Research on the construction and application of a multi-regional waterproof rating system for hard shell jackets

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ABSTRACT – REZUMAT

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As an important piece of outdoor protective clothing, the waterproof performance of hard shell jackets is a crucial indicator for measuring their functionality. Traditional testing methods, which are mostly based on the fabric level, fail to fully consider the complexity of clothing structures. This study proposes an innovative "multi-regional waterproof scoring system". Through simulated rainfall experiments, hard shell jackets were divided into key areas such as the head, neck, shoulders, and chest, and weighted scores were given according to the severity of water infiltration and its impact on wearing comfort. Six commercially available hard shell jacket samples were selected for systematic testing under different rainfall intensities. The results show that zippers and stitching parts are key factors affecting waterproof performance. This rating system can objectively and comprehensively evaluate the protective ability of the entire garment, holding important application value for product research and development, consumer guidance, and the improvement of industry testing standards.

Keywords: *hard shell jackets, waterproof performance evaluation, multi-regional scoring system, rainfall simulation testing, structural design optimisation*

Cercetare privind construirea și aplicarea unui sistem multiregional de evaluare a impermeabilității pentru jachetele cu înveliș exterior

Fiind o piesă importantă de îmbrăcăminte de protecție pentru exterior, performanța de impermeabilitate a jachetelor cu înveliș exterior este un indicator crucial pentru măsurarea funcționalității acestora. Metodele tradiționale de testare, care se bazează în mare parte pe nivelul țesăturii, nu reușesc să ia în considerare pe deplin complexitatea structurilor de îmbrăcăminte. Acest studiu propune un „sistem inovator de evaluare a impermeabilității în mai multe regiuni". Prin experimente simulate de precipitații, jachetele impermeabile au fost împărțite în zone cheie, cum ar fi capul, gâtul, umerii și toracele, și au fost date scoruri ponderate în funcție de gravitatea infiltrării apei și de impactul acesteia asupra confortului la purtare. Au fost selectate șase eșantioane de jachetă impermeabilă disponibile în comerț pentru testare sistematică la diferite intensități ale precipitațiilor. Rezultatele arată că fermoarele și îmbinările sunt factori cheie care afectează performanța de impermeabilitate. Acest sistem de evaluare poate evalua în mod obiectiv și cuprinzător capacitatea de protecție a întregului articol de îmbrăcăminte, deținând o valoare importantă de aplicare pentru cercetarea și dezvoltarea produselor, îndrumarea consumatorilor și îmbunătățirea standardelor de testare din industrie.

Cuvinte-cheie: *jachete cu înveliș exterior, evaluarea performanței de impermeabilitate, sistem de notare multiregional, testare de simulare a precipitațiilor, optimizarea proiectării structurale*

INTRODUCTION

Hard shell jackets are essential for outdoor activities and harsh climates. Their core performance depends on fabrics that block liquid water yet allow water vapour to escape, ensuring dry and comfortable wear [1, 2]. These fabrics block liquid water while allowing water vapour to escape, ensuring comfort. The waterproof and breathable functions are typically realised through three types of technologies: membrane technology, coating treatment, and lamination processes [3, 4]. Studies have shown that nanofiber membranes prepared by electrospinning technology feature high porosity and specific surface area, which can significantly enhance water vapour transmission rates while maintaining good waterproof performance [5–7]. In addition, the application of surface hydrophobic treatment and hydrophobic finishing agents can significantly enhance the water repellency of fabrics [8, 9].

Three-layer structured laminated materials can enhance the mechanical strength of fabrics while maintaining waterproof performance [10, 11]. In recent years, studies have increasingly focused on smart and integrated functions. For example, temperature-responsive materials and graphene-based components enable adaptive breathability and wearable sensing. Researchers have applied temperature-responsive materials and two-dimensional nanomaterials, such as graphene, to fabrics to achieve environment-adaptive breathable regulation and wearable sensing functions [12–15]. These advances are driving outdoor clothing toward high performance with smart integration. At the same time, the concept of sustainable development has prompted the academic community to explore bio-based materials. For example, alginate is blended with aramid to prepare fabrics, which are used to enhance the flame retardancy and environmental friendliness of protective clothing [16]. The design of hard shell jackets integrated with solar cells has also emerged, balancing protective functions and emergency energy supply [17].

Waterproof performance is commonly assessed by spray tests (e.g., AATCC TM22, ISO 4920) and hydrostatic pressure tests (e.g., ISO 811), which respectively measure surface water repellency and resistance to water penetration [18–21]. However, because most standards evaluate fabrics rather than full garments, they struggle to capture performance under realistic wearing conditions. [22, 23]. Hard shell jackets have complex structures, and parts such as seams, zippers, and hoods are often weak areas in waterproofing. Traditional tests struggle to cover their overall protective capabilities [24]. Structural design elements, such as magnetic buttons, spliced sleeves, and sealed zippers, also have a significant impact on waterproof performance.

In recent years, researchers have gradually recognised the necessity of regional evaluation in reflecting the overall performance of garments. Different parts of hard shell jackets are exposed to rain at varying frequencies and pressures, imposing differentiated zonal requirements on their protective performance. Zonal graded testing can identify weak protective points, providing a scientific basis for functional optimisation and structural adjustment.

To address the deficiencies of current standards in evaluating the waterproof performance of garments at the clothing level, this paper proposes the construction of a "multi-regional waterproof scoring system for hard shell jackets". Through empirical research, the waterproof performance of each region is systematically evaluated, aiming to provide precise references for consumers and assist enterprises in product structural optimisation and quality improvement.

MATERIALS AND METHODS

Information on samples

This study selected 6 representative brand hard shell jacket samples from the market, covering different structural designs and material compositions. All samples were men's models (size L or XL) to ensure the consistency and representativeness of the experiment. These samples differ in waterproof fabrics, zipper types, stitching processes, etc., which helps evaluate their regional waterproof performance from multiple perspectives. The basic information of the hard shell jacket samples is shown in table 1.

In addition, each sample was photographed in kind to record its overall structure, providing an intuitive basis for subsequent regional analysis. The physical images of the hard shell jacket samples are shown in figure 1.

Design of the experiment

This study used a high-precision rainfall simulation system to conduct dynamic tests. The system provides adjustable flow, uniform distribution, and stable

Table 1

BASIC INFORMATION OF HARD SHELL JACKET SAMPLE

Sample no.	Brand	Product name	Style no.	Colour	Nominal fabric composition	Size
1	A	Men's Hard Shell Jacket	114301063	Black	Outer layer: 100% nylon Inner layer: 100% polyester (excluding film) Checkered pocket lining: 100% polyester	L
2	B	Hard Shell Jacket	NF0A86WG	Orange	Fabric: 100% nylon Excluding decorative parts/elastic fibres	L
3	C	Men's Hard Shell Jacket	A14CATR861	Purple	Outer layer: 100% polyester Inner layer: 100% polyester	L
4	D	Hard Shell Jacket	KG2411112	Yellow	100% nylon	L
5	E	Men's Woven Sports Top	152427626-1	Olive green	Outer layer: 100% polyester Inner layer: 100% polyester	L
6	E	Men's Lightweight Hard Shell Jacket	152430616-1	Olive green	Fabric - 100% nylon Fabric - Inner layer: 100% nylon Pocket lining - Outer layer: 100% nylon Pocket lining - Inner layer: 100% nylon	XL

Fig. 1. Physical images of hard shell jacket test samples (categorized by brand and product type): *a* – Brand A – Men's Hard Shell Jacket; *b* – Brand B – Hard Shell Jacket; *c* – Brand C – Men's Hard Shell Jacket; *d* – Brand D – Hard Shell Jacket; *e* – Brand E – Men's Woven Sports Top; *f* – Brand E – Men's Lightweight Hard Shell Jacket

spraying, realistically reproducing multi-level rainfall. Coupled with the zones in the next section, it exposes at-risk areas to realistic wetting patterns for reproducible whole-garment assessment.

