

Therapeutic textiles: A promising approach for human skin dysbiosis?

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Abstract

The close interaction between skin and clothing has become an attractive cornerstone for the development of therapeutic textiles able to alleviate skin disorders, namely those correlated to microbiota dysregulation. Skin microbiota imbalance is known in several skin diseases, including atopic dermatitis (AD), psoriasis, seborrheic dermatitis, rosacea, acne and hidradenitis suppurative (HS). Such microbiota dysregulation is usually correlated with inflammation, discomfort and pruritus. Although conventional treatments, that is, the administration of steroids and antibiotics, have shown some efficacy in treating and alleviating these symptoms, there are still disadvantages that need to be overcome. These include their long-term usage with side effects negatively impacting resident microbiota members, antibiotic resistance and the elevated rate of recurrence. Remarkably, therapeutic textiles as a non-pharmacological measure have emerged as a promising strategy to treat, alleviate the symptoms and control the severity of many skin diseases. This systematic review showcases for the first time the effects of therapeutic textiles on patients with skin dysbiosis, focusing on efficacy, safety, adverse effects and antimicrobial, antioxidant and anti-inflammatory properties. The main inclusion criteria were clinical trials performed in patients with skin dysbiosis who received treatment involving the use of therapeutic textiles. Although there are promising outcomes regarding clinical parameters, safety and adverse effects, there is still a lack of information about the impact of therapeutic textiles on the skin microbiota of such patients. Intensive investigation and corroboration with clinical trials are needed to strengthen, define and drive the real benefit and the ideal biomedical application of therapeutic textiles.

KEYWORDS

clothing-based therapy, innovative skin therapies, non-pharmacological interventions, skin dysbiosis control, skin dysbiosis; therapeutic textiles

1 | INTRODUCTION

High microbial diversity is a key feature of healthy skin. Unquestionably, the symbiosis between skin and its microbiota members is an essential

mechanism to maintain a healthy skin, providing an efficient skin barrier and an active immune system while protecting against the overgrowth of pathogens.¹ However, an imbalance in the 'normal skin microbiota', a phenomenon known as skin dysbiosis, is associated with an increased

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growth of specific bacteria followed by a decline in microbial diversity. Such microbiota dysregulation is usually correlated with discomfort, irritation, pruritus, redness and inflammation, being commonly found in several skin diseases, namely atopic dermatitis (AD), psoriasis, seborrheic dermatitis, rosacea, acne and hidradenitis suppurative (HS).^{2,3} These conditions have a high worldwide incidence and a negative impact on the quality of life of millions of patients, costing billions per year due to treatments and healthcare utilisation.⁴

The current treatment for skin dysbiosis includes the following approaches: (i) topical therapy using corticosteroids, calcineurin inhibitors, antibiotics and emollients; (ii) phototherapy (e.g. controlled sessions of narrow-band ultraviolet B and medium-dose of ultraviolet A1) and (iii) systemic treatment with immunosuppressants and antibiotics.⁵ Although these approaches are occasionally effective in treating skin dysbiosis and in the alleviation of symptoms, the rate of disease recurrence is elevated throughout life.² Furthermore, the use of local and systemic administration of antibiotics negatively impacts the colonisation of skin microbiota members and increases antibiotic resistance.² For this, the management of skin dysbiosis has demanded integrated approaches able to decrease pruritus/irritation/discomfort and provide skin hydration, while controlling skin microbiota dysregulation and local inflammation.^{6,7}

In this sense, textile materials and clothing can play a pivotal role in the management of skin dysbiosis due to their close and prolonged contact with the skin. Of note, it is not surprising that patients have a preference for smooth clothing made with natural fabrics such as cotton, silk and flax. These fabrics have a positive influence on dysbiotic skin, being able to reduce itch and lesion severity and facilitating emollient absorption.⁸⁻¹⁰ Subsequently, the incorporation of bioactive agents into textiles, including synthetic, metallic or natural compounds, has emerged as a complementary/adjuvant strategy to modulate the skin microbiota and consequently treat, ameliorate the symptoms and control the severity of many cases of skin dysbiosis.^{3,7,11} Although several therapeutic textiles have been successfully developed, their clinical translation is still quite limited, and the available studies have shown controversial outcomes in the management of skin dysbiosis. Therefore, this updated systematic review aims to provide an overview of the efficacy of therapeutic textiles in patients with diagnosed skin dysbiosis. For that, clinical parameters, disease severity, symptoms, antimicrobial, antioxidant and anti-inflammatory properties, as well as safety and adverse effects, were also assessed. With this data, we aim to provide robust evidence able to emphasise the real impact of therapeutic textiles in patients with skin dysbiosis, clarifying the putative clinical relevance of such products and driving future research towards skin dysbiosis applications.

