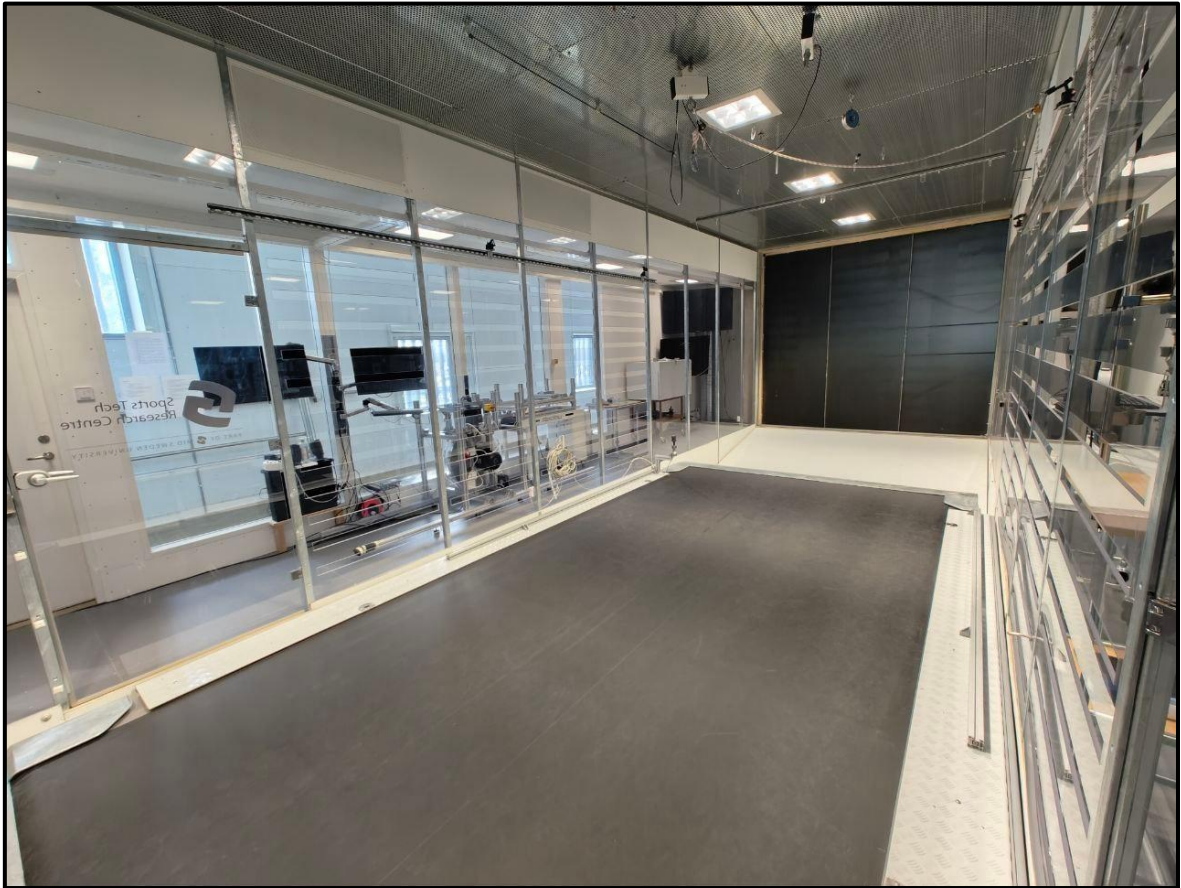


Figure 11 - Wind tunnel located at the Sports Tech Research Centre at MIUN



Figure 12 - Mannequin setup

Each test iteration was structured to evaluate up to six jackets concurrently, as depicted in *Figure 12*. These jackets were separately affixed to wooden mannequins of varying sizes to ensure an appropriate fit. To facilitate the identification of leakage points, a grey T-shirt of the corresponding size was positioned beneath each jacket. These T-shirts functioned as visual indicators of water infiltration during and subsequent to the testing process.

Each mannequin was secured using a custom-designed stand made from aluminium bars, illustrated in *Figure 13*. This structure was engineered to hold the jacket at a consistent 45° angle throughout the experiment. The stand also allowed the mannequin to be turned halfway through the test without compromising the results' integrity or reliability by accidentally wetting the T-shirt. To ensure full exposure, the mannequin's arms were held straight using plastic tubes, which enabled correct spraying of the sleeves and arm areas.

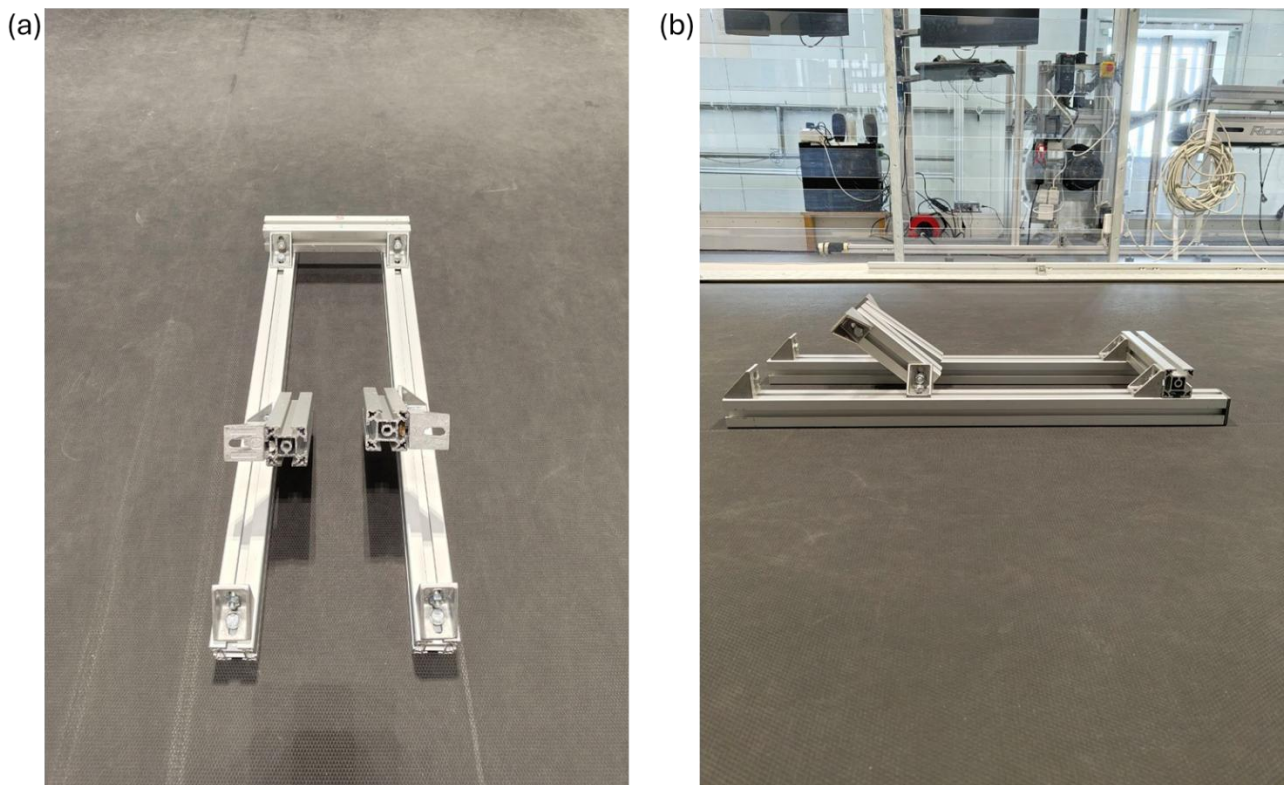


Figure 13 – Aluminium stand for the mannequin: front view (a), side view (b)

Water was supplied through two nozzles mounted inside the tunnel with a flow rate of 2700 ml per minute. The stands holding the jackets were carefully positioned at a calibrated distance from the nozzles' centre point to ensure each sample received an equal volume of water. This distance was

measured before the start of the test using plastic cups to measure rainfall at various distances from the nozzle.

Each test lasted 30 minutes, divided equally between the front and back sides (15 minutes each). To quantify water absorption, each jacket was weighed prior to mounting and after removal, enabling precise calculation of the volume of water absorbed and facilitating the identification of jackets that significantly lost their water-repellent properties. Photographs were captured at two critical moments: after 15 minutes and at the conclusion of the 30-minute test. These images, documenting both sides of each jacket, were used to evaluate performance and section-specific behaviour. Following the removal of the jackets, two additional photographs of the front and back of the grey T-shirts were taken to illustrate areas where water infiltration had occurred.

2.4 Hydrostatic head press

The hydrostatic head pressure test is an essential procedure for evaluating the waterproof properties of a fabric. This method quantifies the water pressure a material can withstand prior to leakage. During the assessment, the fabric specimen is securely clamped between two rubber rings, and the apparatus (refer to *Figure 14*) incrementally increases the water pressure applied on one side of the specimen. The test concludes either when three visible water drops appear and enlarge on the opposite side of the fabric or when the material experiences structural failure and ruptures under the applied pressure. The outcome of the test is generally expressed in millimetres of water (mmH₂O), which represents the height of a water column that the fabric can withstand without failure.