Setting of rainfall intensity

According to the meteorological standard classification of rainfall intensity (light rain, moderate rain, heavy rain, torrential rain), this study set four levels of rainfall flow as simulation parameters, as follows:

- Light rain: 5 l/h
- Moderate rain: 15 l/h
- Heavy rain: 30 l/h
- Torrential rain: 60 l/h.

This study set each rainfall test to 30 min to fully expose performance at the corresponding intensity while limiting system error and external interference; the duration also aligns with typical outdoor rainfall.

Composition of the experimental system

The testing system consists of the following main components:

- Rainfall simulation system: A multi-nozzle uniform rainfall system for flow control;
- Garment support device: Equipped with a wearable dummy model (with a realistic wearing structure);
- Internal circulation system: Enables water recycling to save water.

This study dressed the dummy in a standard wearing state and adjusted all zippers, fasteners, and the hood according to the user guidelines; all tests used the same space and time window to control environmental variation. To facilitate replication, figure 2 lists the full setup, components, and the schematic diagram of the rainfall simulation system; the test duration settings are defined in the previous section, and an example of the rain test for samples is shown in figure 3.

Observation indicators

This study quantified waterproof performance under dynamic rainfall using a structured, multi-region indicator system designed to reflect how rain impinges on garments in use. The framework builds on traditional appearance-based evaluation and considers both function and wearer comfort.

Zonal partitioning and evaluation logic

According to the structural design of the garment and the exposure degree of key human activity areas, the entire hard shell jacket is divided into the following four core functional areas:

- Head Area: Corresponding to the hood and brim, it is the area most directly exposed to rainfall. The evaluation mainly focuses on the anti- infiltration capability of the hood and brim structure.
- Neck Area: One of the parts where the garment fits most closely to the skin. If the sealing performance is insufficient, rainwater can easily penetrate through the splicing gaps.

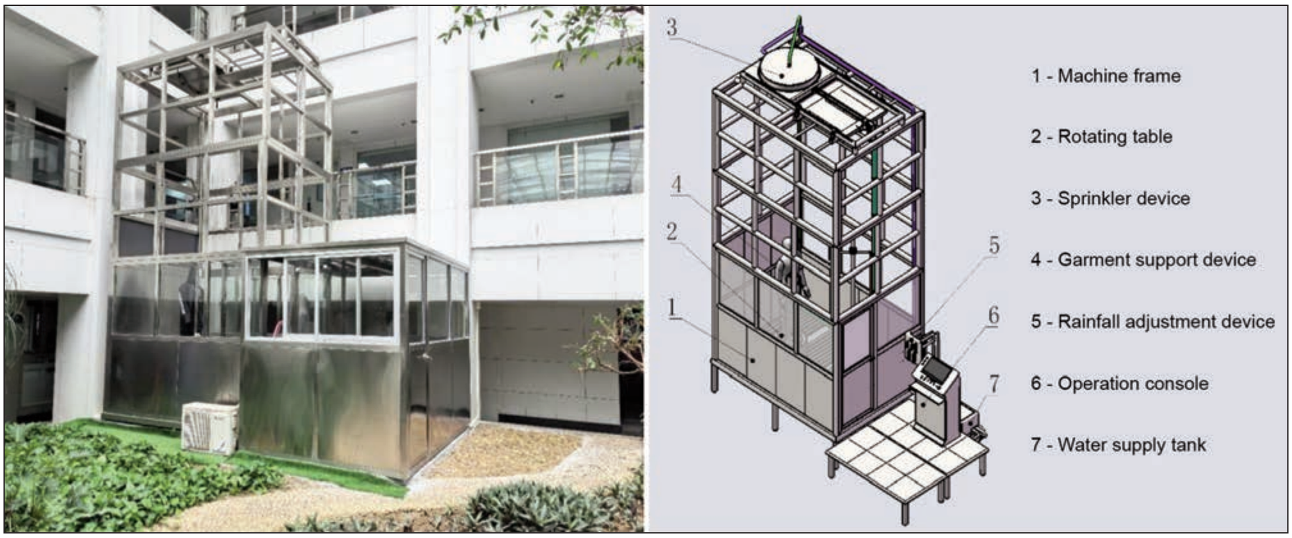

Fig. 2. Example of a rainfall simulation system

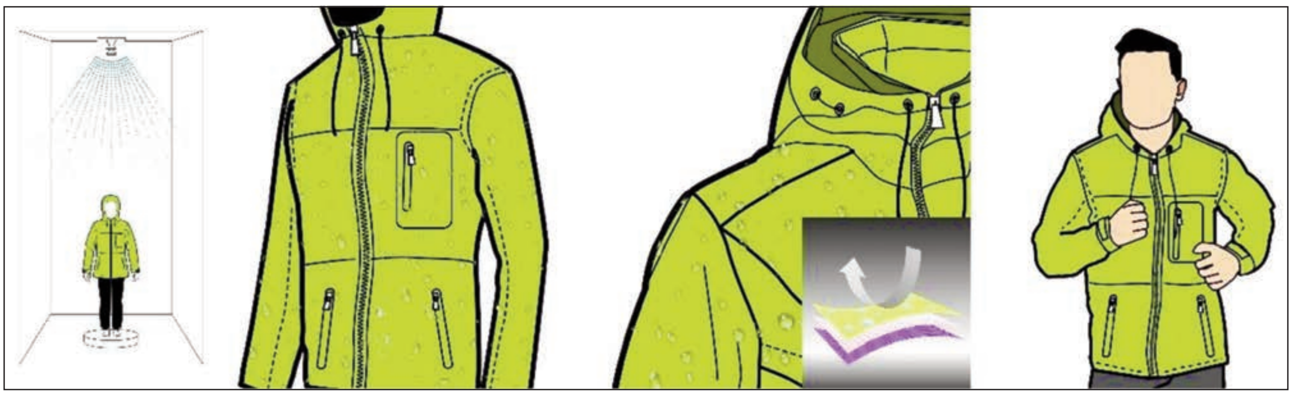

Fig. 3. Example of rain test for samples

- Shoulders Area: This area is subjected to greater force when wearing a backpack or exercising. The sealing integrity of stitching strips and fabric connections is particularly critical.
- Chest Area: Usually containing the main zipper structure, it is one of the areas with the highest waterproof risk. The key observations include the zipper protection piece and the sealing treatment of stitching seams.

These zones mirror typical outdoor exposure: direct impingement at the hood/brim, ingress along neck interfaces, load-affected seams at the shoulders, and runoff/zipper pathways across the chest.