2 | METHODS AND ANALYSIS

In May 2023, a narrative review of the literature was conducted. Literature searches in electronic databases, including PubMed, Scopus, MEDLINE, Google Scholar, ResearchGate and [ClinicalTrials.gov](https://www.clinicaltrials.gov) were conducted. For the search, the following keywords were

used: skin dysbiosis treatment, therapeutic textiles, bioactive textiles, smart textiles, functional textiles, clothing therapy and therapeutic garments. The search was limited to articles in English, and they were selected depending on their relevance for this systematic review. Subsequently, each study was individually evaluated to determine whether it met the entry criteria.

2.1 | Population and eligibility criteria

The target population was patients diagnosed with any type of skin dysbiosis, namely AD, psoriasis, rosacea, acne and HS, that received treatment involving the use of therapeutic textiles. Criteria for inclusion or exclusion are summarised as follows:

2.1.1 | Inclusion criteria

- (i) Children and adults, both male and female.
- (ii) Patients with/without standard medication for skin dysbiosis.
- (iii) Randomised controlled clinical trials, observational studies and case reports.
- (iv) Studies in English published since 2003.

2.1.2 | Exclusion criteria

- (i) Editorials, commentary reports, abstracts and letters to the editors.
- (ii) Studies report only with in vitro evaluation of therapeutic textiles.
- (iii) Animal studies.
- (iv) Ongoing studies.

After selection, all the selected studies were fully scrutinized. Information regarding the following characteristics was extracted from each study: (i) composition of the therapeutic textile; (ii) aim of the study; (iii) design of the study and participants; (iv) intervention strategy; main results and (v) the reference of the study. All these data are summarised in [Tables 1-4](#). The Endnote software was used to manage citations obtained through the different database searches. However, it was not possible to perform a quantitative (statistical) analysis of the results due to the heterogeneity of methodological parameters between the studies.

3 | RESULTS

A total of 18 clinical studies that met the eligibility criteria were included in this review. [Figure 1](#) shows a flow chart of the study, from the initial screening to the selection of studies involving patients with skin dysbiosis. In this sense, 16 studies target AD, one acne and one HS. [Tables 1-4](#) summarise information on the selected studies.

TABLE 1 Characterisation of selected studies in which silk-based clothing were used by patients with skin dysbiosis.