This measurement holds particular importance in the context of outdoor gear and technical apparel, where performance under wet conditions is critical. Fabrics that exhibit a hydrostatic head value below 1,000 mmH₂O are generally capable of resisting only light rain or brief exposure to moisture. Conversely, materials rated at 5,000 mmH₂O or higher can withstand moderate rainfall, while those exceeding 10,000 mmH₂O are typically engineered to endure heavy and sustained exposure to rain. However, it is important to note that the hydrostatic head value alone does not determine a garment's waterproof performance. Construction features, such as seam taping, stitching, zipper

quality, and long-term material wear, also significantly influence a jacket's ability to prevent water ingress.



Figure 14 - Hydrostatic head press machine

While the standard hydrostatic head test continues until three drops of water emerge on the fabric's surface, an alternative testing approach known as the **Suter test** is also employed under specific conditions. Although this method is not governed by any formal standard, it is considered valuable for evaluating the condition of a membrane in a non-destructive manner. Unlike the traditional test, the Suter test involves increasing the water pressure to a predetermined level and then holding the sample at that pressure for a fixed duration of time. Due to the absence of standardised parameters, several trial settings were explored during this study before final test conditions were established.

Utilising a head for the apparatus with an exposure area of 100 cm², two testing configurations were ultimately selected. The first, informed by a personal consultation with Gore-Tex®, employed a maximum pressure of 700 mmH₂O (approximately 1 psi), with a pressure ramp-up rate of 600 mmH₂O per minute and a duration of three minutes for maintaining pressure. The second configuration maintained the same ramp rate and holding period but elevated the maximum pressure to 2100 mmH₂O (approximately 3 psi). These two settings were specifically chosen to

emulate different environmental conditions: the first representing exposure to light rainfall, and the second corresponding to more intense weather scenarios, including heavy rain. If the rain is

The application of the Suter test focused on those areas of the jackets that had previously shown visible defects or leakage, particularly during earlier phases of testing, such as the rain test. In order to accurately identify the specific sections requiring additional evaluation, each jacket was first internally treated with isopropyl alcohol (IPA). The use of IPA was crucial, as its low surface tension allows it to penetrate micro-perforations in the membrane, thereby making otherwise undetectable defects visible. This step was instrumental in locating issues that might not have been apparent to the naked eye or revealed by previous testing methods.

Each identified area was initially subjected to the 700 mmH₂O pressure condition. Only in cases where the fabric successfully withstood this pressure for the full three-minute holding period was it further tested at the higher pressure level of 2100 mmH₂O. This two-step approach ensured that only the most relevant and critical defects were considered in the final evaluation, thereby enabling a more accurate and meaningful assessment of the garment's overall waterproof performance.

3 Results and discussion

In the present study, a total of 256 jacket samples were analysed, representing products manufactured by 35 different companies. This variety of manufacturers aimed to ensure that the dataset covered a wide range of production practices, materials, and quality standards, thereby improving the representativeness of the results. Each sample was analysed following the standardised methodology described in Chapter 2, ensuring consistency and reliability throughout the process. After completing the analytical phase, the data were systematically processed and evaluated using two separate software platforms, KNIME and JASP, which were chosen for their complementary capabilities in data management and statistical analysis. Using both programs enabled a comprehensive and cross-validated interpretation of the experimental findings.

3.1 Visual inspection data analysis

A preliminary visual and physical examination of each product allowed for the collection of various descriptive data concerning the jackets, including their construction characteristics and design features. These initial observations were subsequently compared with the results obtained from the experimental analyses in order to identify potential correlations between observable attributes and measured performance parameters.

3.1.1 Material and technology used

As illustrated in *Figure 15*, which presents the distribution of the main construction types employed by the different manufacturers, it is evident that the predominant technologies are the 3-layer and 2.5-layer constructions, accounting for 41.57% and 39.61% of the total samples, respectively. This indicates a clear preference within the industry for multi-layered composite structures, likely due to their balance between durability, comfort, and protective performance.

TYPE OF CONSTRUCTION

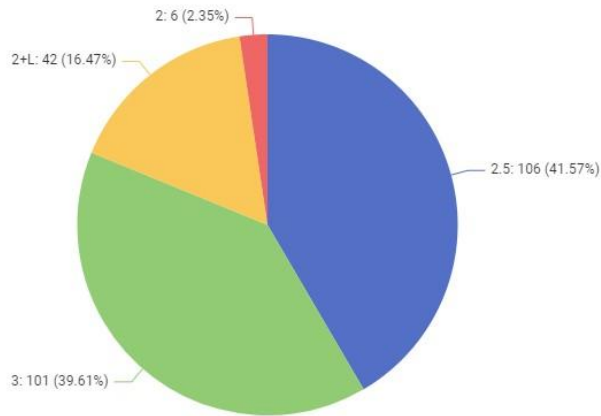


Figure 15 - Jackets construction type distribution graph

Face fabric

As clearly showed by the data in *Figure 16*, the primary material selection for technical face fabrics is heavily dominated by Polyamide (PA), with Polyester (PES) serving as the most prevalent secondary alternative. Ultimately, the specification between these two synthetic polymers represents a calculated engineering compromise, dictated entirely by the environment and operational demands of the garment's intended use-case. A comparative evaluation of their intrinsic material properties delineates distinct functional applications.

FACE FABRIC MATERIAL

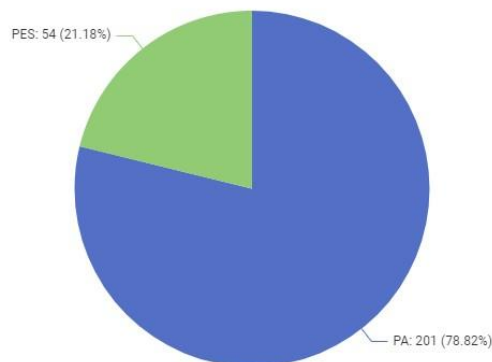


Figure 16 - Face fabric material distribution graph

Polyamide (PA)

Polyamide is systematically specified for high-performance apparel subjected to severe mechanical friction and dynamic kinetic stress, such as sustained abrasion against rock faces in alpine environments or the continuous shear forces exerted by heavy load-bearing backpacks. This engineering preference is driven by PA's superior mechanical profile; the polymer chain exhibits exceptional tensile strength, benchmark abrasion resistance, and a high degree of inherent elasticity. These characteristics allow the textile matrix to absorb and dissipate mechanical energy without suffering structural failure.

However, a primary functional limitation of Polyamide is its molecular-level hydrophilicity. PA fibers exhibit a natural tendency for moisture regain. Consequently, when the external Durable Water Repellent (DWR) treatment inevitably degrades or fails through mechanical wear, the PA face fabric becomes highly susceptible to saturation, commonly referred to as "wetting out." This localized moisture retention significantly increases the garment's mass, accelerates conductive heat loss, and critically impairs the Moisture Vapor Transmission Rate (MVTR) and overall waterproof efficacy of the underlying internal membrane system.

Polyester (PES)

Conversely, Polyester is frequently the optimal material choice for specialized applications encompassing ultralight rainwear, garments deployed in high-ultraviolet (UV) index environments, and technical products where rapid drying kinetics and ecological sustainability supersede the requirement for maximum abrasive toughness. From a materials science perspective, PES is intrinsically hydrophobic. This natural resistance to aqueous absorption ensures that the fabric matrix resists saturation, thereby maintaining its functional hydrostatic properties and breathability significantly better than PA during sustained precipitation, even after DWR failure.

Furthermore, Polyester demonstrates exceptional resistance to photodegradation, retaining its structural and tensile integrity despite prolonged exposure to intense UV radiation. Beyond its direct performance metrics, PES offers a profound advantage within the framework of a circular textile economy. The polymer's specific chemical architecture facilitates highly efficient and scalable recycling processes. This ease of recyclability is an increasingly critical material property in contemporary engineering, aligning with systemic industry directives designed to mitigate the

environmental impact and resource consumption associated with the lifecycle of technical outerwear.

Backing

The results in *Figure 15* underscore, also, the essential function of the internal layer, which not only acts as an auxiliary barrier safeguarding the membrane from mechanical stress and contamination but also plays a pivotal role in enhancing the tactile comfort experienced by the wearer. This internal component directly affects the overall sensation of the garment against the skin, thereby significantly contributing to its ergonomic and sensory performance. Regarding material composition, polyamide (PA) is identified as the most frequently used fibre, accounting for 71.54% of the analysed samples, while polyester (PES) is employed in only 28.46% of the instances. The predominance of PA can be ascribed to its advantageous balance of softness, elasticity, and durability, attributes that render it particularly appropriate for applications where comfort and flexibility are of utmost importance.