Figure 4 shows the regional division. The evaluation focuses on infiltration in the lining and base layer, supplemented by external structural observations.

Observation methods and recording methods

To enhance the objectivity of interpretation and the intuitiveness of comparison, a grey highly hygroscopic base layer is used as the water infiltration display substrate during the test. Its colour difference is significant when wet, which helps identify the water infiltration trajectory and scope in each area, as shown in figure 5. In addition, after each round of testing, high-definition photography is immediately used to record before-and-after comparisons, supplemented by infrared imaging technology to correct judgment errors caused by local reflection or light changes.

Fig. 4. Key areas for key observation of hard-shell ackets: *1* – Head; *2* – Neck; *3* – Shoulders; *4* – Chest

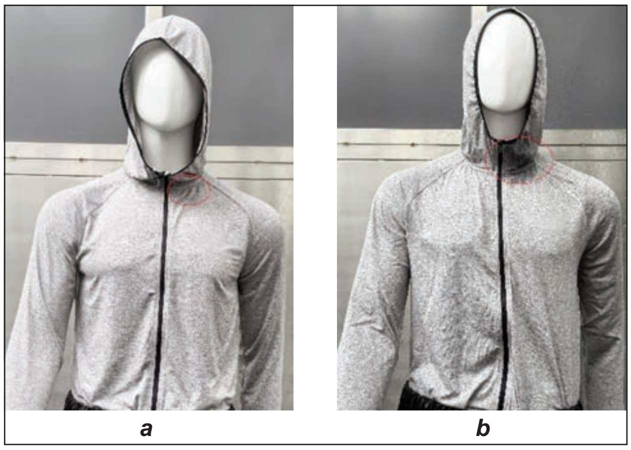

Fig. 5. Examples of the base underwear layer before and after water absorption and wetting: *a* – before; *b* – after

Water infiltration degree grading standard

In this study, the water infiltration conditions of each garment area were classified into the following four states, with corresponding quantitative scores assigned:

- Dry (Score 0): No obvious wet marks observed on the surface or interior.
- Moist (Score 1): Local fabric surface is wet but has not penetrated the inner layer, and no water droplets are formed.
- Water pooling (Score 2): Liquid water accumulates in structural parts of the garment, such as water pools in pockets.
- Soaked (Score 3): Both the inner and outer layers of the garment are wet, and the base underwear layer shows an obvious colour change.

Special Note: If the observation object is the base underwear layer, it is only divided into two levels: "Dry" and "Completely Soaked" (Scores 0 and 1), to reflect the sensitivity to the direct impact on wearing comfort.

Multi-regional waterproof scoring system

This study constructed a multi-index comprehensive scoring model based on zonal weighting. The calculation formula of the model is as follows:

$$S_{total} = \sum_{i=1}^{n} S_i \cdot W_i \quad (1)$$

where W is the waterproof score (overall score for the garment); S_i – observation score of the i-th area; W_i – weight assigned to the i-th area; n – total number of garment areas considered.

The design of each weight is based on the following principles. Regional weights (W_r) are summarised in table 2 and reflect wearer protection and ingress risk. Table 2 provides an at-a-glance summary linking the zones, the corresponding scoring rules, and the assigned weights; lower scores indicate better waterproof performance. Level definitions are given in the previous section.

Data collection and error control

This study tested each sample three times at every rainfall intensity and used the average as the final score. Two trained observers cross-validated the ratings, and the protocol adopted a blind procedure to minimise subjective bias. All tests were conducted in the same experimental environment to avoid external interference.

Table 2

MULTI-REGION WATERPROOF SCORING SYSTEM FOR HARD SHELL JACKETS

Inspection area		Description and scoring	Weight
The pockets of the jacket		Levels per section *Water infiltration degree grading standard* (0–3)	1.0
Inner surface of jacket lining	Head	Binary per section *Water infiltration degree grading standard* (0/1)	2.0
	Neck		2.0
	Shoulders		2.0
	Chest		2.0
	Others		1.5
Base underwear layer	Head		3.0
	Neck		3.0
	Shoulders		3.0
	Chest		3.0
	Others		2.0

RESULTS AND DISCUSSION

This study analysed waterproof performance across four rainfall intensities using the multi-regional scoring system. Six commercial jackets were tested, and all data were recorded and statistically evaluated. Through comparisons of regional scoring results, overall score trends, typical water infiltration patterns, and material composition differences, the comprehensive impacts of various factors on the garment's waterproof performance were discussed.

Statistical analysis of regional scoring

Table 3 shows the zonal scores of six hard shell jackets quantified by the scoring system under four simulated rainfall conditions: light rain, moderate rain, heavy rain, and torrential rain. Overall, Sample 2 exhibited more frequent infiltration in light to moderate rain, especially moisture at the neck and the base-layer chest. This pattern suggests insufficient protection around the main zipper. Sample 4 showed no notable infiltration at any rainfall intensity, indicating consistently strong protection.

Figure 6 further statistically analysed the frequency of water infiltration in each key area. The chest and pocket areas showed the highest overall water infiltration frequency, indicating that these parts were common weak links in structural design and sealing treatment of current products.

Pearson correlation analysis between jacket samples and regional waterproof scores

To further examine the influence of garment structure and material differences on regional waterproof

Table 3

STATISTICAL TABLE OF SCORING RESULTS BY REGION FOR EACH SAMPLE							
Rainfall condition	**Region**	**Sample 1#**	**Sample 2#**	**Sample 3#**	**Sample 4#**	**Sample 5#**	**Sample 6#**
Light rain (5 l/h)	the pockets of the jacket	0	0	0	0	2	2
	inner surface of jacket lining	0	2	0	0	0	0
	base underwear layer	0	3	0	0	0	0
Moderate rain (15 l/h)	the pockets of the jacket	2	0	2	0	2	2
	inner surface of jacket lining	1.5	2	0	0	0	0
	base underwear layer	2	3	0	0	0	0
Heavy rain (30 l/h)	the pockets of the jacket	2	0	2	0	2	2
	inner surface of jacket lining	0	2	0	0	0	0
	base underwear layer	0	3	0	0	0	0
Torrential rain (60 l/h)	the pockets of the jacket	2	0	0	0	2	2
	inner surface of jacket lining	0	0	0	0	0	0
	base underwear layer	0	0	0	0	0	0

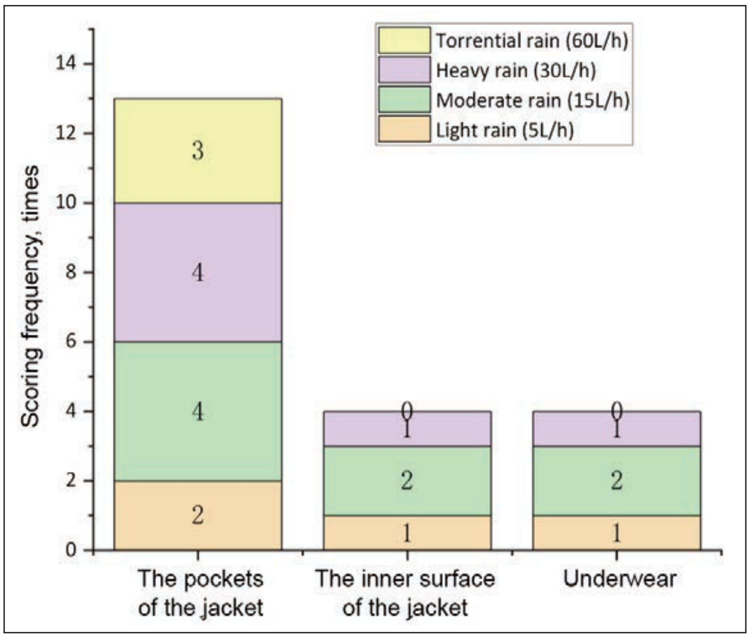

Fig. 6. Statistical chart of scoring frequency in each region

performance, Pearson correlation analysis was conducted to explore the relationships between clothing sample identifiers and scores across three key functional zones: pocket areas, inner surface of jacket lining, and base underwear layer. The results are presented in tables 4 to 6.