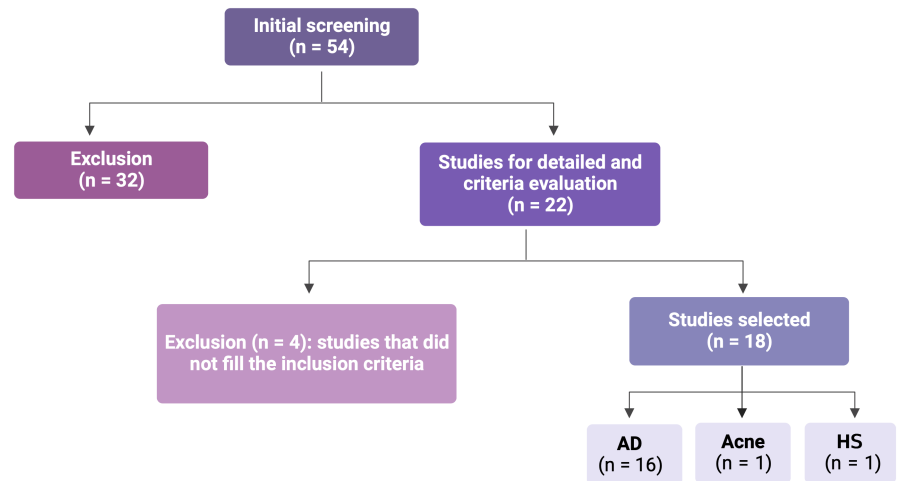
Silk-based clothing		Study design/Target population	Intervention	Main results	Reference
Composition of therapeutic textiles					
Pure silk clothing (under-clothes type, 100% silk; Danee Silk International Co., Ltd., Taiwan).		Observational study - 30 patients with AD (both children and adults).	All the patients received under-clothes and were instructed to wear it for the whole day during the observational period without any additional medication; The patients did not interrupt their medication routine (if any). Pre- and post-therapy to estimate the comprehensive effects of pure silk clothing intervention in all patients were assessed by research nurses following 0, 2, 4 and 8 weeks of trial.	<ul style="list-style-type: none"> The use of pure silk as a clothing-based therapy generated an appearance of good skin, increased the level of comfort and improved the quality of life of patients significantly during the management of AD symptoms. These findings demonstrated that this clothing can be used as an advisable non-pharmacological therapy for controlling the severity of AD, both in adults and children. 	10
Aim: To evaluate the possibilities of using pure silk clothing in the therapy for AD patients.					
Silk therapeutic garments (CLOTHES trial):		Randomised controlled trial - 300 children aged 1-15 years with moderate or severe AE	Participants were randomised to standard care or standard care plus 100% silk garments made from DermaSilk or DreamSkin. Three sets of garments were supplied per participant, to be worn for up to 6 months (day and night). At 6 months the standard care group received the garments to use for the remaining 2-month observational period.	<ul style="list-style-type: none"> Garments were worn for at least 50% of the time by 82% of participants. The CLOTHES trial found no evidence of clinical or economic benefit from use of silk clothing for the management of eczema. Skin infections occurred in 39 out of 141 (28%) and 36 out of 142 (25%) participants for standard care and silk clothing groups, respectively. Two of the patient-reported secondary outcomes suggested a small benefit favouring silk clothing, but these effects are unlikely to be clinically meaningful, as the effects were small and expectation in the benefits of the clothing was high, leading to potential bias detection. 	12
Aim: To assess the effectiveness and cost-effectiveness of silk garments for the management of atopic eczema (AE) in children with moderate to severe disease.					
Silk therapeutic garments (CLOTHES trial)		Exploratory qualitative study with convenience sampling, in-person focus groups and telephone interviews and a framework data analysis process.	18 children aged 5-15 years (included in the previous clinical trial).	<ul style="list-style-type: none"> For parents (28 mothers and 5 fathers): non-pharmacological interventions were very popular; Few parents were familiar with the silk garments. Parents reported limited improvement in skin condition although there was some symptomatic relief. For children: The conclusions from this nested qualitative study are that there was some limited improvement in eczema for some children but that hoped-for 'miracle cure' did not transpire. A mixed picture of knowledge, beliefs and experiences of using the silk garments emerged. 	14
Aim: To perform a qualitative evaluation of child participants' experiences of using silk garments for the treatment of AE.					

(Continues)

TABLE 1 (Continued)

Silk-based clothing	Study design/Target population	Intervention	Main results	Reference
Composition of therapeutic textiles				
Silk therapeutic garments (CLOTHES trial)	A parallel group, observer-blind, pragmatic, multi-centre randomised controlled trial of 6 months duration period.		<ul style="list-style-type: none"> The results were published in the study of reference 5. 	15
Aim: To test the hypothesis that 'silk therapeutic garments' plus 'standard eczema care' is superior to 'standard care alone' for children with moderate to severe eczema.				
1. A silk fabric (MICROAIR DermaSilk) coated with alkoxyisilane quaternary ammonium	16 children – 12 affected by AD with symmetric eczematous lesions on the antecubital areas and 4 without any cutaneous disease.	The children used, for 7 days, tubular arm covers made of this special silk fabric but only one of each pair was coated with AEGIS AEM 5572/5.	<ul style="list-style-type: none"> A significant improvement in the mean value of the 'local SCORAD' index was observed in both the covered areas compared to the values obtained at baseline. The reduction in the mean number of colony forming units of <i>S. aureus</i> per square centimetre was similar in both areas. Although this special silk fabric seems to be able to improve skin lesions in AD, the study was unable to demonstrate that such silk fabrics coated with AEGIS AEM 5572/5 have an antibacterial activity in vivo, as shown in vitro. 	13
2. The same formulation above coated with durable antimicrobial properties (AEGIS AEM 5572/5).				
Aim: To evaluate the effectiveness of the antimicrobial activity of a silk fabric (MICROAIR DermaSilk) coated with alkoxyisilane quaternary ammonium with durable antimicrobial properties (AEGIS AEM 5572/5) in children affected by AD.				
Silk textile with antimicrobial AEM5572/5 (Dermasilk)	A pilot study – 14 patients with acne vulgaris papulopustulosa on the back.	The patients wore the Dermasilk T-shirts every night for 6 weeks.	<ul style="list-style-type: none"> After 6 weeks, a significant reduction in acne lesions on the back of these patients was observed without any concomitant treatment or change in lifestyle and living conditions. These findings demonstrated the safe and effective use of silver-coated textiles in the management of acne vulgaris papulopustulosa. 	16
Aim: To evaluate the effects of Dermasilk T-shirts in the management of patients with acne vulgaris on the back and trunk.				