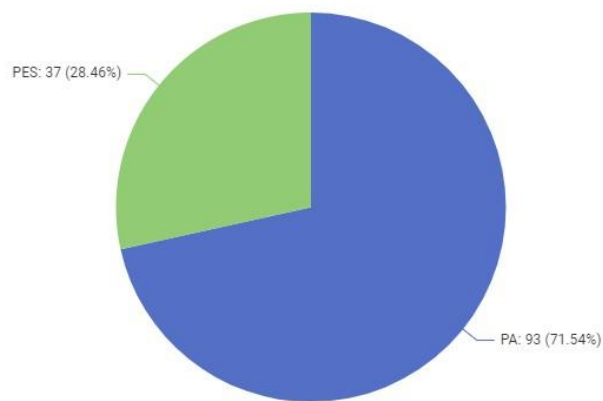


Figure 17 - Jacket's backing material distribution graph

As previously discussed, the primary function of the internal layer is centred on enhancing comfort rather than delivering extensive technical performance. Accordingly, the criteria guiding the selection of materials are predominantly related to manufacturability, ease of processing, and production efficiency. Consequently, manufacturers often opt to construct the internal layer from the same material as the external layer. This design approach not only streamlines procurement and processing but also facilitates the lamination process, as the use of identical or chemically

compatible materials improves adhesion between the membrane and the adjacent textile surfaces, as illustrated in *Figure 17*. The enhanced bond integrity contributes to the overall durability of the composite structure and aids in maintaining the garment's performance characteristics over time.

Alongside these functional benefits, using similar materials for both layers also demonstrates a growing focus on sustainability and circular design principles within the textile industry. Employing a uniform material composition reduces the complexity of recycling processes at the end of the product's life cycle. Specifically, reducing the variety of polymers used simplifies mechanical and chemical separation procedures, leading to lower processing costs, reduced energy consumption, and fewer environmental impacts. As a result, this strategy not only promotes more efficient manufacturing but also aligns with modern efforts to create highperformance garments that are both technically advanced and environmentally sustainable.

Membrane

In contrast to the textile layers, the membranes integrated within the jackets analysed in this study are, as shown in *Figure 18*, predominantly composed of three principal materials: expanded polytetrafluoroethylene (ePTFE), polyamide (PA), and polyurethane (PU). Among these, ePTFE is the most prevalently utilised material, chiefly owing to the extensive adoption of Gore-Tex technology by the manufacturers included in this sample. Gore-Tex, an internationally renowned company recognised for its pioneering development and patenting of ePTFE-based membranes, has historically established industry standards for highperformance waterproof and breathable fabrics. Its technology has become synonymous with durability, comfort, and superior protection in outdoor and technical apparel.

As previously discussed, ePTFE membranes belong to the category of hydrophobic microporous membranes, characterised by their fine pore structure that allows the passage of water vapour while preventing the penetration of liquid water. Despite these advantageous properties, the environmental impact associated with the production and disposal of fluorinated polymers has raised significant concerns in recent years. In light of the new European Union regulations addressing the use of persistent and potentially harmful substances, it is expected that the utilisation of ePTFE and similar technologies will decrease substantially in the near future.

MEMBRANE MATERIAL

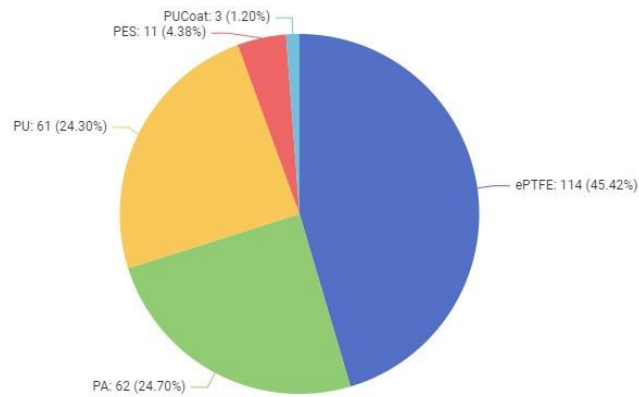


Figure 18 - Jacket membrane material distribution graph

During a personal discussion with a representative of Gore-Tex, it was indicated that, in response to these regulatory and environmental challenges, the membrane industry is progressively moving toward the development and adoption of monolithic membrane technologies. These new systems are designed to provide equivalent levels of protection and overall performance while aligning with stricter sustainability and environmental standards. Nevertheless, one of the major technical challenges associated with this transition concerns breathability. Monolithic membranes, which rely on molecular diffusion rather than microporous structures, tend to exhibit lower permeability to water vapour. This limitation could impact the thermal comfort and moisture management properties of future garments.

As a consequence, this technological shift is expected to influence several aspects of jacket design and manufacturing. The anticipated reduction in breathability, together with the changes in material composition, will likely require rethinking the overall construction strategy, including layer configuration, ventilation solutions, and bonding techniques. Thus, the evolution from microporous to monolithic membranes not only represents a regulatory adaptation but also signals a broader transformation in the design philosophy and performance optimisation of outdoor apparel.

3.1.2 Visual evaluation

The assessment of garment grading consistently indicates that certain high-stress regions are disproportionately prone to premature failure. According to the data presented in *Table 1*, the areas

identified as most critical include the cuffs, the neckline, the hood, and the front. Among these vulnerable regions, the cuffs exhibit the highest incidence of damage. This heightened deterioration is primarily attributable to their frequent and substantial exposure to mechanical abrasion resulting from contact with external objects, as well as their status as one of the most frequently handled parts of the jacket. The neckline is identified as the second most commonly damaged area. However, the nature of the damage differs: while the face fabric typically remains in good condition, the waterproof membrane and seam integrity are generally severely compromised.

A pivotal common factor connecting both the deterioration of the cuffs and the distinct damage observed at the neckline is their heightened exposure to the wearer's skin and biological secretions. As highlighted in the introductory context, human skin functions as a significant source of degrading agents, primarily through perspiration (sweat) and a range of chemical compounds (e.g., salts, oils, urea) inherently present on the epidermal layer. This ongoing exposure promotes chemical hydrolysis and deterioration, especially targeting polymer-based membranes and seam sealants, thereby elucidating the specific failure modes observed in the neck area and contributing to the wear profile of the cuffs. This phenomenon emphasises the importance of considering biochemical interactions as a fundamental factor in the long-term durability of garments.

Table 1 - Mean values for the visual inspection of each main section of the jackets

	Face fabric	Membrane	Seams
Hood	3,866	3,420	3,211
Neck	3,851	3,063	2,824
Shoulders	3,898	3,456	3,348
Upper back	3,902	3,739	3,809
Lower back	3,780	3,611	3,731
Underarms	3,924	3,747	3,477
Arms	3,620	3,690	3,794
Cuffs	3,498	3,367	3,254
Front	3,417	3,420	3,424

Zips

An examination of the various features of the jackets reveals a significant disparity in the condition of the zippers across different sections of the garment. Specifically, as evidenced by the results

presented in *Table 2*, the Central zipper generally exhibits a more advanced state of degradation compared to both the Pocket zippers and the Armpit zippers.

This observed differential wear can be primarily attributed to the frequency of operational use. The Central zipper is subjected to a substantially higher number of functional cycles, as its operation is mandatory for every instance of donning and doffing the jacket. Consequently, the average cumulative number of working cycles experienced by the Central zipper is statistically far greater than that of the other two zipper types. Zippers represent a critical functional element of any outdoor garment, performing the dual role of providing a secure barrier against the external environment while simultaneously acting as a necessary access point. The failure of any zipper component, particularly the main closure, can compromise the overall functional integrity of the jacket, especially when exposed to adverse meteorological conditions such as precipitation or snowfall.

Conversely, a notable advantage of zipper systems is their relative ease of repair and replacement. Although damage to core materials, such as the waterproof membrane or face fabric, often requires temporary repair through patching, a damaged zipper can be entirely replaced with a new component. This high level of reparability reduces the long-term effect of zipper failure on the overall assessment of a second-hand product's viability. Nevertheless, considering their crucial functional role, the condition of the zippers remains a key factor in the comprehensive evaluation of a used jacket's suitability and remaining lifespan.

Table 2 - Mean values for the visual inspection of each zips of the jackets

Central zip	Pockets zip	Armpits zips
3,837	4,189	4,284

With regard to the residual auxiliary components of the jacket, a comprehensive aggregate metric was computed. The “Average trim” value, as detailed in *Table 3*, serves as the benchmark representing the overall condition of all secondary features. A systematic comparison of each individual feature's mean condition value against this composite average provides clear insights into the varying rates of degradation across the garment.

Table 3 - Average values for trim sections

Cuffs velcro	Central velcro	Press studs zip end	Press studs zip central	Bottom cords	Hood front cords	Hood back cords	TRIM AVERAGE
3,907	3,529	4,427	3,579	4,030	4,197	4,278	4,103

Velcro (hook-and-loop) and Press Studs

The Velcro, both the central closure system and those located on the cuffs, demonstrates mean condition values that are below the established "Average trim" threshold. The central hook-and-loop fastening is notably degraded, likely attributable to the same mechanisms responsible for the wear of the main zipper: a high frequency of operational cycles resulting from each use of the jacket. A mitigating consideration is that this fastener, along with the central zipper, is relatively easier to replace, thereby reducing long-term maintenance impact. Additionally, this particular fastener generally does not serve as a critical barrier function essential to the core performance of the garment, indicating that its suboptimal condition typically does not impair the jacket's overall usability. The hook-and-loop value at the cuffs is slightly higher but remains below average, indicating a similar, albeit less severe, pattern of wear.

In contrast, the press studs, which are less prevalent features (particularly the central zipper studs often located on older models), exhibit a condition value that ranks among the lowest recorded, comparable to that of the central Velcro fastener. The causes of degradation are presumed to be analogous to those affecting the high-usage central fasteners. Nevertheless, a notable drawback of press studs is the increased complexity associated with their replacement relative to simple hook-and-loop fasteners or zippers. Despite this repair challenge, it is important to emphasise that press studs are generally among the least functionally critical components concerning the garment's operational integrity.