Table 4

PEARSON CORRELATION ANALYSIS OF CLOTHING SAMPLE AND POCKETS SCORE	
Variable	**Pockets Score**
Pearson correlation coefficient	0.367*
Significance (2-tailed)	0.078
N (Sample Size)	24

Note: * Correlation is not significant at the 0.05 level (2-tailed).

As shown in table 4, the correlation coefficient between sample number and pocket score was 0.367, with a p-value of 0.078. This indicates a moderate positive trend, but the result does not reach statistical significance ($p>0.05$). Therefore, it can be concluded that there is no statistically significant linear relationship between the specific clothing samples and their performance in pocket waterproofing. This may be attributed to the high variability in pocket design across samples, with factors such as flap structure, drainage design, and sealing treatment differing substantially, resulting in inconsistent outcomes.

In contrast, table 5 reveals a statistically significant negative correlation between clothing sample and inner surface of jacket lining score, with a Pearson coefficient of −0.434 and a p-value of 0.034 ($p<0.05$). This suggests that as the sample number increases (i.e., from sample 1 to 6), the inner surface of the jacket lining's waterproof performance improves (indicated by lower scores). Such a result implies that garments with more advanced or refined construction, such as taped seams, laminated linings, and integrated waterproof panels, are

Table 5

PEARSON CORRELATION ANALYSIS OF CLOTHING SAMPLE AND INNER SURFACE OF JACKET LINING SCORE	
Variable	**Inner surface of jacket lining score**
Pearson correlation coefficient	–0.434*
Significance (2-tailed)	0.034
N (Sample Size)	24

Note: * Correlation is significant at the 0.05 level (2-tailed).

more effective in preventing water infiltration into the internal layers.

Similarly, table 6 shows a significant negative correlation between sample number and base underwear layer score, with a coefficient of −0.442 and a p-value of 0.031. This finding indicates that garments with more robust structural waterproofing features are less likely to allow moisture penetration to the base layer, which directly impacts wearer comfort. The base underwear layer score, representing the final line of defence, serves as a sensitive indicator of total waterproof system failure; thus, lower values in later samples reflect superior design and material integration.

Table 6

PEARSON CORRELATION ANALYSIS OF CLOTHING SAMPLE AND BASE UNDERWEAR LAYER SCORE

Variable	Base underwear layer score
Pearson correlation coefficient	–0.442*
Significance (2-tailed)	0.031
N (Sample Size)	24

Note: * Correlation is significant at the 0.05 level (2-tailed).

While the correlation between pocket score and sample is not statistically significant, both the inner surface of the jacket lining and the base underwear layer exhibit significant negative correlations with sample identifiers. These results underscore the importance of garment-level structural waterproofing in determining actual protective performance. They also validate the effectiveness of the proposed multi-regional scoring system in sensitively identifying critical vulnerabilities in jacket designs under simulated rainfall conditions.

Overall waterproof score comparison

Figures 7 and 8 show the total scores of six hard shell jackets under different rainfall conditions and their radar chart distributions, respectively. A lower score indicates better waterproof performance.

Observations from the radar charts show that:

- Sample 4# has the lowest overall score, maintaining good protection under all rainfall intensities.
- Sample 2# has higher scores in multiple rainfall intensities, indicating obvious deficiencies in its overall waterproof performance.
- Samples 5# and 6# show average overall performance, but their pockets have Water pooling under all rainfall intensities, indicating defects in the waterproof design of the pockets that need improvement.

This result verified the sensitivity and scientificity of the zonal scoring system in distinguishing the protection capabilities of different structural schemes.

Analysis of typical waterproof failure modes

Guided by the zonal scores, we inspected low-scoring regions and observed the following typical failure patterns under simulated rainfall. Figure 9 shows typical waterproof failure cases recorded during the testing process, from which the following common failure modes are summarised:

- Zipper water infiltration: The main zipper area fails due to insufficient width of the protective piece or lack of sealing glue, causing rainwater to penetrate the chest along the zipper track.
- Poor seam sealing: The connecting seams between the shoulder and hood are not fully taped, allowing rainwater to enter the inner layer through gaps.
- Structural water pooling: Some pocket designs have flanged edges or lack drainage holes, making them prone to water accumulation and infiltration into the lining.
- Design and manufacturing implications are straightforward: widen or stiffen the storm flap and consider waterproof zippers to block track ingress; ensure continuous seam taping at hood–shoulder junctions with adequate seam allowance; add drainage or re-orient pocket openings to avoid water pooling.