FIGURE 1 A representative flowchart: from the initial screening to the selection and characterisation of the studies included in the systematic review. AD: atopic dermatitis; HS: hidradenitis suppurativa.



The data from the tables was then used as a key tool to organise the results and to evaluate the effectiveness of therapeutic textiles. The studies included (male and female) participants between 0 and 80 years old, with no restriction on disease severity or medication use. According to the composition and the presence of active compounds, the studies were subdivided into the following groups:

- (i) Silk-based clothing (pure silk or silk fabrics with the incorporation of active compounds)^{10,12-16};
- (ii) metal as active compounds in the fabrics^{11,17-24};
- (iii) chitosan as an active compound in the fabrics^{23,25} and
- (iv) other compounds.²⁶

The intervention rates were 33, 3%, 50%, 11,1% and 5,5%, respectively for each group.

In this regard, five studies evaluated the effect of silk clothing with/without active compounds in patients (both children and adults) with diagnosed AD,^{10,12-15} and one pilot study explored the influence of DermaSilk T-shirts in adult patients with acne vulgaris on the back.¹⁶ Herein, most studies presented some kind of antimicrobial as a bioactive compound incorporated into the silk fabric (Table 1). The fabric with metals included eight fabrics with the incorporation of silver^{3,11,17-19,21-24} and another one with zinc²⁰ (Table 2). Likewise, the studies were performed on both children and adults/male and female. In the fabrics with metals, eight studies targeted AD and one silver-coated textile was used in a 14-year-old boy with HS exacerbations.³ Regarding the chitosan group, only two studies evaluated the clinical benefits of chitosan-coated textiles in patients with AD^{23,25} (Table 3). Lastly, one study evaluated the effect of anion textile garments in patients with AD²⁶ (Table 4).

3.1 | AD severity: SCORAD and EASI

Taking into consideration that 88.8% ($n = 16$) of the studies targeted AD, SCORAD or EASI were used as key tools to evaluate the severity of dermatitis under different periods of intervention with therapeutic textiles. In this sense, a significant improvement in the

mean value of the local SCORAD index in the covered areas was reported when compared to the values obtained at the baseline^{13,18,20} and when the use of silver-coated textiles was compared with placebo.^{11,17-19} Furthermore, Kim et al.²⁶ reported that in patients who wore anion (constructed from pure polyester filaments containing nano-sized fine-crusted tourmaline powder) textile garments, the mean SCORAD index decreased significantly from 47.2 ± 14.0 to 36.1 ± 16.5 ($p < 0.0001$) when compared to the baseline. In contrast, no statistical significance for SCORAD was observed for the group of chitosan-coated textiles versus the placebo group.²⁵ Likewise, no significant difference was observed between groups who wore anion textile garments and pure cotton textile garments (placebo).

Regarding the EASI score, one study reported no difference between the standard group and the interventional group using silk garments.¹² Besides the evaluation of SCORAD and EASI, one study evaluated the severity of AD through a dermatological questionnaire. In this case, at the 8th week of intervention with pure silk, a significant decrease in the disease severity was observed.

4 | SYMPTOMS

The main symptoms reported by patients with skin dysbiosis/disorders include pruritus, pain, irritation, discomfort, redness and difficulty sleeping. In this sense, three studies using silk fabrics with/without incorporation of active/antimicrobial compounds, six studies with metals and one anion textile reported that the use of such therapeutic textiles, in general, provide an improvement in symptoms in comparison to the baseline, that is, the pre-test evaluation time^{10,13,16,20,26} or when compared to control groups (placebo).^{3,11,18,21,26} Furthermore, Portela et al.¹⁹ reported a statistically relevant reduction of pruritus and irritation after only 7 days, correlated with the use of silver-seaweed-cotton fibres. Additionally, the use of boxer underwear made of silver-coated textiles (polyamide and elasthan) and worn at night for a couple of nights to treat HS exacerbations resulted in a significant reduction of both size and number of inflammatory papules and nodules in comparison to pre- and post-intervention period.³ However, the CLOTHES trial found no

TABLE 2 Characterisation of selected studies in which textiles incorporated with metals were used by patients with skin dysbiosis.