Adjustable Cords

Conversely, the adjustable drawcords are generally observed to be in a superior overall condition. Nonetheless, a notable distinction exists: the bottom cords (hem adjusters) are the most deteriorated among this group. The cause for this differentiated wear is multifaceted and difficult to attribute definitively. A plausible hypothesis suggests that the hem section experiences greater exposure to external abrasion and friction due to its proximity to the body's movement and other

surfaces, relative to the more protected hood section. This physical location, combined with potentially less frequent usage and movement of the jacket's upper portion, leads to a significantly lower rate of consumption and wear on the head-section cords compared to those governing the bottom periphery.

3.2 Spray test

The selection of the spray test (AATCC 22) as the primary analytical method for evaluating Durable Water Repellent (DWR) conditions was made with an understanding of its status as a benchmark protocol within the global textile industry. Its widespread adoption by both major corporations and smaller enterprises is largely due to its procedural efficiency and the relatively low cost of the testing machine. This experiment was conducted on a smaller batch of 39 jackets to determine the efficacy of the test in accurately quantifying the hydrophobic degradation of used garments.

To ensure statistical relevance and account for localised wear patterns, each garment was tested across four distinct zones. An arithmetic mean was then calculated to establish a representative overall value for each sample. To facilitate a more rigorous comparative analysis, these mean values were categorised according to the standardised rating scales prevalent in textile engineering:

- Qualitative Thresholds: All average values falling below the 50-point threshold were classified as 0, signifying a total failure.
- Standardisation: Remaining values were rounded to the nearest standard increment (e.g., 60, 70, 80) to align with industry evaluation metrics.

As delineated in *Figure 19*, the empirical data reveal a significant performance deficit; the vast majority of the samples were relegated to the 0 category, highlighting the severe degradation of DWR integrity common in second-hand apparel. Even those units that avoided a zero rating demonstrated marginal performance, with the plurality of scores clustering at or below 60. Of the total 39 jackets analysed, a mere 6 units maintained a performance rating above 70. These findings provide clear evidence that the DWR layer is highly susceptible to mechanical abrasion and environmental exposure, leading to a loss of functionality over time.

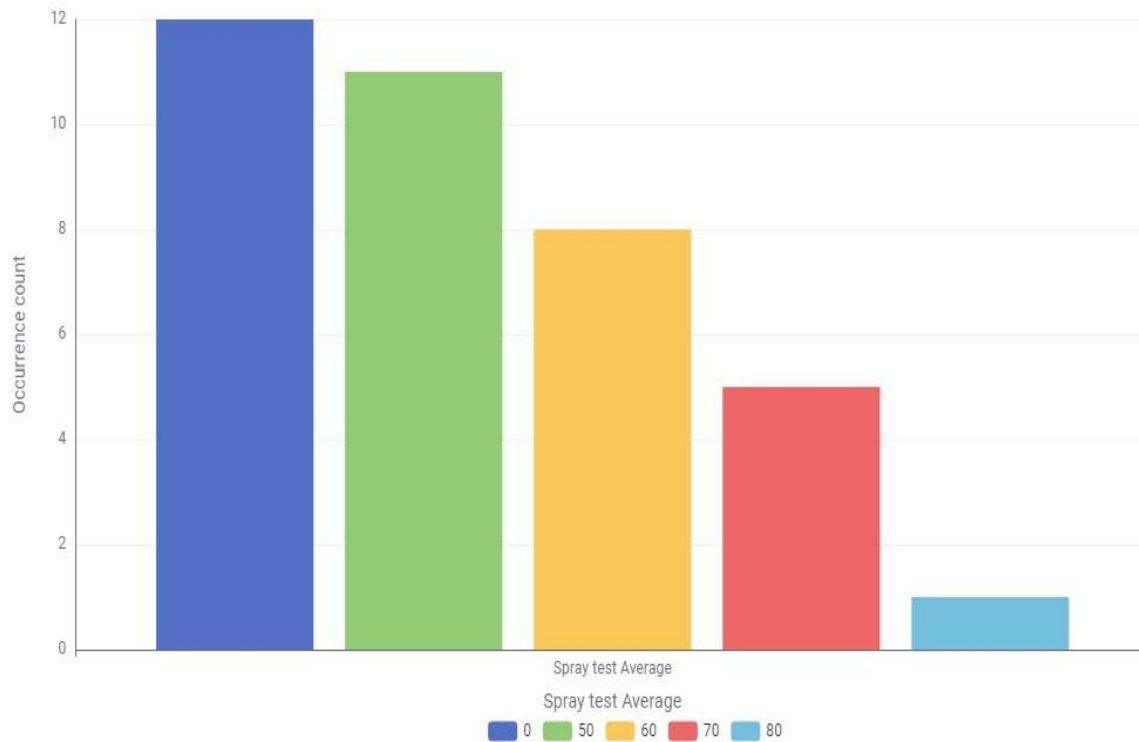


Figure 19 - Spray test average distribution for the 39 jackets tested

While the degradation of fluorinated polymers is a natural consequence of use, these results highlight a looming challenge for the outdoor apparel industry. In light of the forthcoming EU ban on PFAS, manufacturers are compelled to transition toward PFC-free alternatives. The data suggests that these next-generation DWR treatments must achieve a durability profile that at least matches, if not exceeds, legacy standards. Failure to achieve performance parity with traditional finishes would lead to a premature phenomenon where the external textile layer loses its hydrophobic properties and absorbs moisture. This behaviour risks tarnishing the reputation of the technical textile industry. Despite a gradual shift in market perception, a significant segment of consumers continues to equate a decline in surface water repellency with the total functional failure of the garment. This misconception, if exacerbated by subpar material performance, could trigger a surge in premature product replacement. Such a cycle of hyper-consumption directly contradicts the scientific community’s efforts to establish a circular economy and mitigate the environmental impact of textile waste.

3.3 Rain test

From the total sample population of 256 garments, only a subset of 116 jackets was subjected to a simulated rain test. This specific methodology was implemented to conduct a comprehensive behavioural evaluation of the garments under controlled precipitation conditions. The primary objective of this protocol was to ascertain the structural integrity and functional condition of the internal waterproof membrane. Furthermore, when compared to a standard superficial spray test, this extended exposure provides a more realistic and longitudinal assessment of the Durable Water Repellent (DWR) coating's performance over time.

3.3.1 Statistical analysis

Consistent with the methodology detailed in Chapter 2, the quantitative evaluation of water through the membrane used a standardised grey t-shirt positioned beneath the test specimen to serve as a visual indicator. To minimise subjective observer variance and enhance the reliability of the assessment, the scoring range was from 1 to 3, deliberately avoiding a broader 5-point spectrum.

The diagnostic criteria for the assigned values were strictly defined as follows:

- **Value of 1 (Critical Failure):** Complete saturation of the underlying T-shirt within the designated zone, indicating a total failure of the membrane's waterproofing capabilities.
- **Value of 2 (Partial Compromise):** Localised or partial moisture permeation on the T-shirt, denoting degraded membrane efficacy while still retaining some baseline functionality.
- **Value of 3 (Intact Functionality):** The T-shirt remained entirely devoid of moisture, signifying optimal performance and a fully functional membrane.

This localised scoring methodology facilitated a highly precise analysis of membrane degradation across distinct anatomical sections of the jackets. As illustrated in *Table 4* below, a comparative analysis between the localised mean values and the global average score across all tested jackets (Average score = 2.322) isolates specific structural zones that demonstrate sub-average performance and elevated vulnerability to water penetration.

Table 4 - Rain test mean values

	Membrane mean value
Head	2,345
Shoulder	2,276
Back	2,509
Underarms	2,440
Complete arms	2,164
Front	2,388
Hem	2,241
Zip	2,284

A more granular examination of the statistical distributions underlying the experimental outcomes reveals a discernible divergence between the individual subsets and the aggregated data. Specifically, a comparative analysis highlights a significant variance when contrasting the localised distribution of each distinct part against the overall average value distribution.

Focusing explicitly on the distribution of the average values, as graphically delineated in *Figure 20*, a quantitative assessment demonstrates a pronounced disparity in the frequency of discrete outcomes. The observed frequency for the value 1 is comparatively low, with fewer than 11 occurrences. In stark contrast, the higher-magnitude values exhibit significantly greater representation and dominate the dataset. The frequency of the value 2 exceeds 40 discrete observations, while the value 3 has the highest prevalence, surpassing 50 recorded instances. This pronounced stratification unequivocally indicates that the aggregated results are heavily weighted toward the higher values (2 and 3), rendering the occurrence of the lowest value (1) statistically marginal by comparison.

