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Typha Fluff as a Sustainable Thermal Filling Material: A Comparative Study with Down and Polyester Fibre

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Article

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ABSTRACT

To explore the feasibility of using Typha fluff as a filling material in textiles, this study conducted a systematic investigation of its performance as a sustainable alternative. Comparative tests were performed on Typha fluff, down, and polyester fibre—three commonly used filling materials—evaluating their fill power, compression resilience, thermal resistance, downproof performance, moisture regain, and antibacterial activity. The results indicate that although Typha fluff exhibits slightly lower fill power and thermal insulation than white duck down, it demonstrates notable advantages in resilience, downproof performance, antibacterial potential, and renewability. These combined merits highlight its potential as an eco-friendly thermal filling material. This work provides both a theoretical foundation and experimental evidence to support the green application of natural plant fibres in textiles.

KEYWORDS

Typha fluff, thermal insulation, fill power, sustainable material, textile filling material

INTRODUCTION

With the improvement of living standards and the growing awareness of sustainable consumption, consumers are increasingly considering not only thermal insulation and comfort when selecting textile filling materials, but also the ecological and renewable properties of these materials [1,2]. Although traditional white duck down filling exhibits excellent fill power and thermal resistance, its dependence on animal-derived resources presents limitations such as restricted supply, feather leakage, allergic reactions, and ethical concerns [3,4]. As a common alternative, polyester fibre offers high mechanical strength and dimensional stability, yet it is derived from non-renewable petrochemical resources and exhibits poor biodegradability, which hinders the transition of the textile industry toward sustainability [1].

In recent years, plant-based natural fibres have gained increasing attention as substitutes for conventional fillings due to their wide availability, low carbon footprint, renewability, and biodegradability. Among them, Typha spp. (cattail) has emerged as a promising candidate owing to its rapid growth, high fibre yield, favourable thermal properties, and environmental adaptability [5,6]. Its moisture absorption behaviour, thermal resistance, and dyeability are comparable to cotton, making it suitable for textile applications [3]. Moreover, studies have shown that Typha fibres can exhibit significant antibacterial activity when modified with silver nanoparticles or quaternary ammonium compounds [7]. Beyond individual fibres, Typha has also been explored as a bulk fluffy material. Rahman et al. [3] demonstrated that degummed Typha leaves and spongy core tissues can be processed into thermally efficient fluffy materials, with a moisture evaporation rate nearly twice that of down [8,9]. Xu et al. [10] confirmed that the porous structure of Typha fibres enables effective regulation of fluid penetration and evaporation, while Linjala et al. [11] reported that Typha improves the sound absorption properties of polyurethane composites, indicating its application potential in home textile products and eco-functional textile materials. Furthermore, Dieye et al. [12,13] developed low-thermal-conductivity, high-strength bio-based insulation boards by combining Typha with soil and natural binders, expanding its prospects in construction materials.

Internationally, pilot projects such as "Fluff Stuff" have commercialised Typha fluff as a sustainable textile filling material, showcasing competitive performance in terms of fill power, moisture evaporation rate, and environmental sustainability [8,9]. In addition, the low density, high elasticity, excellent compression resilience, and moisture-regulating structure of Typha fibres provide a strong physical basis for replacing down or polyester filling materials [5,6,14]. However, systematic comparative studies on the performance of Typha fluff remain scarce in China and abroad. In particular, there is a lack of quantitative comparisons with down and polyester fibre regarding fill power, compression resilience, thermal resistance, downproof performance, moisture absorption behaviour, and antibacterial activity [15,16].

In this context, the present study conducts a systematic evaluation of the core wearability properties of Typha fluff, white duck down, and polyester fibre. Through thermal and functional performance testing, we assess the feasibility of Typha fluff as a sustainable textile filling material and provide theoretical and experimental support for its substitutional application in clothing, home textile products, and eco-functional textile solutions.

TEST SAMPLES

This study selected three typical types of filling materials—Typha fluff, white duck down, and polyester fibre—as test subjects to explore the performance advantages and potential of Typha fluff in apparel filling applications.

The Typha fluff was harvested from mature inflorescences and retained in its natural state without any chemical pretreatment. Before testing, the samples underwent mechanical pretreatment only: manual separation to remove coarse bracts and debris, gentle carding and coarse sieving/air classification to eliminate dust and loosely attached particulates, followed by air-drying at 40 °C for 12 h and standard conditioning (20±2 °C, 65±4% RH for≥48 h). No chemical degreasing or alkali treatment was applied; therefore, the waxy surface layer was largely retained, and any ‘partial removal’ refers solely to incidental loss of loosely bound surface wax due to mechanical handling. The preparation process followed green treatment protocols commonly used in industrial production, ensuring the relevance and applicability of the test results.

The white duck down samples were sourced from high-quality commercial products with a down cluster content of≥90%, conforming to the Grade I standard of EN 12934:2025 White duck down-Composition labelling of processed feathers and down for use as sole filling material [17]. This type of down is widely used in mid- to high-end thermal garments and bedding due to its excellent fill power and thermal resistance, making it a representative high-performance filling material.

The polyester fibre samples consisted of commercial hollow-type polyester fibre incorporating a manufacturer-applied antimicrobial finish (e.g., silver-ion or quaternary-ammonium based). For reproducibility, the polyester fibre was purchased from a mainstream domestic supplier (Sinopec Yizheng Chemical Fibre Co., Ltd., Yizheng, Jiangsu, China) as a hollow-conjugated, siliconized polyester staple fibre (HCS, 7 denier×64 mm). No additional antimicrobial finishing was applied in our laboratory; only standardised drying and subsequent conditioning under the testing environment were performed to ensure consistency.