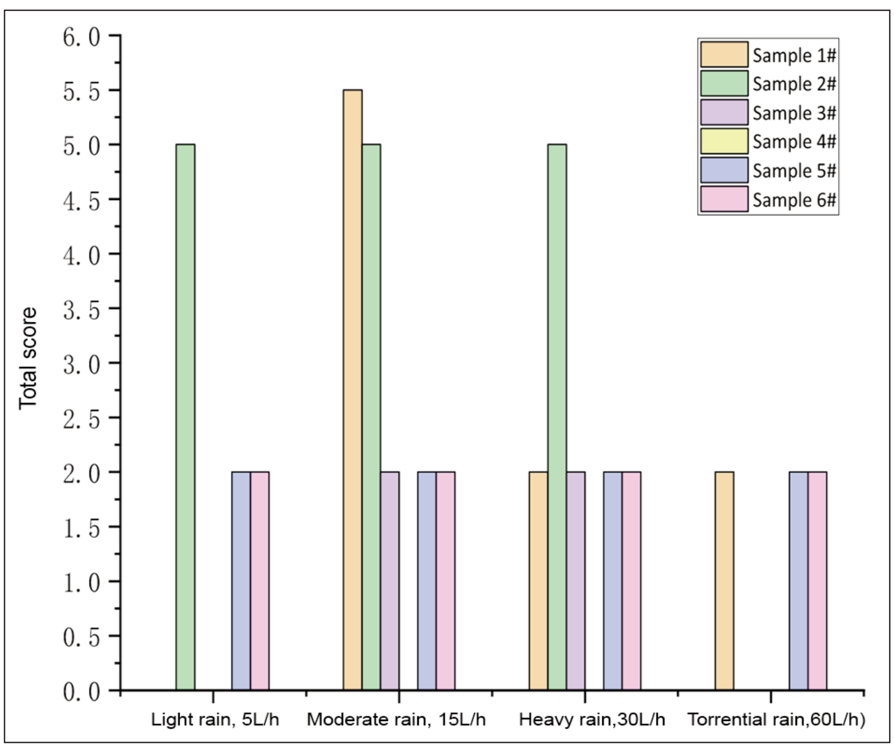

Fig. 7. The total waterproof scores of each sample

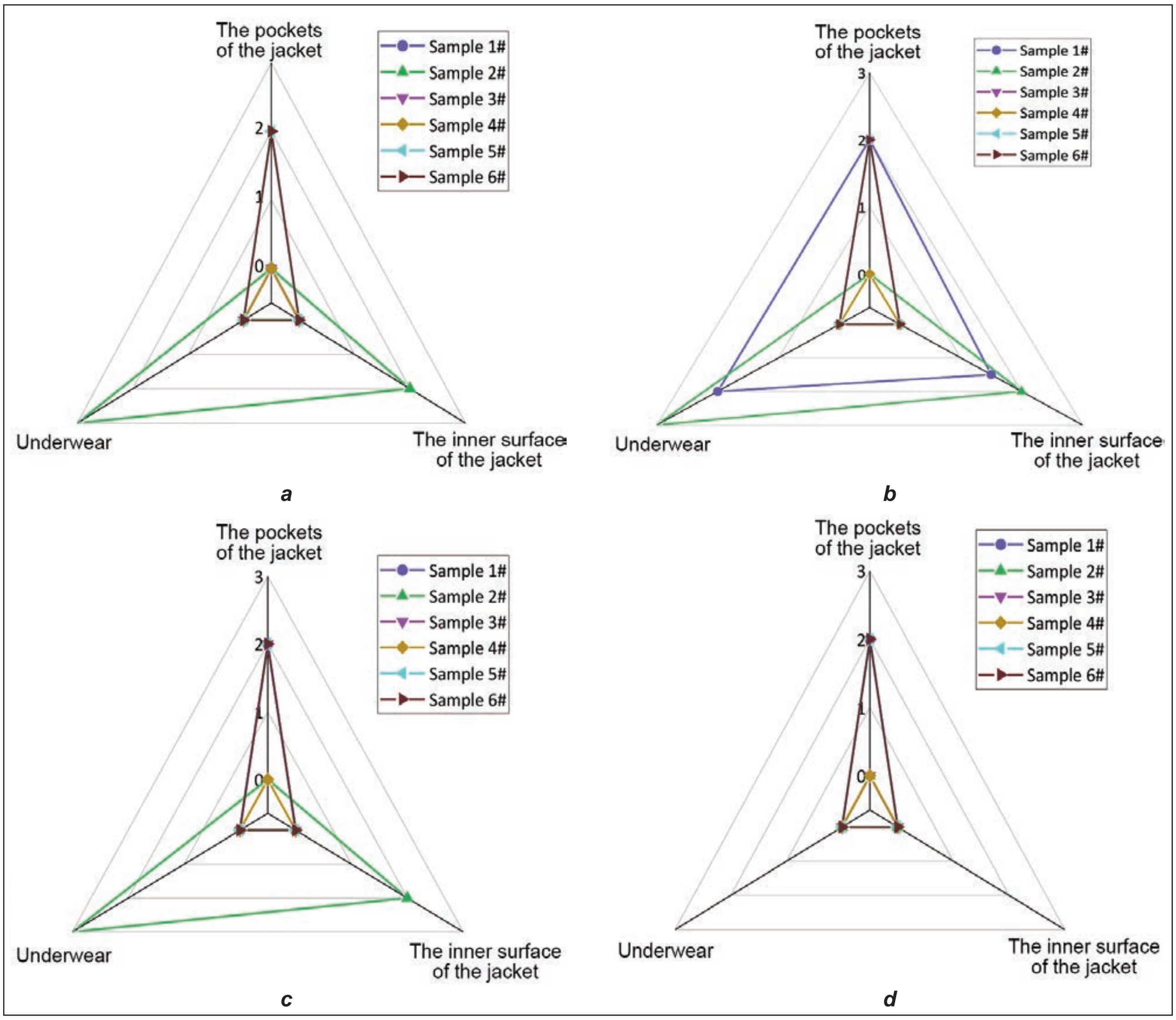

Fig. 8. Radar chart of total waterproof scores for each sample: *a* – light rain (5 l/h); *b* – moderate rain (15 l/h); *c* – heavy rain (30 l/h); *d* – torrential rain (60 l/h)

Fig. 9. Typical waterproof failure cases: zipper infiltration, incomplete seam sealing, and pocket water pooling

These phenomena are all reflected in the scoring results, indicating that the scoring system has practical value in identifying weak links.

Analysis of the relationship between fabric structure and waterproof performance

A review of the fabric information of the samples reveals that some samples with excellent scores, such as Sample 4#, mostly use three-layer composite structures or fabrics with DWR (durable water repellent) treatment on the surface, and their zippers and splicing parts are mostly equipped with hot-pressed adhesive strips or waterproof cover designs. In contrast, samples with poor scores often lack systematic sealing designs or use ordinary double-layer materials.

The combined analysis results of table 3 and the basic sample information show that fabric composition has a fundamental impact on overall waterproofness, but the packaging processes of structural details, such as taping, flanging, waterproof lip design, etc., are key factors determining actual performance.

Adaptability of the scoring system and standard extension value

The multi-regional waterproof scoring system established in this study can identify water infiltration risks in detailed structures under wearing conditions, effectively addressing the limitations of traditional fabric testing methods in overall garment evaluation. Compared with existing fabric-level testing methods such as ISO 811 and ISO 4920, this system better simulates real-world usage scenarios and applies to product R&D, quality assessment, and consumer guidance. Using the same exposure duration defined in the previous section, the method yields an overall grade together with zone scores. Table 2 summarises the weighting, and table 8 provides the final grade scale. This combined view supports targeted redesign and procurement decisions while remaining compatible with standard garment-level rain tests.

Regression Modelling of Sample Number and Regional Waterproof Scores

To further elucidate the influence of jacket design and material differences on regional waterproof performance, this study employed regression analysis to quantify the relationship between the clothing sample number and waterproof scores in three critical areas: pockets, inner surface of jacket lining, and base underwear layer. Linear and polynomial regression models were constructed based on scatter plot trends to assess the explanatory power of sample differences on regional performance variation.

Linear regression analysis

Figure 10 illustrates the linear regression trends between clothing sample number and scores in each region. The corresponding regression equations and R^2 values are as follows:

- Inner surface of jacket lining score:
  $y = 0.692 - 0.132 \times \text{sample}$
  $R^2 = 0.188$
- Pocket score:
  $y = 0.167 + 0.107 \times \text{sample}$
  $R^2 = 0.135$
- Base underwear layer score:
  $y = 0.950 - 0.182 \times \text{sample}$,
  $R^2 = 0.1195$

Here, *y* denotes the regional score, *sample* denotes the jacket ID (1–6), and R^2 denotes the coefficient of determination.