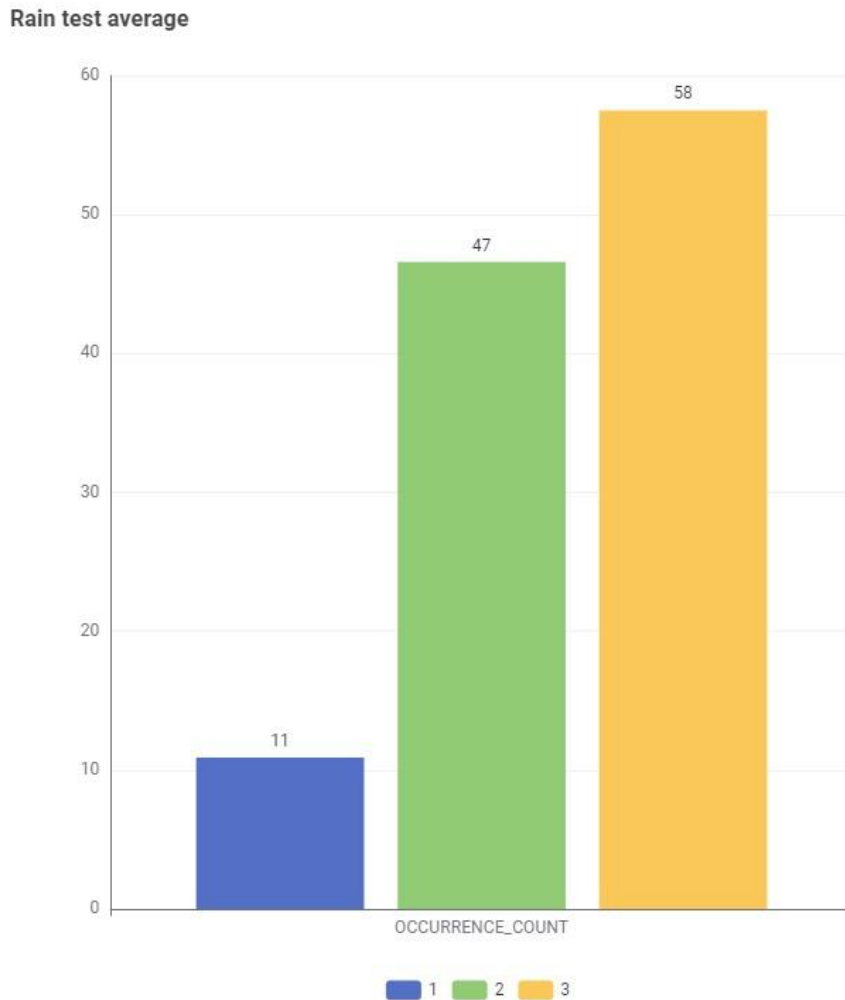


Figure 8 – Distribution of value for rain test average

A comparative analysis of the regional data distributions reveals that, among all the different zones exhibiting performance below the aggregate mean, the arm sections demonstrate the most significant degradation in structural integrity. This pronounced deterioration is highly likely attributable to the environmental exposure and physical interaction these specific regions endure. Functioning as the primary interface with the external environment, the arms, alongside the shoulders, are subjected to disproportionate levels of mechanical stress.

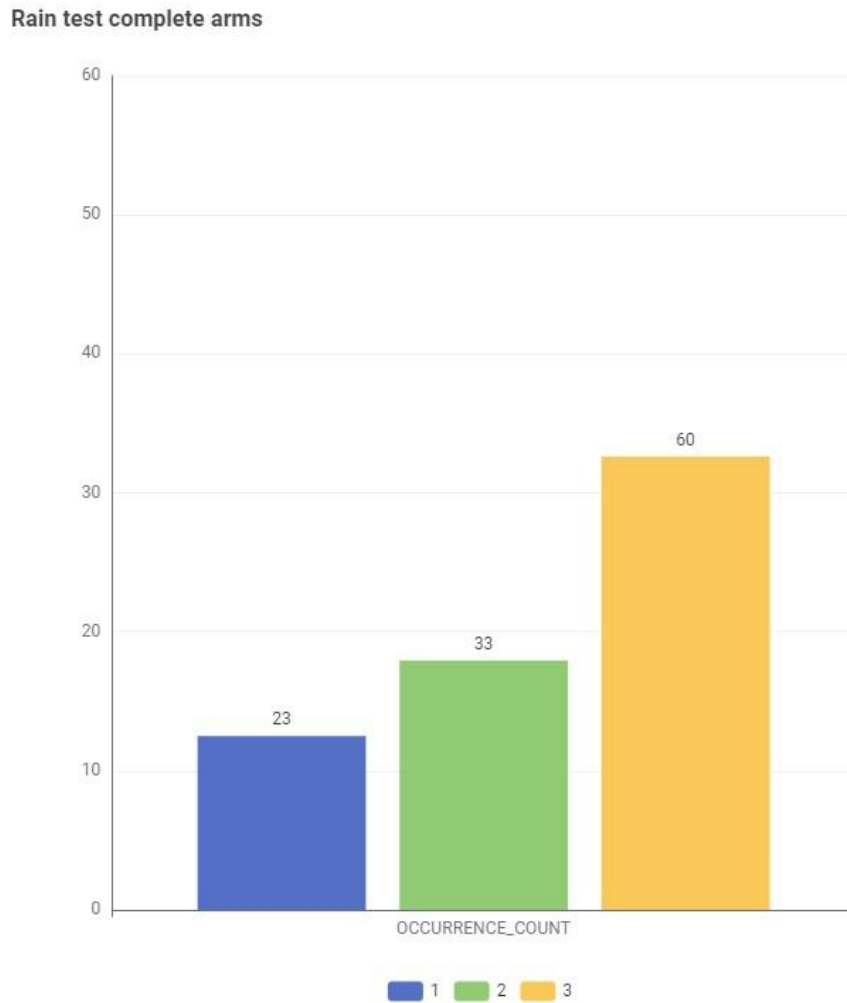


Figure 9 - Distribution of value for rain test complete arms

Specifically, the arm sections recurrently interact with various external objects and abrasive surfaces. Over time, this repetitive frictional contact enhances localised wear, ultimately culminating in membrane failure characterised by the formation of micro-perforations and macroscopic tearing.

Similarly, the shoulder regions are highly susceptible to distinct mechanical and environmental stressors. The continuous dynamic load and frictional shear exerted by backpack straps constitute a primary mechanism for abrasive wear. Furthermore, the anatomical orientation of the shoulders maximises their surface area exposure to direct precipitation, accelerating the breakdown of the membrane.

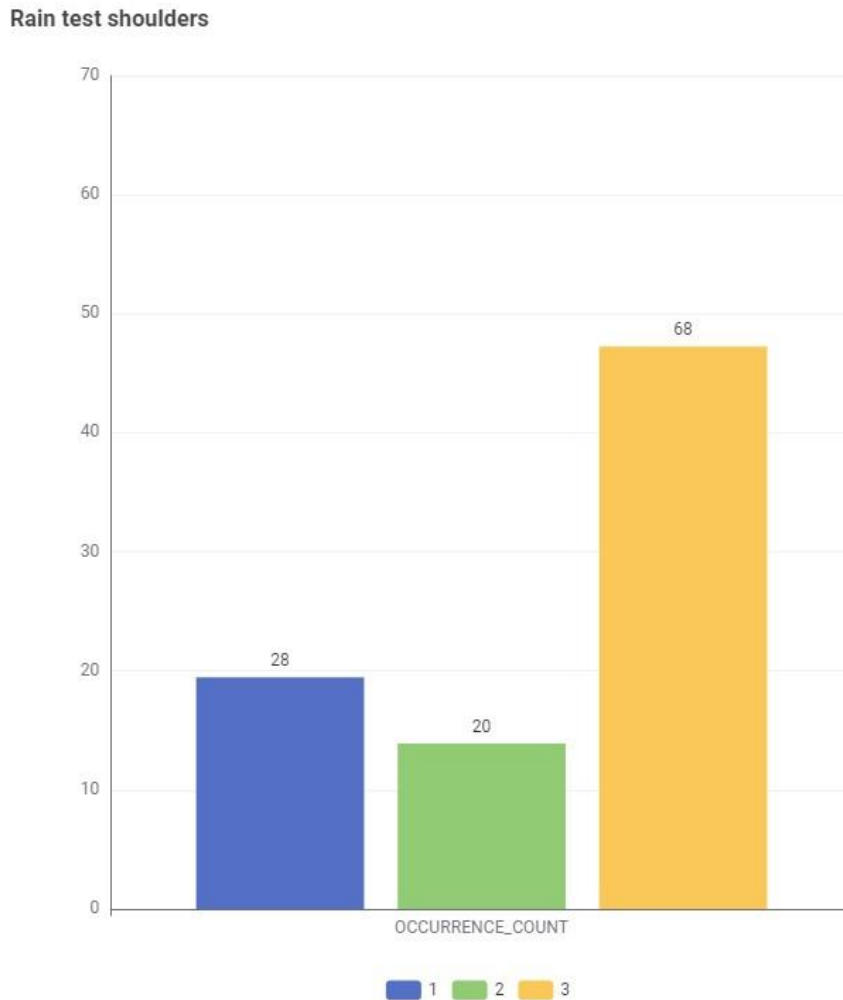


Figure 10 - Distribution of value for rain test shoulders

The premature failure of these critical functional zones represents a substantial vulnerability that must be systematically addressed. This localised degradation is particularly problematic concerning the lifecycle and viability of garments within the circular economy, as compromised structural integrity in high-wear areas drastically diminishes the functional utility and resale value of second-hand garments. To mitigate this localised degradation, future design iterations should mandate the strategic integration of specialised protective overlays. Reinforcing these highly exposed zones with advanced, abrasion-resistant material layers presents a highly viable engineering solution to extend the functional lifespan of the underlying waterproof membrane.