All three types of materials were prepared as two parallel samples according to the experimental design to ensure the repeatability and statistical reliability of the results. Before testing, all samples were conditioned in accordance with ISO standard requirements in a standard atmospheric environment (20±2 °C, 65±4% relative humidity (RH)) until constant weight or for no less than 48 hours, to guarantee uniform measurement conditions.

EXPERIMENTAL

To comprehensively evaluate the performance of Typha fluff as a clothing filling material, this study conducted systematic tests based on six key performance indicators, covering its thermal insulation, mechanical behaviour, moisture absorption, and functional properties. Comparative analyses were performed against white duck down and polyester fibre. All Typha fluff test specimens were prepared using the mechanical-only pretreatment described in TEST SAMPLES; no chemical degreasing or alkali steps were employed.

Fill Power

The fill power was measured following the Steam Conditioning Method specified by the International Down and Feather Bureau (IDFB) Fill Power Testing Method, IDFB Part 10-B:2020 [18]. After steam treatment, the samples were conditioned under standard atmospheric conditions (20 ± 2 °C, 65 ± 4% RH) for at least 48 hours. A 30 g (± 0.1 g) sample was placed in a standard measuring cylinder, and the natural loft height was recorded. The result was converted to fill power (in^3/oz) according to the IDFB conversion formula to assess the material's fluffiness and thermal insulation potential.

Compression Resilience

Compression resilience was evaluated in accordance with the International Organisation for Standardisation (ISO) 1856:2018, Flexible cellular polymeric materials — Determination of compression set [19]. A 20 cm×20 cm sample of the filling material was subjected to constant load under defined deformation conditions. The compression set was calculated based on the original thickness (H0) and the recovered thickness after unloading (H2), reflecting the material's ability to recover from long-term compression and indicating its structural durability.

Downproof Performance

The downproof performance was tested according to the International Down and Feather Bureau (IDFB) Annex B: Fabric Testing and Downproof Testing (IDFB Annex B:2013) [20]. The filling materials were sealed in standard test bags and tumbled in a box containing rubber balls for a specified number of cycles to simulate real-use compression and friction. The number of penetrated fibres per unit area (pcs/100 cm^2 or pcs/m^2) on the inner surface of the bag was recorded to assess the containment performance of the fabric and the potential for fibre leakage in final products.

Thermal Resistance

Thermal resistance was tested using the sweating guarded-hotplate method, following ISO 11092:2014, Textiles — Measurement of thermal and water-vapour resistance under steady-state conditions [21]. Standard filling pads were prepared from each material, and both the thermal resistance (expressed as clothing insulation (CLO) value) and thermal conductivity coefficient ($W/m^2 \cdot ℃$) were measured to quantify the static insulation capability of the materials.

Moisture Regain

Moisture regain was assessed for all filling materials in accordance with ASTM D2654-22, Standard Test Methods for Moisture in Textiles [22]. The mass difference before and after drying was used to calculate the moisture regain percentage, which reflects the material's moisture absorption behaviour and its impact on physiological comfort under varying humidity conditions.

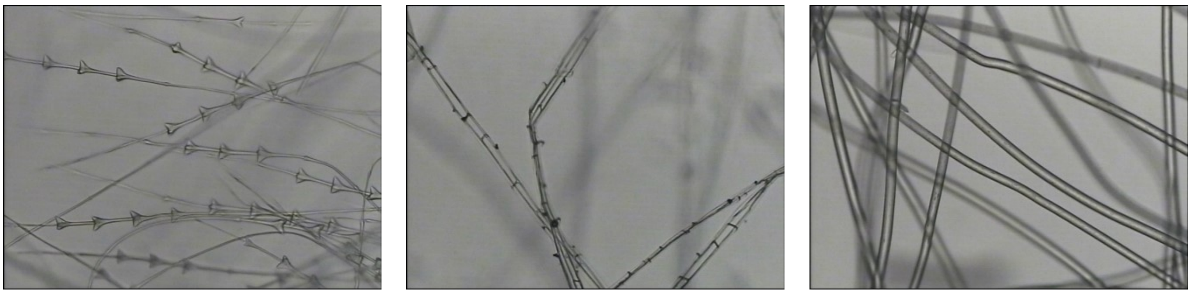
Antibacterial Activity

Antibacterial activity was evaluated based on ISO 20743:2021, Textiles — Determination of antibacterial activity of textile products, using the Shake Flask Method [23]. The test strains included *Escherichia coli*, *Staphylococcus aureus*, and *Candida albicans.* After shaking, incubation and colony counting, the inhibition rate was calculated to determine the materials' effectiveness in suppressing microbial growth and their potential in hygienic and functional textile applications.

EXPERIMENTAL RESULTS AND ANALYSIS

To aid interpretation of the subsequent results, representative longitudinal morphologies were acquired by a fibre fineness tester and compiled in Figure 1. The images visualise the branched/barbed network of white duck down, the nodal and irregular textures of Typha fluff, and the smoother cylindrical appearance with crimp for hollow polyester staples, thereby providing visual evidence for differences in loft, heat transfer, and downproof behaviour.

a) White duck down (200X) c) Typha fluff (200X) e) Polyester (200X)



b) White duck down (500X) d) Typha fluff (500X) f) Polyester (500X)

Figure 1. Longitudinal views captured by a fibre fineness tester for white duck down, Typha fluff, and polyester fibres

Note: As a scanning electron microscope (SEM) was not available during this study, cross-sectional and longitudinal SEM images could not be obtained. Instead, representative longitudinal views were acquired using a fibre fineness tester equipped with an imaging/projection module to provide direct morphological evidence for the comparative analysis.