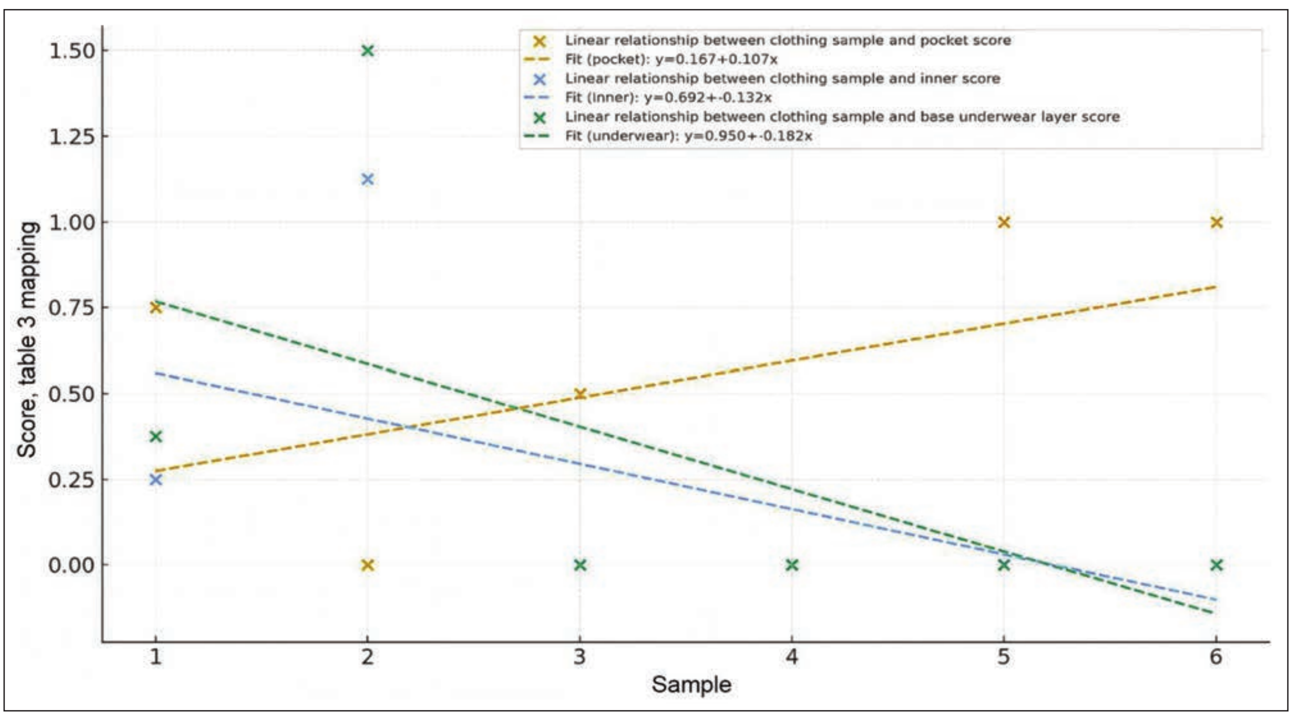

Fig. 10. Combined linear relationships between clothing sample and pocket/inner/base-underwear scores

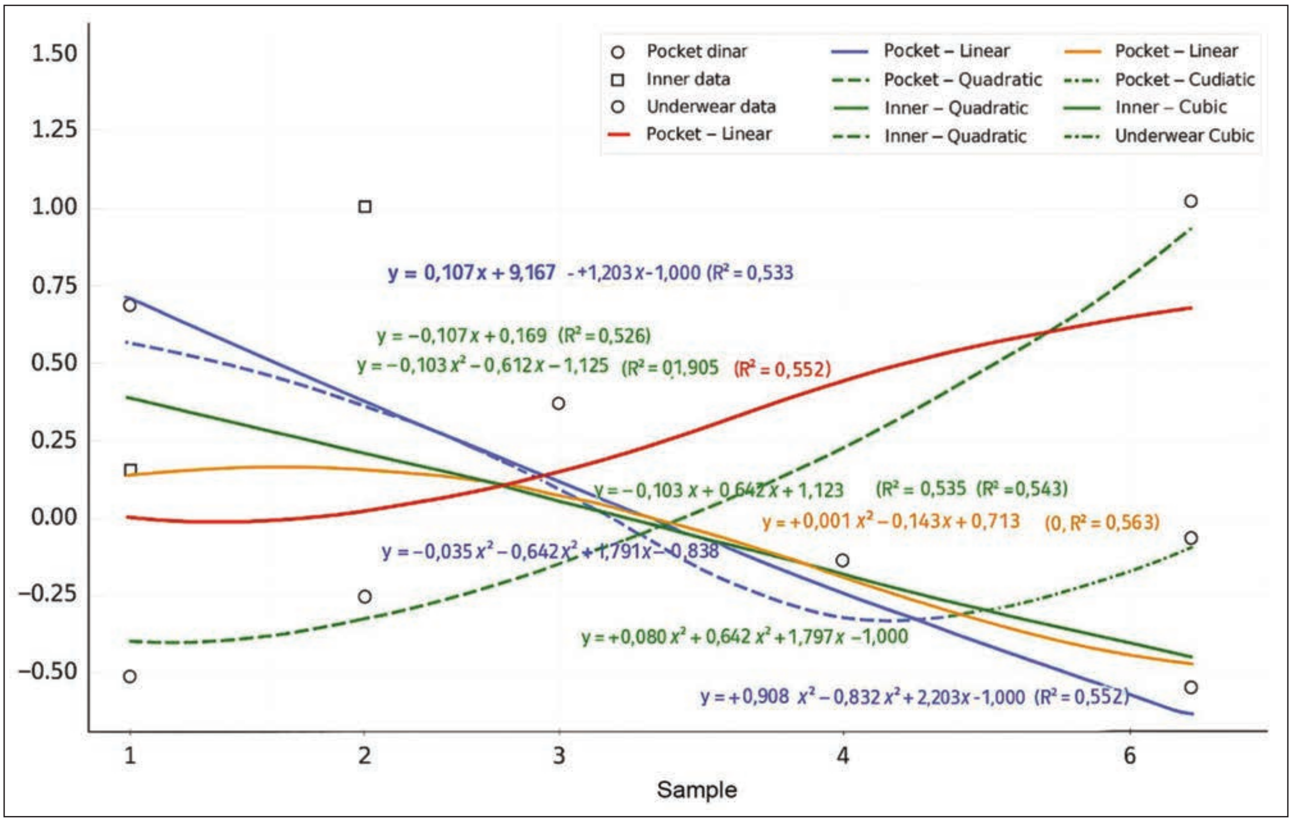

Fig. 11. Pocket, inner, and base-layer scores vs. sample: linear, quadratic, and cubic fits

These results indicate that, under a linear framework, the sample number explains only 11.9% to 18.8% of the variance in regional waterproof scores. The explanatory power of the linear model is therefore limited. This suggests that while structural and material differences across samples do exert some influence, the relationships are likely to be nonlinear or affected by other interactive variables such as seam complexity, zipper design, and surface treatments, which are not adequately captured by a simple linear approximation.