Conversely, an analysis of the garment's closures and structural junctions, specifically the hem and zipper assemblies, indicates a distinct type of failure that is primarily governed by mechanical and manufacturing-induced vulnerabilities. The construction of the hem typically necessitates traditional stitching methodologies. This mechanical joining process inherently compromises the structural

integrity of the waterproof membrane by introducing a linear series of needle punctures during manufacturing.

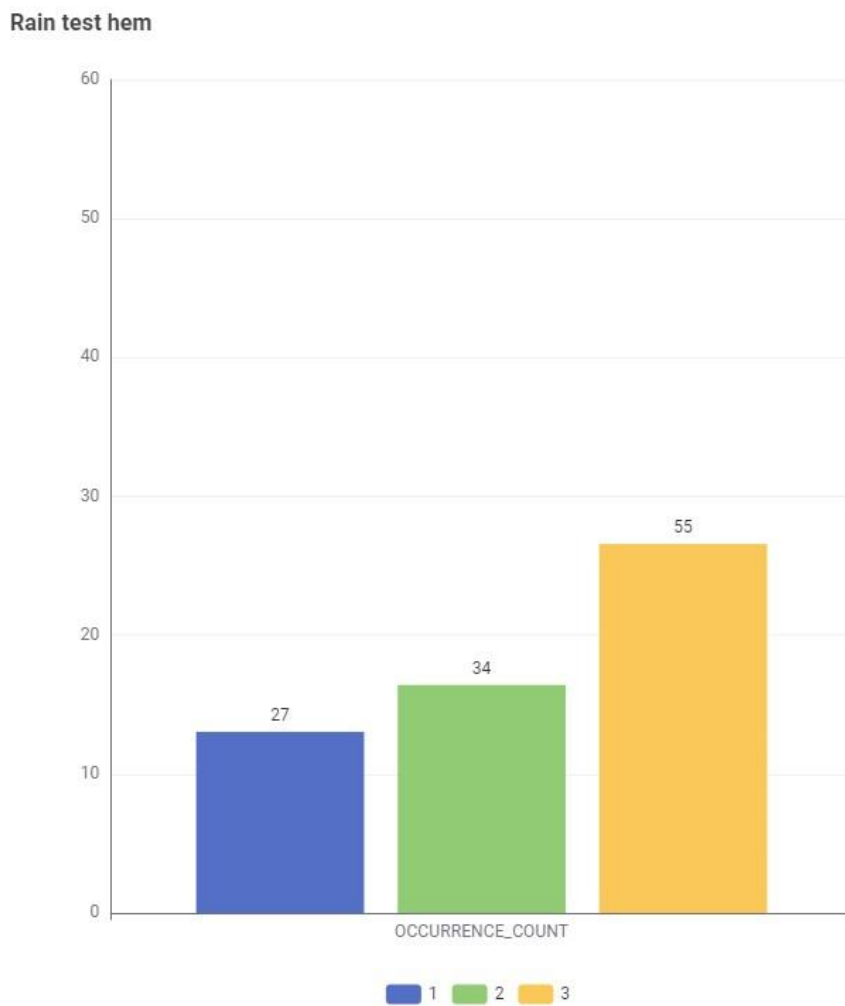


Figure 11 - Distribution of value for rain test hem

These manufacturing-induced perforations act as direct capillary conduits, significantly degrading the hydrostatic resistance of the textile. Consequently, when the garment is subjected to external moisture, such as active precipitation or elevated environmental humidity, these micro-holes provide an unimpeded pathway for moisture ingress, ultimately compromising the wearer's internal microclimate.

The zipper mechanisms exhibit analogous structural vulnerabilities. By their fundamental design, these linear closures disrupt the continuous waterproof barrier of the outer shell. To counteract this inherent permeability, manufacturers frequently employ specialised protective interventions, such as polyurethane (PU) laminated zipper tapes or overlying textile storm flaps, to augment the waterproof profile of the component.

However, the integration of these protective barriers is not a universal industry standard across all product tiers. Furthermore, even when adequately implemented, these protective elements remain highly susceptible to mechanical degradation over time. The frequent, repetitive cyclic action of opening and closing the zipper exerts substantial kinetic stress and localised friction. This constant mechanical actuation can rapidly erode or delaminate the protective coating, thereby nullifying its water-resistant properties and reinstating the component's vulnerability to moisture penetration.

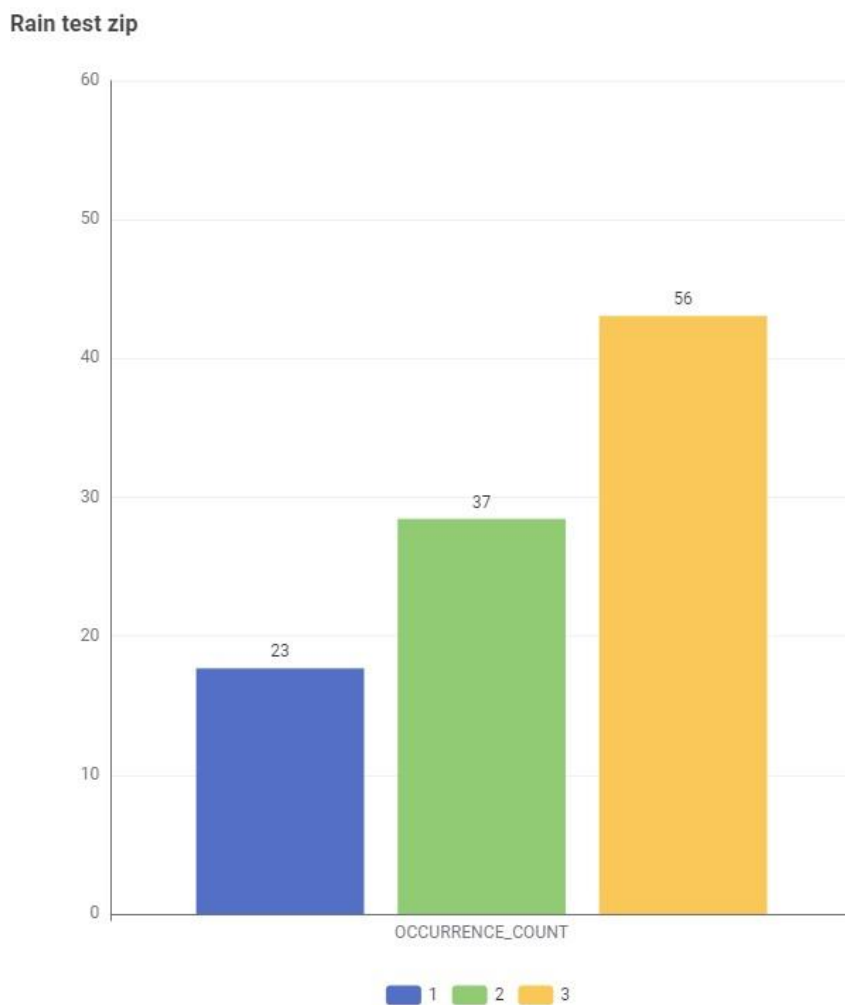


Figure 12 - Distribution of value for rain test zip

3.3.2 Correlation between Rain test and Spray test

To quantitatively assess the total moisture absorption during the rain test, a weight analysis was conducted. The mass of each garment was precisely recorded both prior to and immediately following the rain chamber test. The primary objective of this procedure was to evaluate the

potential correlation between the efficacy of the surface Durable Water Repellent (DWR) coating, as determined by the standardised spray test, and the actual volume of water retained by the textile matrix.

Theoretically, an inverse correlation is expected: a garment exhibiting superior superficial water repellence should inherently demonstrate lower volumetric water absorption. However, a significant methodological limitation arises when relying solely on the spray test. The standard spray test protocol subjects the fabric to moisture for only a short period, raising fundamental concerns regarding its predictive validity for real-world scenarios characterised by prolonged, continuous environmental exposure.

To facilitate a robust non-parametric statistical analysis, the continuous raw data obtained from the spray tests were systematically transformed into an ordinal scale comprising six discrete tiers (labelled 0 through 5). The stratification of the raw scores was executed according to the following intervals:

- **Raw score 0–50** = Category 0
- **Raw score 51–60** = Category 1
- **Raw score 61–70** = Category 2
- **Raw score 71–80** = Category 3
- **Raw score 81–90** = Category 4
- **Raw score 91–100** = Category 5

This categorical optimisation was implemented to clarify the dataset and improve the resolution of the correlation analysis.

The outcomes of the statistical correlation are detailed below:

		Spearman's rho	p
Weight increase %	- spray test	-0.309	.063

* $p < .05$, ** $p < .01$, *** $p < .001$

As indicated by the statistical output, the calculated probability value ($p = 0.063$) exceeds the standard significance threshold of $p = 0.05$. Consequently, the observed negative correlation

(Spearman's rho = -0.309) between the variables lacks statistical significance, indicating that the relationship is exceptionally weak or entirely non-existent within this sample set.

This analytical outcome underscores a critical finding: the standardised spray test, when utilised in isolation, is an inadequate diagnostic tool for comprehensively predicting the performance of technical outerwear under realistic environmental conditions. Evaluating the superficial DWR condition does not provide sufficient predictive data regarding overall moisture management and structural saturation. Therefore, comprehensive, time-intensive rain chamber testing represents a fundamentally superior and necessary methodology for accurately characterising the complex hydrodynamic behaviour and functional state of specific garments.