As observed in Figure 1, white duck down forms a three-dimensional branched-barbule network with fine, crimped filaments that stabilise air pockets and provide structural support, consistent with its higher loft and thermal resistance (see Tables 1 and 5 / Figures 2, 3 and 6). Typha fluff exhibits nodal/“beaded” textures and irregular surfaces; although less branched than down, it can still build an air buffer, aligning with its low compression set and low effective leakage (microfibres≤2 mm excluded; see Tables 3–4). Hollow polyester staples appear smoother and more cylindrical, yielding lower inter-fibre friction and limited self-locking, which constrains loft retention and thermal resistance; however, their geometric uniformity and lack of barbs led to no observed penetrations in the downproof test, evidencing good containment integrity (Tables 3–4). These morphology-property relationships are consistent with the measured results.

Comparative Analysis of Fill Power Performance

Fill power is a key indicator of the volume expansion capability and thermal insulation performance of filling materials. It directly affects the material's ability to trap static air layers and resist heat transfer. In this study, the Steam Conditioning Method specified in the International Down and Feather Bureau (IDFB) Fill Power Testing Method [18] was used to evaluate and compare the fill power of three types of filling materials: white duck down, Typha fluff, and polyester fibre. The results are summarised in Table 1 and visualised in Figure 2 as mean ± SD (n = 3). The detailed trial results for each sample are available in the supplementary material.

Table 1. Comparative results of fill power for different filling materials

Filling Material	Sample ID	Test 1 (in^3/oz)	Test 2 (in^3/oz)	Test 3 (in^3/oz)	Average fill power (in^3/oz)	Filling material
White duck down	1#	645	650	650	649.6	1#
	2#	650	645	650	648.02	2#
Typha fluff	3#	285	290	290	288.49	3#
	4#	290	295	290	290.87	4#
Polyester fibre	5#	315	310	315	313.49	5#
	6#	315	315	315	313.49	6#

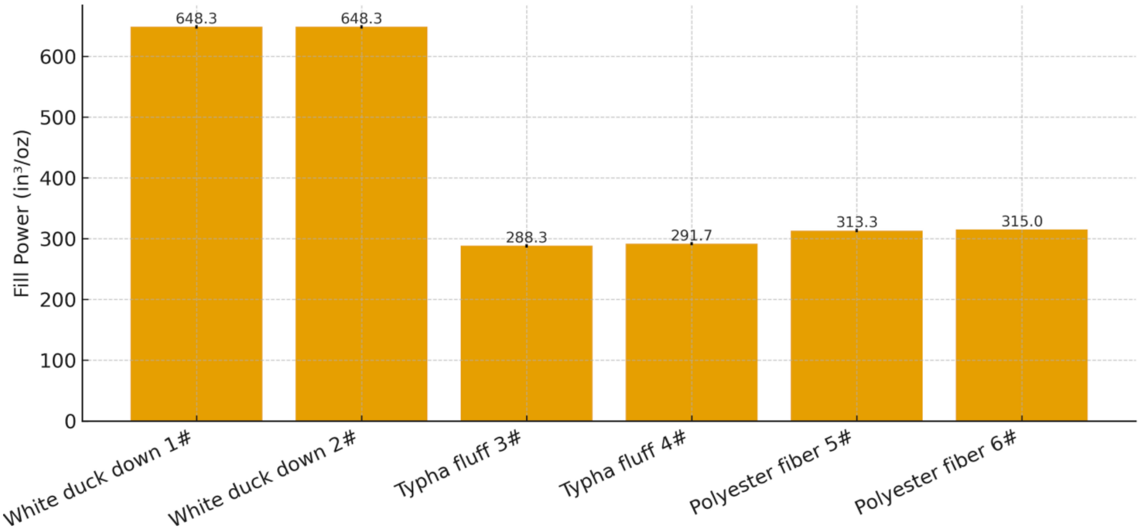


Figure 2. Fill power of different samples (mean ± SD, n=3)

a) White duck down b) Typha fluff c) Polyester fibre

Figure 3. Fill power test results

The test results indicate that the white duck down samples demonstrated significantly superior fill power compared to the other two materials. The average fill power, as calculated according to the IDFB method, was approximately 648.8 in^3/oz. In contrast, Typha fluff and polyester fibre showed lower fill powers of 289.7 in^3/oz and 313.5 in^3/oz, respectively. Although both alternatives exhibit inferior volume expansion capability, they are relatively close in performance and show potential for substitution under certain applications. Detailed data are provided in Table 1 and Figure 2.

The outstanding fill power of white duck down is primarily attributed to its intrinsic three-dimensional cluster structure with abundant branching. Microscopic observation reveals that down fibres interlock to form a stable and voluminous spatial network, enhancing their structural rigidity and ability to trap air. Each fibre possesses fine branching and curling features, enabling the formation of highly expanded structures with minimal mass, thereby trapping a greater volume of static air. Moreover, the down samples exhibited the lowest bulk density, indicating a higher content of microvoids and internal cavities. As the maturity and volume of the down clusters increase, this volumising effect becomes more pronounced and significantly enhances fill power.