Polynomial regression analysis

To improve model fit and capture potential nonlinearities, polynomial regression models were constructed. Figure 11 presents the best-fitting polynomial trends for each regional score. The polynomial models yielded substantially improved coefficients of determination (R^2), indicating moderate explanatory power:

- Pocket score (Quadratic Fit):

  $R^2 = 0.452$

This suggests that the model explains 45.2% of the variance in pocket waterproof performance, revealing more complex, non-monotonic influences possibly related to specific pocket design elements.

- Inner surface of jacket lining score (Cubic Fit):

  $R^2 = 0.339$

The cubic model accounts for 33.9% of the variance in inner layer scores, indicating moderate explanatory power and reflecting the nuanced relationship between garment construction and internal protection.

- Base underwear layer score (Cubic Fit):

  $R^2 = 0.334$

The model explains 33.4% of the variation in base underwear layer score, reinforcing the relevance of higher-order modelling to capture cumulative effects of structural features.

Summary and interpretation

The improved R^2 values in polynomial models underscore the inadequacy of linear regression in capturing the complex interplay between structural design elements and waterproof performance. While the models remain moderate in explanatory strength, they provide useful insights into performance patterns and may serve as a reference for more refined predictive modelling in future research. These results also support the validity of the multi-regional scoring system, as it successfully differentiates samples based on actual protective performance under simulated rainfall.

CONSTRUCTION AND APPLICATION OF MULTI-REGIONAL SCORING SYSTEM

Building on a review of existing waterproof testing systems, we combine rainfall simulation with garment structural features to develop an adaptable, scalable, multi-regional scoring system for hard shell jackets. Taking structural zoning, weight assignment, and state quantification as the core methods, the model aims to achieve a comprehensive quantitative evaluation of the overall waterproof performance of the entire garment.

Structure and calculation formula of the scoring model

The overall waterproof scoring system is built on the multi-regional scoring system and assigns weights based on the actual impact of different rainfall intensities on the garment's waterproof function. The calculation formula of the model is as follows:

$$S_{total} = \sum_{i=1}^{n} S_i \cdot W_i \quad (1)$$

where S_{total} is the overall waterproof score of the garment; S_i – waterproof score under the i-th rainfall intensity; W_i – weight coefficient corresponding to the i-th rainfall intensity; n – total number of rainfall intensities.

Intensity weights are summarised in table 7; definitions are given in previous section. The model can expand the regional dimension according to the application scenarios, and has good adaptability.

Table 7

WEIGHT SETTINGS FOR RAINFALL INTENSITIES

Rainfall Intensity	Weight	Description
Light rain	0.1	High frequency but low intensity
Moderate rain	0.2	Common scenario
Heavy rain	0.3	Risk escalation
Torrential rain	0.4	Extreme conditions

Classification criteria for scoring grades

To facilitate result interpretation and user decision-making support, this study further classifies the overall scores into three grades, as shown in table 8.

The grading system provides intuitive references for consumers, testing institutes, and enterprises, supporting cross-product comparisons and procurement decisions.

Table 8

CLASSIFICATION CRITERIA FOR SCORING GRADES

Overall score range	Waterproof performance grade	Description
0–1	Grade A	No water infiltration; excellent structural sealing and material protection
1–2	Grade B	Slight wetting in individual areas; can meet the usage requirements in moderate rainfall environments.
>2	Grade C	Multiple water infiltration or water accumulation; significant structural defects exist; recommended to avoid use in heavy rainfall environments.

Application example of the model in product testing

The scoring model was applied to analyse the results of this experimental test, as shown in table 9.

Table 9

CLASSIFICATION OF SCORING GRADES FOR THIS EXPERIMENTAL RESULT

Sample no.	Overall score	Waterproof performance grade
1#	2.5	Grade C
2#	3	Grade C
3#	1	Grade A
4#	0	Grade A
5#	2	Grade B
6#	2	Grade B

According to the scoring results in the table, Samples 1# and 2# received overall scores of 2.5 and 3, both classified as "Grade C". This indicates multiple water infiltration or accumulation issues in actual testing, significant structural defects, and unsuitability for heavy rainfall environments. It is recommended to systematically optimise the waterproof structural design. Samples 3# and 4#, with overall scores of 1 and 0, respectively, were rated "Grade A", meaning essentially no water infiltration and excellent structural sealing and material protection. In particular, Sample 4#'s zero-infiltration performance strongly verifies the outstanding reliability of its waterproof technology. Samples 5# and 6#, both with an overall score of 2, fall into the "Grade B" grade, indicating slight wetting in individual areas. While they can meet the usage requirements in moderate rainfall environments, there is still room for improvement. These results show that the scoring model accurately quantifies garment waterproof performance and pinpoints design deficiencies. The actionable grades guide design optimisation and process control, helping raise industry waterproofing standards (table 9 and figure 9). Readouts at the zone level, therefore, translate into targeted fixes, zipper flap/garage optimisation, complete seam sealing at critical joints, and pocket drainage or cover redesign, before re-testing to confirm gains in the affected scores.

Practical applicability and industry value

This model is practical to implement and delivers value at multiple levels. Because the protocol pairs a controllable rainfall simulator with anatomically grounded zones, its outcomes track outdoor wearing conditions, making the results actionable for design and procurement. Using the same exposure duration defined in the previous section, the method yields an overall grade together with zone scores. Table 2 summarises the weighting, and table 8 provides the final grade scale. This combined view supports targeted redesign and procurement decisions while remaining compatible with standard garment-level rain tests.

- Product R&D optimisation: Identifies weak protection links and supports structural optimisation and adjustment of material selection strategies.
- Consumer guidance and label design: In the future, a "regional protection label" can be developed

based on scoring results to enhance the accuracy of users' purchase decisions.
- Standard system extension: The model can serve as a supplementary dimension to the existing garment testing system, promoting the industry's transformation to a testing model of "functional zoning-wearing status-situation adaptation".
- Multi-category expansion: The model's methodology is universal and applicable to various protective garments such as softshell jackets, raincoats, and cycling suits.

CONCLUSION

The proposed multi-regional waterproof rating system yields a concise whole-garment grade while revealing actionable zone-level weaknesses. Applied to six commercial hardshell jackets, it cleanly separated performance into A to C grades and consistently pinpointed vulnerable structures such as main zippers, neck–shoulder seams, and pockets, findings supported by zonal scores and images. Garments with continuous seam sealing and well-integrated three-layer laminates delivered the strongest protection, including a zero-infiltration case, whereas inadequate zipper shielding or pocket drainage repeatedly underperformed and received lower grades.

These readouts translate directly into practice and enable faster design iteration, tighter quality control and supplier qualification, better informed procurement, and clearer guidance for consumers.

The study used six samples under controlled rainfall, which limits generality. Future work will broaden garment categories and sample size, incorporate dynamic movement and ageing or cleaning cycles, and cross-validate against field use and standardised tests to refine thresholds and strengthen external validity.