3.3.3 Correlation between Rain test and Visual inspection

A primary objective of this study was to ascertain whether a statistically significant correlation exists between the empirical outcomes of the simulated rain tests and the qualitative data derived from visual garment inspections. The main objective for this investigation was highly pragmatic: establishing a robust correlation would validate a simplified, non-destructive evaluation protocol. Such a framework would empower everyday consumers to accurately assess the functional condition of technical outerwear without necessitating access to specialised laboratory equipment or invasive testing procedures.

To rigorously examine this potential correlation, a comparative statistical analysis was performed, aligning the quantitative rain test data with the numerically coded visual inspection scores. A preliminary methodological discrepancy existed in the respective grading rubrics: the rain test outcomes were categorised on a ternary scale (1 to 3), whereas the visual inspections originally utilised a 5-point scale (1 to 5). To rectify this dimensional incongruity and facilitate a more robust comparative analysis, the visual inspection dataset underwent a systematic data transformation. The original 1 to 5 values were normalised and mathematically re-scaled to map onto the corresponding 1 to 3 framework. This standardisation protocol ensured that analogous data points were dimensionally aligned, thereby optimising the dataset for subsequent statistical modelling and highlighting underlying correlational trends more effectively.

Given that the fundamental purpose of the simulated rain test is to empirically evaluate the structural integrity and hydrostatic resistance of the internal waterproof-breathable layer, the initial phase of the correlational analysis specifically targeted this component. Consequently, the primary

statistical comparison was conducted between the aggregated mean scores of the membrane's visual condition and the corresponding average performance values recorded during the dynamic rain simulation.

		Spearman's rho	p
Rain test Average	- Membrane Average	0.282**	.002

* p < .05, ** p < .01, *** p < .001

An overarching correlational analysis between the Rain test average data and the Membrane average visual inspection scores yielded a highly significant statistical relationship, characterised by a p-value approaching 0.001. This robust statistical threshold strongly validates the central hypothesis: a systematic visual inspection serves as a highly reliable diagnostic proxy for estimating the general functional condition and residual hydrostatic resistance of a technical garment.

It is imperative to note, however, that qualitative visual assessments cannot perfectly predict internal membrane integrity with absolute certainty. The dataset contained a statistically minor subset of anomalous outliers exhibiting inverse behaviours. Specifically, certain garments presented as "false positives", registering high visual inspection scores due to pristine exterior conditions, yet failing catastrophically during the dynamic rain simulation. Conversely, a selection of "false negatives" occurred wherein garments exhibited severe macroscopic wear during visual evaluation but maintained exceptional waterproof integrity within the climate chamber. Because these divergent cases represent a marginal fraction of the total sample size, they do not statistically negate the overarching, highly positive correlation established between the two testing methodologies.

To further isolate which specific anatomical zones and structural layers (face fabric, internal membrane, and taped seams) exhibit the strongest predictive correlation with the rain test outcomes, a localised component statistical analysis was executed. Analysing the resulting correlation matrix, specifically focusing on the diagonal vectors which map the visual score of a specific localised section directly to its corresponding rain test performance, reveals critical nuances in the garment's failure mechanics.

Face Fabric Correlation

An examination of the correlation vector associated with the external face fabric, *Figure 25*, indicates a demonstrably weak predictive relationship. Statistically significant correlation was isolated to merely two anatomical zones: the head and the arms. Furthermore, the correlation coefficient within these specific zones remained relatively low. This outcome scientifically demonstrates that assessing the macroscopic condition of the exterior shell is fundamentally insufficient for evaluating overall garment health. Critical structural failures, such as internal membrane delamination or micro-perforations, frequently occur without manifesting any visually detectable damage on the outer textile layer.

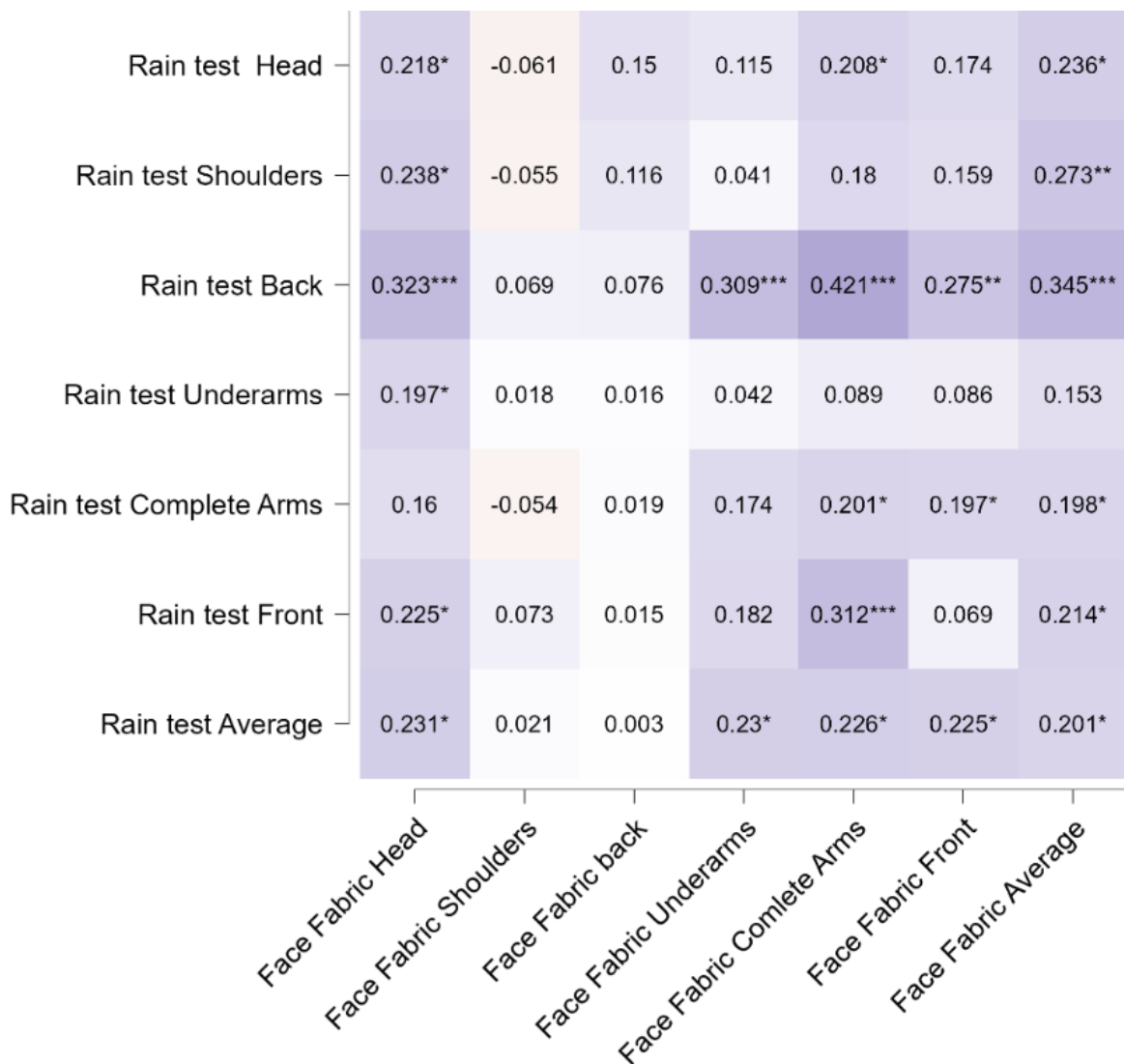


Figure 13 - Heat map for the correlation between the rain test and the face fabric

Seam Integrity Correlation

A parallel analysis of the seam conditions, visualised in the heat map designated as *Figure 26*, presents a shifting correlational dynamic. While a marginal correlation persists within the head region, the previously observed correlation in the arms entirely dissipates. Conversely, a highly significant correlation emerges within the posterior (back) region of the garment, registering a robust statistical significance of $p < 0.01$. Despite this strong localised indicator, the variance across the other zones reiterates that seam inspection alone cannot reliably predict systemic waterproofing failure alone.



Figure 14 - Heat map for the correlation between the rain test and the seams

Membrane Correlation

Finally, incorporating the visual assessment data specific to the internal waterproof-breathable membrane (*Figure 27*) identifies a strong predictive correlation within the back region, coupled with a lower, yet observable, correlation in the shoulder zones.

Synthesising these component-specific findings leads to a definitive conclusion: no single structural layer or isolated anatomical zone provides a comprehensive diagnostic overview of the garment's condition. The mechanisms of membrane degradation are complex and multifactorial. However, when the visual inspection data from all discrete layers (face fabric, seams, and membrane) and zones are mathematically aggregated, the resulting composite average provides a highly robust, statistically validated metric for accurately understanding the remaining functional utility of the technical apparel.