In contrast, Typha fluff possesses a simpler fibre morphology with shorter length and fewer branches, which limits its spatial expansion capability. Additionally, its relatively higher density results in lower volume occupancy under the same weight, thereby reducing its fill power. Nevertheless, even without chemical modification or structural optimisation, Typha fluff achieved a fill power of approximately 289.7 in^3/oz (IDFB method) [18], which Under the IDFB Part 10-B steam-conditioning method, Typha fluff achieved a fill power of 289.7 in^3/oz. Together with a low compression set of 2.3% by ISO 1856:2018, low effective downproof leakage per IDFB Annex B:2013 because most observed penetrations were≤2 mm and excluded from counts, a basic but usable thermal insulation of CLO=2.59 by ISO 11092, and a moisture regain of 12.1% by ASTM D2654-22, these empirical results satisfy the essential functional requirements for fluffy fillings—namely loft, resilience, containment, and moisture/thermal comfort. We note that in its current unmodified state, Typha fluff does not meet ISO 20743 antibacterial classification (e.g., 63% against *E. coli*), which is optional for non-hygiene-critical applications.

Regarding polyester fibre, its uniform and compact structure—resulting from synthetic processing—limits its fill power. Although structural modifications (e.g., hollow or crimped designs) can increase internal air pockets, the total void volume is typically less than that of natural down. Additionally, the smooth surface of polyester fibres reduces inter-fibre rigidity, making it difficult to maintain loft, which further limits its ability to support bulk volume.

Therefore, from a fill power perspective, white duck down maintains a clear performance advantage. However, Typha fluff, despite its relatively lower performance, offers potential as a renewable, bio-based, and eco-friendly alternative. With further modification techniques, its fill power could be significantly improved, offering a promising direction for the development of sustainable thermal insulation materials.

COMPARATIVE ANALYSIS OF COMPRESSION RESILIENCE

Compression resilience refers to a filling material's ability to maintain its original thickness after long-term compression, directly affecting its durability, comfort, and loft retention during use. In this study, standardised tests were performed on white duck down, Typha fluff, and polyester fibre, following the procedures outlined in ISO 1856:2018 (Flexible cellular polymeric materials — Determination of compression set) [19]. The test evaluated the ratio between the recovered height and the original thickness after compression, expressed as the compression set (%), which serves as a measure of deformation recovery capability. The results are summarised in Table 2, and the corresponding material performance is illustrated in Figure 4.

Table 2. Comparative results of compression resilience for different filling materials

Filling material	Sample ID	Original thickness H0 (mm)	Recovered thickness H2 (mm)	Compression set (%)
White duck down	1#	70	67	4.3
	2#	69	67	2.9
Typha fluff	3#	43	42	2.3
	4#	43	42	2.3
Polyester fibre	5#	62	61	1.6
	6#	61	60	1.6

a) Initial thickness b) Compressed thickness c) Recovered thickness

Figure 4. Compression resilience test diagram

From the comparison of compression set values, polyester fibre exhibited the lowest residual deformation with an average of 1.6%, indicating the best deformation recovery and compression durability. As a typical synthetic fibre, polyester possesses a tightly packed polymer chain structure with good flexibility, enabling non-plastic deformation under pressure and rapid rebound upon release. From a macroscopic mechanical perspective, its high elastic modulus allows it to efficiently store mechanical energy during compression and release it quickly as rebound energy. Moreover, the smooth surface and low friction coefficient of polyester fibres reduce inter-fibre resistance and van der Waals forces, minimising internal dissipation and enhancing recovery efficiency.

The White duck down samples exhibited compression set values of 4.3% and 2.9%, indicating good resilience, though slightly inferior to polyester fibre. The natural three-dimensional branching structure and hollow morphology of down contribute to its ability to recover shape. However, factors such as fatigue of the filaments and internal friction may lead to fluctuations in recovery performance. Typha fluff exhibited a consistent compression set of 2.3%, slightly better than down. This favourable resilience is likely attributed to its soft, fine fibres with hollow structures and the absence of rigid break points, which support recovery after compression. However, due to its lower initial thickness, the available deformation space is limited, which slightly reduces its overall support capacity compared to the other materials.

Therefore, the ISO 1856:2018 test method clearly differentiates the compression durability among the materials. Polyester fibre, with the lowest permanent deformation, is suitable for applications involving frequent compression. White duck down, combining elasticity and thermal resistance, remains ideal for winter insulation. Although Typha fluff exhibits lower initial fill power, it demonstrates promising recovery characteristics as a bio-based material, making it a suitable option for eco-friendly home textiles and lightweight thermal insulation products.

Analysis of Downproof Performance

Downproof performance is a key indicator for evaluating whether a filling material tends to penetrate the fabric structure under external mechanical disturbances. It directly impacts product durability and wearer comfort. In this study, testing was conducted according to IDFB Annex B: Fabric Testing and Downproof Testing [20]. Samples of White duck down, Typha fluff, and polyester fibre were individually placed into standardised test bags, which were then tumbled in a test chamber containing a specified number of rubber balls. The process simulated dynamic agitation—including compression, friction, and vibration—that occurs during actual use.

Upon completion, the test bags were inspected, and penetrated fibres adhering to the inner fabric surface were collected and quantified by number per unit area (fibres/m^2). This value was used to evaluate the materials' tendency to breach the fabric barrier. The results are summarised in Table 3, with the testing procedure illustrated in Figure 5.