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REFERENCES

[1] Chang, Y., Liu, F., *Review of waterproof breathable membranes: preparation, performance and applications in the textile field*, In: Materials, 2023, 16, 15, 5339, https://doi.org/10.3390/ma16155339

[2] Özek, H.Z., *Development of waterproof breathable coatings and laminates*, In: Waterproof and Water Repellent Textiles and Clothing, Woodhead Publishing, 2018, 25–72, https://doi.org/10.1016/b978-0-08-101212-3.00002-2

[3] Yu, X., Wu, W., Xu, G., Wang, L., Yu, H., Kan, C.W., Yan, J., Wang, X., Wang, Z., Wu, Y., Wen, L., *Thermostable, water-repellent, moisture-permeable Nomex nanofibrous membranes with a connected PTFE network for personal protective fabrics*, In: Colloid and Interface Science Communications, 2024, 60, 100782, https://doi.org/10.1016/j.colcom.2024.100782

[4] Tehrani-Bagha, A.R., *Waterproof breathable layers - A review*, In: Advances in Colloid and Interface Science, 2019, 268, 114–135, https://doi.org/10.1016/j.cis.2019.03.006

[5] Ren, G., Lu, D., Zhang, Y., Cui, Z., Li, Z., Yu, H., et al., *Poly(methyl methacrylate) embedded fluorine-free polyurethane electrospun nanofiber membranes with enhanced waterproof and breathable performance*, In: Composites Communications, 2023, 43, 101698, https://doi.org/10.1016/j.coco.2023.101698

[6] Li, S., Duan, G., Zhang, G., Yang, H., Hou, H., Dai, Y., et al., *Electrospun nanofiber nonwovens and sponges towards practical applications of waterproofing, thermal insulation, and electromagnetic shielding/absorption*, In: Materials Today Nano, 2024, 25, 100452, https://doi.org/10.1016/j.mtnano.2024.100452

[7] Hasanzadeh, M., Ahmadi, M.S., Behbahani, S.A., Nezhad, N.A., *Fabrication of nanosilica-incorporated poly(vinylidene fluoride)/polyurethane electrospun nanofibrous membranes for breathable, windproof and waterproof clothing applications*, In: Materials Today Communications, 2024, 38, 108135, https://doi.org/10.1016/j.mtcomm.2024.108135

[8] Wang, F., Pi, J., Song, F., Feng, R., Xu, C., Wang, X.L., Wang, Y.Z., *A superhydrophobic coating to create multi-functional materials with mechanical/chemical/physical robustness*, In: Chemical Engineering Journal, 2020, 381, 122539, https://doi.org/10.1016/j.cej.2019.122539

[9] He, B., Hou, X., Liu, Y., Hu, J., Song, L., Tong, Z., Zhan, X., Ren, Y., Liu, Q., Zhang, Q., *Design of fluorine-free waterborne fabric coating with robust hydrophobicity, water-resistant and breathability*, In: Separation and Purification Technology, 2023, 311, 123308, https://doi.org/10.1016/j.seppur.2023.123308

[10] Ghezal, I., Moussa, A., Marzoug, I.B., El-Achari, A., Campagne, C., Sakli, F., *Development of a breathable polymeric membrane and process optimisation by using a general full factorial design*, In: Chemical Industry & Chemical Engineering Quarterly, 2025, 31, 2, 95–104, https://doi.org/10.2298/CICEQ240202017G

[11] Zhang, H., Zhai, Q., Cao, Y., Hu, J., Zhen, Q., Qian, X., *Design and facile manufacturing of tri-layer laminated polyolefin microfibrous fabrics with tailoring pore size for enhancing waterproof breathable performance*, In: Materials & Design, 2023, 228, 111829, https://doi.org/10.1016/j.matdes.2023.111829

[12] Sun, S., Nie, L., Yang, N., Okoro, O.V., Shavandi, A., *Breathable and adaptive thermo-responsive personal protective clothing*, In: Protective Textiles from Natural Resources, Woodhead Publishing, 2022, 377–394, https://doi.org/10.1016/B978-0-323-90477-3.00010-9

[13] Liu, C., Liao, X., Shao, W., Liu, F., Ding, B., Ren, G., et al., *Hot-melt adhesive bonding of polyurethane/fluorinated polyurethane/alkylsilane-functionalized graphene nanofibrous fabrics with enhanced waterproofness, breathability, and mechanical properties*, In: Polymers, 2020, 12, 4, 836, https://doi.org/10.3390/polym12040836

[14] Wang, S., Huang, H., Liu, C., Xia, Y., Ye, C., Luo, Z., et al., *Waterproof and breathable graphene-based electronic fabric for wearable sensors*, In: Advanced Materials Technologies, 2022, 7, 11, 2200149, https://doi.org/10.1002/admt.202200149

[15] Nag, A., Simorangkir, R.B., Gawade, D.R., Nuthalapati, S., Buckley, J.L., O'Flynn, B., Altinsoy, M.E., Mukhopadhyay, S.C., *Graphene-based wearable temperature sensors: A review*, In: Materials & Design, 2022, 221, 110971, https://doi.org/10.1016/j.matdes.2022.110971

[16] Chen, X., Li, M., Yu, M., Li, Y., *Preparation and performance study of waterproof and breathable layer of alginate/aramid-based fabrics and flame-retardant multilayer combination*, In: Designed Monomers and Polymers, 2024, 27, 1, 1–4, https://doi.org/10.1080/15685551.2024.2301804

[17] Park, J., *Developing designs and making men's outdoor breathable waterproof jackets with solar cells for emergency communications*, In: Journal of Fashion Business, 2014, 18, 3, 59–72, https://doi.org/10.12940/JFB.2014.18.3.59

[18] Davies, A.J., *Performance evaluation and testing of water repellent textiles*, In: Waterproof and Water Repellent Textiles and Clothing, Woodhead Publishing, 2018, 347–366, https://doi.org/10.1016/B978-0-08-101212-3.00012-5

[19] Razzaque, A., Tesinova, P., Hes, L., Salacova, J., Abid, H.A., *Investigation on hydrostatic resistance and thermal performance of layered waterproof breathable fabrics*, In: Fibers and Polymers, 2017, 18, 1924–1930, https://doi.org/10.1007/s12221-017-1154-1

[20] Hill, P.J., Kirton, D., Taylor, M., Blackburn, R.S., *Quantifying water repellency by modifying spray test method AATCC TM22 to extend test duration allowing discrimination between similarly graded fabrics*, In: AATCC Journal of Research, 2020, 7, 6, 8–14, https://doi.org/10.14504/ajr.7.6.2

[21] Razzaque, A., Tesinova, P., Hes, L., *Enhancement of hydrostatic resistance and mechanical performance of waterproof breathable laminated fabrics*, In: Autex Research Journal, 2019, 19, 1, 44–53, https://doi.org/10.1515/aut-2018-0015

[22] Zelova, K., Glombikova, V., *The effect of cyclic wrinkling on the durability of waterproof breathable functional outdoor materials for sportswear*, In: Journal of the Textile Institute, 2025, 116, 3, 469–482, https://doi.org/10.1080/00405000.2024.2343121

[23] Bougourd, J., McCann, J., *Designing waterproof and water repellent clothing for wearer comfort - A paradigm shift*, In: Waterproof and Water Repellent Textiles and Clothing, Woodhead Publishing, 2018, 301–345, https://doi.org/10.1016/B978-0-08-101212-3.00011-3

[24] Kumar, A., Manshahia, M., *Investigation of the effects of different needle hole covering techniques on seam characteristics of waterproof breathable fabric*, In: International Journal of Clothing Science and Technology, 2024, 36, 5, 803–821, https://doi.org/10.1108/ijcst-02-2024-0035

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