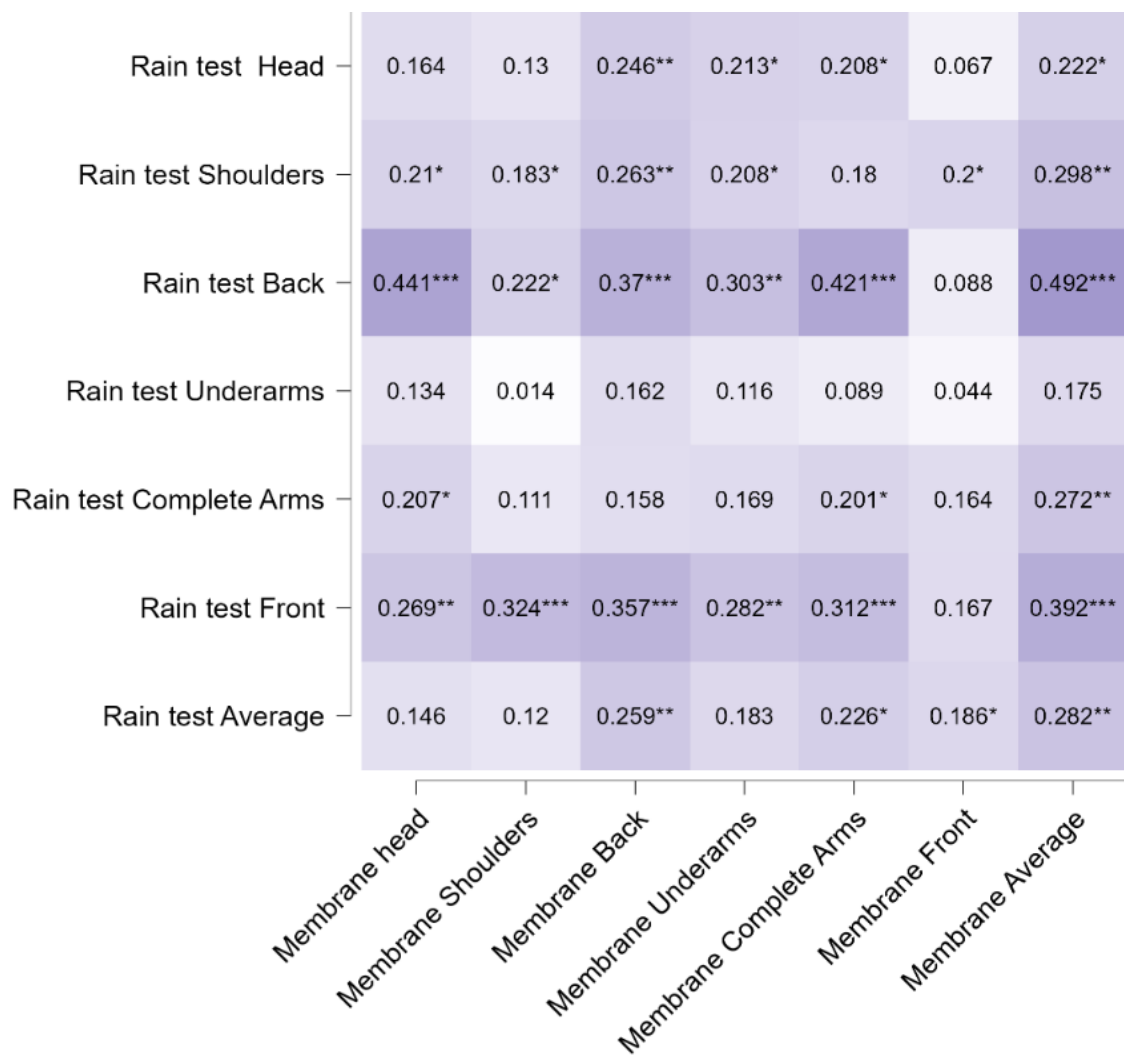


Figure 15 - Heat map for the correlation between the rain test and the membrane

3.4 Hydrostatic head press

For this specific phase of the experimental methodology, a reduced sample size was utilised. Parallel to the standardised spray test, the primary objective of this subset analysis was to validate the diagnostic efficacy of a non-destructive Suter hydrostatic head test within the broader testing framework. To accurately isolate and target localised vulnerabilities before mechanical pressure testing, the internal surface of each garment was systematically pretreated with an Isopropyl Alcohol (IPA) solution. Because IPA possesses a significantly lower surface tension than water, it rapidly penetrates compromised areas of the oleophobic layer and the underlying membrane, as seen in *Figure 28*. This chemical interaction effectively highlights micro-perforations and structural defects that would otherwise remain visually imperceptible to the naked eye.



Figure 16 - Effects of IPA on micro holes in the membrane

The central aim was to evaluate whether the Suter test could be effectively adapted as a diagnostic tool for this specific batch of garments. Standard hydrostatic head testing often necessitates destructive sampling (e.g., cutting physical fabric swatches from the garment); however, preserving

the functional integrity of the jackets for subsequent circular economy applications mandated a purely non-invasive approach. Following the IPA-assisted visual mapping of the membrane, targeted hydrostatic testing was performed exclusively on the identified defect loci, alongside adjacent, visually intact control areas.

Empirical data derived from the compromised zones revealed a critical performance threshold. The majority of the IPA-identified micro-perforations experienced catastrophic hydrostatic failure at an applied pressure of approximately 300 mm H₂O. This failure point is exceptionally low, occurring well below the preliminary holding pressure baseline of 700 mm H₂O established for this non-destructive protocol. This inability to withstand even minimal hydrostatic loads indicates a high probability of rapid and unimpeded moisture permeation under standard environmental conditions.

Because 300 mm H₂O represented the mean failure pressure for anatomical zones that exhibited preliminary moisture ingress during the macroscopic rain test, this value was established as a quantitative diagnostic threshold.

- **Critical Failures:** Tested areas failing below this pressure benchmark were classified as critical failures, representing immediate, active pathways for water ingress.
- **Potential Failures:** Conversely, areas that sustained pressures above this threshold, yet still exhibited underlying structural anomalies during the IPA treatment, were categorised as potential failures. These latent defects indicate regions where the membrane's structural integrity is compromised and localised fatigue has initiated, though absolute hydrostatic failure has not yet occurred.

To establish a robust comparative baseline, regions of the membrane entirely devoid of IPA-identified defects were subjected to the identical hydrostatic parameters. The outcomes across these control samples were uniform: the intact membrane sections exhibited zero instances of failure during the modified Suter test. These uncompromised zones successfully maintained their hydrostatic barrier, withstanding both the preliminary holding pressure of 700 mm H₂O and the maximum standardised test pressure of 21,000 mm H₂O.

4 Conclusion

In conclusion, this study initiates the development of a comprehensive, multi-stage testing protocol designed to rigorously evaluate the functional viability and residual performance of second-hand and end-of-life technical rain jackets. The empirical findings systematically demonstrate that while highly accessible diagnostic tools provide foundational data, they exhibit significant limitations when employed alone. Specifically, the short duration of the spray test does not reliably predict a garment's performance under realistic, prolonged environmental stress. Similarly, while macroscopic visual scoring proves to be a generally reliable prognostic indicator, as evidenced by its statistically significant correlation with the rain simulation outcomes, superficial examination alone inherently fails to detect latent structural degradation and internal membrane vulnerabilities.

Consequently, the continuous 30-minute climate chamber rain simulation emerged as the most critical and definitive methodology within the testing framework. This dynamic exposure is essential for accurately revealing true membrane integrity and identifying the presence of micro-perforations that remain entirely invisible to the naked eye. The targeted implementation of a non-destructive Suter hydrostatic head test, using preliminary application of isopropyl alcohol (IPA) as a penetrating agent, was able to give important information about the pressure withstand by micro defects, but in the end, it is not fundamental for the evaluation of the residual properties of a second-hand jacket.

Ultimately, although robust statistical analysis confirms a strong, positive correlation between aggregated visual assessment scores and physical rain test performance, an extensive and dynamic rain simulation remains an absolute, indispensable requirement for the accurate and comprehensive validation of used technical garments. To effectively support the transition toward a circular textile economy and demonstrably extend the functional lifespan of technical apparel, future research initiatives must focus on expanding and refining this diagnostic testing matrix to encompass all complex variables inherent to the degradation of end-of-life textiles

References

- [1] L. Nilsson, *Opportunities for Enhancing Durability and Environmental Sustainability in Shell Jackets*. Sundsvall: Mid Sweden University, 2024.
- [2] Y. Chang and F. Liu, «Review of Waterproof Breathable Membranes: Preparation, Performance and Applications in the Textile Field», *Materials*, vol. 16, fasc. 15, p. 5339, lug. 2023, doi: 10.3390/ma16155339.
- [3] A. van Leeuwenhoeklaan e M. Bilthoven, *CONTACT DETAILS OF THE DOSSIER SUBMITTERS*:
- [4] «WATERPROOF definition and meaning | Collins English Dictionary». Consultato: 4 settembre 2025. [Online]. Disponibile su:
<https://www.collinsdictionary.com/dictionary/english/waterproof>
- [5] «SPRAY TEST (Surface Wetting Spray Tester)», Caimi srl. Consultato: 4 dicembre 2025. [Online]. Disponibile su: <https://www.caimi.net/en/product/spray-test/>
- [6] P. J. Hill, D. Kirton, M. Taylor, and R. S. Blackburn, «Quantifying Water Repellency by Modifying Spray Test Method AATCC TM22 to Extend Test Duration Allowing Discrimination between Similarly Graded Fabrics», *AATCC J. Res.*, vol. 7, fasc. 6, pp. 8–14, Nov. 2020, doi: 10.14504/ajr.7.6.2.