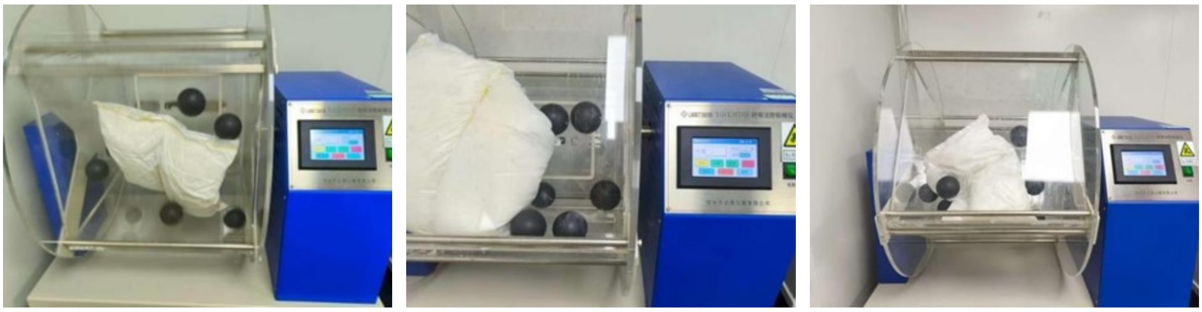
Table 3. Comparative downproof performance of different filling materials

Filling material	Sample ID	Number of penetrated fibres (fibres/m^2)	Average (fibres/m^2)
White duck down	1#	47	44
	2#	41	
Typha fluff	3#	34	30
	4#	26	
Polyester fibre	5#	0	0
	6#	0	

Table 4. Length category of penetrated fibres and IDFB counting rule (Downproof test)

Filling material	Observed penetrations (fibres/m²)*	Observed length category	Counted as effective leakage (IDFB Annex B:2013)
White duck down	44	N/A (length not specified)	Yes (penetrations counted per IDFB)
Typha fluff	30	≤ 2 mm (microfibres)	No (microfibres≤2 mm are excluded)
Polyester fibre	0	--	--

Note: Penetration counts correspond to Table 3. Microfibres≤2 mm are excluded from effective counts under IDFB Annex B:2013 criteria.



a) Specimen loading b) Tumble testing c) Fibre penetration evaluation

Figure 5. Downproof performance testing procedure

The results reveal that white duck down exhibited the highest number of penetrated fibres, averaging 44 fibres/m^2, significantly greater than that of Typha fluff (30 fibres/m^2) and polyester fibre (0 fibres/m^2). The fine, barbed, and branched filaments in down are prone to disruption by airflow and repeated rubber ball impact during tumbling, resulting in free fibres breaching the fabric surface [24]. The IDFB Annex B: Fabric Testing and Downproof Testing method strictly standardises bag construction, fill weight, and tumbling cycles [20], thus ensuring that the test accurately reflects the inherent downproof capacity of the material.

Although Typha fluff is also a natural fluffy material, its fibres are relatively short, smooth, and lack hook-like projections. While tumbling generates air turbulence that can cause minor fibre escape, most penetrations were ≤2 mm in length (see Table 4). According to IDFB Annex B: Fabric Testing and Downproof Testing criteria [20], such microfibres are classified as non-functional fibre leakage and are excluded from effective downproof counting. Consequently, Typha fluff demonstrates a comparatively low effective fibre leakage, highlighting its favourable downproof potential.

In contrast, polyester fibre showed no observable penetration. Its smooth, cylindrical fibres exhibit strong cohesion and elasticity, with no branching or barbs that would facilitate escape. Even under repetitive tumbling and impact, the fibres remained fully contained, demonstrating exceptional downproof performance. These structural advantages make polyester fibre well-suited for intensiveuse textile applications.

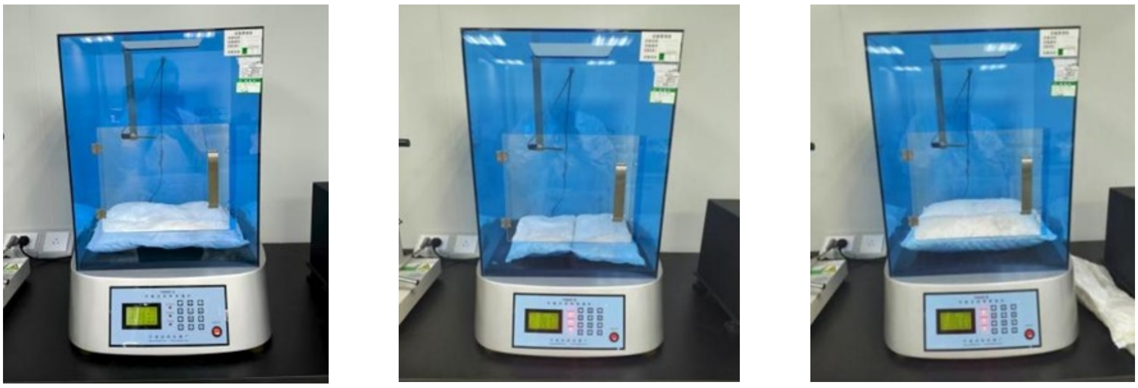
In conclusion, while white duck down offers superior thermal insulation, they are clearly disadvantaged in terms of downproof performance. Typha fluff, on the other hand, strikes a balance between loft and containment, offering a promising sustainable alternative in textile fillings. Polyester fibre, due to its structural uniformity and containment integrity, exhibits outstanding downproof properties, making it ideal for cost-effective and high-performance product design.

Thermal Insulation Performance Analysis

Thermal resistance is a core parameter for evaluating the heat retention capacity of filling materials, directly determining their suitability for applications in apparel and bedding products. In this study, thermal conductivity coefficient (W/m^2·℃), thermal insulation rate (%), and CLO value were measured using the sweating guarded-hotplate method, in accordance with ISO 11092:2014 [21]. The comparative results for white duck down, Typha fluff, and polyester fibre under standard environmental conditions are presented in Table 5, with experimental setups shown in Figure 6(a). Typha fluff, (b) Polyester fibre, and (c) White duck down.

Table 5. Comparative thermal insulation properties of different filling materials

Filling material	Sample ID	Thermal insulation Rate (%)	Thermal conductivity coefficient (W/m^2·℃)	CLO value
White duck down	1#	94.28	0.93	6.97
	2#	92.88	1.20	5.38
Typha fluff	3#	86.68	2.34	2.75
	4#	85.11	2.67	2.42
Polyester fibre	5#	87.74	2.13	3.02
	6#	88.25	2.03	3.17



a) Typha fluff thermal testing b) Polyester thermal testing c) Down feather thermal testing

Figure 6. Thermal Insulation testing setups (Source: by the authors) (a) Typha fluff; (b) Polyester fibre; (c) White duck down.

According to the data, white duck down exhibited the best overall thermal insulation performance, with an average CLO value of approximately 6.18, significantly outperforming Typha fluff (2.59) and polyester fibre (3.10). The superior heat retention of white duck down is primarily attributed to its unique hollow branched filament structure, which enables the entrapment of large volumes of static air to form a multilayer thermal barrier. Additionally, its high fill power and low material density allow more air to be stored within a given volume, greatly enhancing heat retention by impeding thermal conduction.

The average CLO value for Typha fluff was measured at 2.59. Although this value is lower than that of white duck down, it is comparable to polyester fibre, indicating a certain degree of thermal insulation capability. Its fibres, characterised by a naturally hollow and slightly crimped morphology, can form a basic air-buffering layer even without chemical modification, providing a modest level of thermal resistance. However, due to its relatively low fill power and irregular fibre orientation, the overall thermal efficiency remains limited.

Polyester fibre showed slightly better insulation than Typha fluff, with an average CLO value of 3.10. Its moderate thermal resistance and structural stability make it suitable for use in humid environments or everyday wear. Nevertheless, due to its high crystallinity and compact molecular structure, polyester fibre lacks internal resilience when compressed, resulting in a slower compression recovery rate. Prolonged use or frequent compression may reduce loft and, consequently, degrade its insulation capacity over time.

Therefore, white duck down continues to set the benchmark for high-performance thermal insulation materials, owing to its complex three-dimensional architecture and low-thermal-conductivity cavity system. Although Typha fluff demonstrates lower thermal performance, it surpasses that of many conventional plant-based fibres and exhibits promising potential as a sustainable alternative, especially when combined with modification techniques or composite processing. Polyester fibre, with its structural consistency and resilience under moist conditions, remains an effective option for cost-efficient, moisture-tolerant textile applications.

Moisture Regain Analysis

Moisture regain is a key parameter reflecting the moisture absorption behaviour of fibre-based materials under ambient humidity, directly affecting their wearability properties, breathability, and dimensional stability. In this study, tests were conducted in accordance with ASTM D2654-22 [22] using the oven-drying method to evaluate the moisture regain of white duck down, Typha fluff, and polyester fibre. The percentage change in mass before and after drying was used to quantify moisture regain. Results are summarised in Table 6.

Table 6. Comparative moisture regain results of different filling materials

Filling material	Sample ID	Pre-drying weight (g)	Post-drying weight (g)	Moisture regain (%)	Avg. moisture regain (%)
White duck down	1#	25.17	22.41	13.63	13.8
	2#	26.5	23.22	14.13	
	3#	25.52	22.36	13.60	
Typha fluff	4#	28.13	25.06	12.25	12.1
	5#	27.74	24.71	12.08	
	6#	27.48	24.48	11.97	
Polyester fibre	7#	25.11	25.03	0.32	0.35
	8#	28.17	28.08	0.36	
	9#	28.68	28.58	0.37	

Moisture regain directly influences thermal-moisture comfort, as materials with appropriate moisture absorption can buffer changes in humidity, reduce clamminess caused by perspiration, and enhance overall wear comfort. The test results reveal that white duck down exhibited the highest average moisture regain (13.8%), followed by Typha fluff (12.1%), while polyester fibre showed a significantly lower value of only 0.35%. As an animal-based protein fibre, down contains abundant hydrophilic functional groups such as amino (—NH2) and carboxyl (—COOH) groups within its keratin molecules, resulting in a strong affinity for moisture. In addition, its microstructure contains extensive amorphous regions that facilitate water molecule diffusion. According to Gao J et al., the crystallinity of duck down is approximately 40.5%, indicating the presence of numerous hydrophilic sites favourable for moisture absorption[25].

Typha fluff, a cellulose-based bio-based material derived from Typha spp., contains a high density of hydroxyl (—OH) groups in its monomeric units, endowing it with inherent hydrophilicity. Its crystallinity, around 39.6%, is comparable to that of down, which explains its considerable moisture regain under standardised test conditions. The average moisture regain of Typha fluff was only slightly lower than that of down, suggesting it is capable of effectively absorbing moisture from the air in dry environments, thus contributing to improved thermal-moisture comfort during use in arid seasons or air-conditioned spaces. However, its relatively high moisture absorption behaviour may lead to moisture saturation in highly humid environments, potentially compromising its dryness and comfort. Hence, material selection should be tailored to specific application scenarios.

In contrast, polyester fibre demonstrated the lowest moisture regain among the three materials, which can be attributed to its high crystallinity (typically exceeding 70%) and absence of hydrophilic functional groups in its molecular structure. This configuration significantly hinders water molecules from penetrating the fibre interior, limiting moisture retention to physical adsorption on the fibre surface. Even under different drying protocols defined in ASTM D2654-22 (e.g., hot air drying or vacuum drying), the test consistently yielded minimal moisture regain, confirming its intrinsically low hygroscopicity. While this characteristic enhances its dryness under humid conditions, it may negatively affect its breathability and physiological comfort in wear.

Therefore, both white duck down as well as Typha fluff exhibit favourable moisture regain properties, enhancing their suitability as textile filling materials with good thermal-moisture comfort. Although polyester fibre shows poor moisture absorption behaviour, it remains advantageous in scenarios that demand high dryness. The comparable moisture regain of Typha fluff to that of down underscores its practical potential as a sustainable alternative to animal-based filling materials.

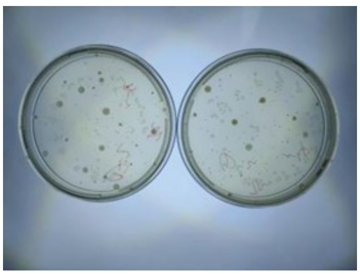
Antibacterial Activity Evaluation

With the growing demand for functional and hygienic textiles, the antibacterial activity of filling materials has become an increasingly important criterion in evaluating their application value. In this study, the antibacterial performance of White Duck Down, Typha fluff, and polyester fibre was assessed according to ISO 20743:2021 [23]. Three test strains representing typical microorganisms were selected: *Escherichia coli* (*E. coli*, Gram-negative), *Staphylococcus aureus* (*S. aureus*, Gram-positive), and *Candida albicans* (*C. albicans*, fungi). The shake flask method and colony counting method were used to determine the bacterial reduction rate of each material. The test results are summarised in Table 7, and the inhibition effect visuals are shown in Figure 7.

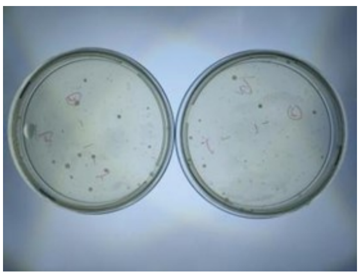
Table 7. Comparative antibacterial activity of different filling materials

Filling material	*E. coli* (EC)	*S. aureus* (SA)	*C. albicans* (CA)	Antibacterial determination
White duck down	93%	56%	94%	Not antibacterial
Typha fluff	63%	98%	89%	Not antibacterial
Polyester fibre	98%	96%	85%	Antibacterial

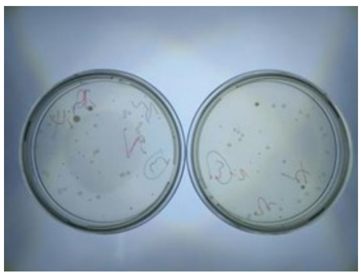
Note: Polyester fibre specimens were antimicrobial-finished per manufacturer specification; white duck down and Typha fluff received no antimicrobial finishing.



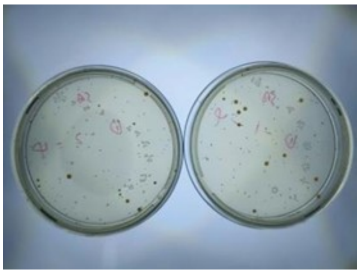
a) *E. coli*: White duck down



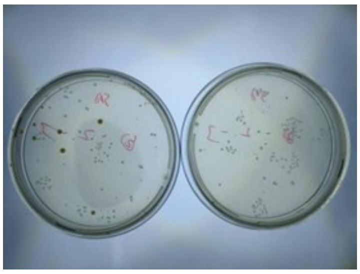
b) *E. coli:* Typha fluff



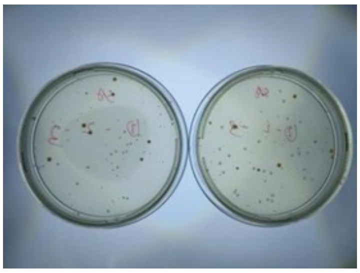
c) *E. coli*: Polyester fibre



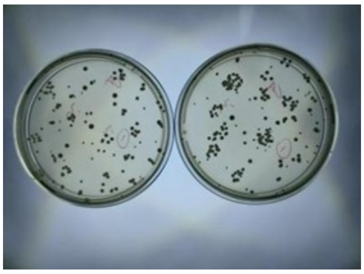
a) *S. aureus*: White duck down



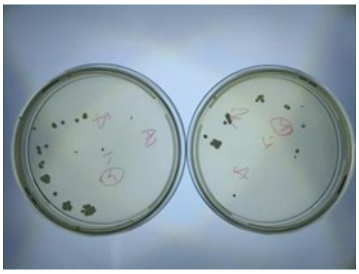
b) *S. aureus*: Typha fluff



c) *S. aureus*: Polyester fibre



a) *C. albicans*: White duck down



b) *C. albicans*: Typha fluff

c) *C. albicans*: Polyester fibre

Figure 7. Comparative antibacterial activity of different filling materials against three representative microorganisms (*E. coli*, *S. aureus*, *C. albicans*)

According to the determination criteria of ISO 20743:2021 [23], materials are considered antibacterial if they exhibit a≥70% inhibition rate against *E. coli* and *S. aureus*, or≥60% against *C. albicans.*

Among the three tested materials, polyester fibre demonstrated consistent and robust broad-spectrum antibacterial activity, with inhibition rates exceeding 85% against all tested strains. This meets the ISO antibacterial threshold and highlights its suitability for hygiene-critical applications. As specified in TEST SAMPLES, the polyester specimens used here already contained a manufacturer-applied antimicrobial finish, which accounts for the observed broad-spectrum inhibition. No antimicrobial finishing was applied to white duck down or Typha fluff in this study.

Typha fluff, as a bio-based material, exhibited excellent inhibition against *S. aureus* (98%) and *C. albicans* (89%), yet fell below the threshold for *E. coli* (63%). This organism-specific difference is consistent with cell-envelope architecture: as a Gram-negative bacterium, *E. coli* possesses an outer membrane rich in lipopolysaccharides (LPS) that limits diffusion and can diminish the activity or uptake of contact-active or leaching-type antimicrobial substances, whereas Gram-positive *S. aureus* lacks this barrier. In addition, natural phenolic/waxy constituents in Typha may interact more effectively with Gram-positive cell walls than with the LPS-containing outer membrane of Gram-negative cells, contributing to the lower inhibition observed for *E. coli*. As a result, it does not meet the standard for being classified as an antibacterial fibre. The underlying mechanisms are yet to be fully understood, but its antimicrobial potential is likely related to the presence of natural waxes, polyphenolic compounds, and its hollow structure, which may interfere with microbial colonisation or proliferation.

White duck down showed relatively high inhibition against *C. albicans* (94%) and *E. coli* (93%), but its performance against S. aureus was lower (56%), disqualifying it from meeting the ISO antibacterial threshold. This suggests partial antibacterial behaviour but insufficient consistency for functional classification.

Therefore, polyester fibre displayed the most reliable and effective antibacterial performance, making it suitable for medical textiles, infant products, and functional garments requiring enhanced hygiene. Typha fluff, though not meeting ISO classification standards, demonstrated promising antimicrobial potential—particularly as a natural plant-based fibre—which could be further enhanced through integration with natural antibacterial agents or surface functionalization. This reveals new prospects for the development of sustainable antibacterial textiles utilising bio-based materials.

CONCLUSION

Using harmonised IDFB/ISO/ASTM protocols, this study delivers a standardised, side-by-side evaluation of Typha fluff versus white duck down and polyester across six core wearability metrics, clarifying trade-offs and establishing an evidence-based basis for its sustainable application. The main findings are summarised as follows:

Fill power and thermal insulation: White duck down remains the benchmark for high-performance insulation materials, exhibiting an average fill power of 648.8 in^3/oz and a CLO value of 6.18. While Typha fluff shows lower fill power (~289.7 in^3/oz), it achieved an average CLO value of 2.59, outperforming most plant-based fibres and demonstrating a basic level of thermal insulation. Its performance could be further enhanced through structural modification.

Compression resilience: Polyester fibre showed the lowest compression set (1.6% on average), indicating superior shape recovery and structural stability. Typha fluff (2.3%) slightly outperformed down (2.9%–4.3%), suggesting promising elasticity under moderate compression and making it one of the most resilient bio-based filling materials studied.

Downproof performance: Polyester fibre exhibited no fibre leakage, indicating excellent structural integrity. Typha fluff showed an average leakage of 30 fibres/m^2, significantly better than 44 fibres/m^2 observed for down. According to the IDFB Annex B: Fabric Testing and Downproof Testing [20], Typha fluff demonstrated superior fabric penetration resistance due to its inherent fibre morphology.

Moisture regain: Down and Typha fluff recorded high moisture regain rates of 13.8% and 12.1%, respectively, offering inherent advantages in thermal-moisture comfort. These results were significantly better than the 0.35% observed for polyester fibre. As a cellulose-based natural material, Typha fluff exhibits moisture regulation capability comparable to animal-based fibres.

Antibacterial activity: Polyester fibre, treated with antimicrobial finishing agents, showed broad-spectrum antibacterial efficacy, with inhibition rates exceeding 85% for all three tested strains, meeting ISO 20743:2021 criteria [23]. Typha fluff showed strong antibacterial activity against *Candida albicans* (89%) and *Staphylococcus aureus* (98%), though its effect on *Escherichia coli* (63%) was less pronounced. These findings highlight the potential of plant-derived materials to exhibit selective antibacterial properties, which could be enhanced through functional finishing or surface modification. Therefore, although Typha fluff falls short of down in terms of fill power and thermal performance, it demonstrates competitive advantages in shape resilience, moisture absorption, antibacterial potential, and downproof behaviour. Combined with its natural renewability, biodegradability, and low carbon footprint, Typha fluff represents a strong, sustainable alternative to both down and synthetic fibres. Considering standardized outcomes—IDFB fill power (289.7 in^3/oz), ISO 1856:2018 compression set (2.3%), IDFB Annex B:2013 effective downproof performance (microfibres≤2 mm excluded), ISO 11092 thermal insulation (CLO=2.59), and ASTM D2654-22 moisture regain (12.1%)—Typha fluff meets the essential functional requirements for fluffy filling materials, while ISO 20743 antibacterial classification is not yet achieved without finishing and is application-dependent. To further close the gaps in fill power and to consolidate antibacterial performance, particularly against Gram-negative strains, future work should prioritise structure-preserving fibre modification to increase loft (e.g., controlled crimping or hollowization, mild swelling to reduce bulk density), eco-benign surface functionalization tailored to improve *E. coli* inhibition (e.g., silver-ion, quaternary-ammonium, or bio-polyphenol finishes), and composite processing with web-architecture optimisation (e.g., blending with hollow polyester or low-melt binder fibres) to enhance loft retention and downproof behaviour without sacrificing breathability. With further advancements in fibre modification, composite processing, and surface functionalization, its thermal-physical and functional performance could be significantly improved, enabling broader applications in apparel, home textiles, and eco-functional textiles, and contributing to the green and low-carbon transformation of the textile industry.

Author Contributions

Conceptualisation – Yang C, Zhang Y; Methodology – Yang C, Xiao N; Formal analysis – Zhang Y; Investigation – Xiao N, Xia H, Cheng B; Resources – Yang C; Writing–original draft preparation – Xiao N, Zhang Y; Writing, review and editing – Yang C; Visualisation – Xiao N; Supervision – Yang C. All authors (Xiao N, Zhang Y, Xia H, Cheng B, Zhang X, Yang C) have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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