Metal as active compound in the fabrics		Study design/Target population	Intervention	Main results	Reference
Composition of therapeutic textiles					
Micromodal fibre, 13% Polyamide Ag and 7% lycra	Observational study – 30 Caucasian subjects (15 healthy subjects and 15 subjects with AD; 15 males and 15 females), with a mean age of respectively 41,9 and 26,5 years.	2 sleeves: one contained silver and the other one was a placebo were worn for 8h during the night on 5 consecutive days.	<ul style="list-style-type: none"> The percutaneous penetration and excretion of silver in urine revealed that dermal absorption of silver after wearing a garment containing 13% silver is low and do not cause any systemic effects. Dermal exposure to silver did not alter expression of inflammatory cytokines in the skin, indicating absence of a local pro-inflammatory effect between the silver- and placebo treated arm in both healthy volunteers and in AD patients. 	22	
Aim: To analyse the percutaneous penetration of silver and its inflammatory potential.					
Silver-loaded seaweed-based cellulosic fibre					
Randomised controlled trial – 37 adult patients (aged 20–82 years) with known AD and mild-to-moderate eczema.	The patients were randomly assigned to use either silver-loaded seaweed fibre T-shirts or cotton T-shirts for 8 weeks.	<ul style="list-style-type: none"> Clinical signs and physiological parameters showed a slightly positive effect but did only reach statistical significance for the silver group compared with cotton. The silver T-shirt-treated group showed antimicrobial activity against <i>S. aureus</i> without any negative effects on apathogenic bacteria. 	The results showed an excellent safety profile. Silver-loaded seaweed fibre T-shirt seems to be suited as bio-active textile in atopic dermatitis.	21	
Aim: To analyse the effects of wearing the textile on epidermal skin physiology of patients with AD.					
Silver-coated textiles					
An open-labelled controlled side-to-side comparative trial – 15 patients diagnosed as having generalized or localized AE.	Flexures of the elbows were covered with silver-coated textiles on one arm, and cotton on the other for 7 days followed by a 7-day control period.	<ul style="list-style-type: none"> Significant lower number of <i>S. aureus</i> was observed on the silver-coated textile site in comparison to cotton at the end of treatment as well as at the initial time point. Clinical improvement (local SCORAD) correlated with the reduction of <i>S. aureus</i> colonisation. A superior improvement achieved by silver-coated compared to cotton textiles paralleled a potent anti-<i>S. aureus</i> effect. 	17		
Aim: To investigate the influence of silver-coated textiles in patients with AE with special consideration of <i>S. aureus</i> colonisation.					

TABLE 2 (Continued)

Metal as active compound in the fabrics		Study design/Target population	Intervention	Main results	Reference
<p>Composition of therapeutic textiles</p> <p>Silver-coated textiles</p> <p>Aim: To evaluate the clinical effectiveness and safety of a special silver textile in the treatment of patients suffering from acute AD.</p>	<p>A randomised phase II monocenter parallel-group comparative study – 30 patients (average age 25.5 years, min. 4 years, max. 70 years).</p>	<p>From day 1 to day 14, 10 patients received a silver textile (Group 1), 10 a silver-free textile (Group 2) and 10 prednicarbate ointment (Group 3). In the second phase from day 15 to day 28 all patients wore the silver textile, and during the follow-up period from day 28 to day 56 no textiles were used. (Prednicarbate ointment was allowed as emergency medication).</p>	<ul style="list-style-type: none"> Phase 1: the SCORAD improved significantly in the patients of Groups 1 (74.6–29.9, $p=0.005$) and 3 (57.8–24.0, $p=0.009$). Phase 2: healing of eczema continued in Group 1 (SCORAD 29.9–18.1, $p=0.037$), was observed in Group 2 (48.2–24.1, $p=0.015$), and remained at an improved level in Group 3 (SCORAD 24–23.5). Consumption of prednicarbate ointment (Phase 1, Phase 2, follow-up period, medians are given): Group 1: 135 g, 10 g, 45 g; Group 2: 13 g, 0 g, 0 g; Group 3: 145 g, 30 g, 90 g. Silver textiles reduced the severity of the pruritus ($p=0.031$); silver-free textiles (n.s.) and prednicarbate (n.s.) were less effective. No undesired events were observed. 	11	
<p>Composition of therapeutic textiles</p> <p>Silver-coated textiles</p> <p>Aim: To investigate the clinical efficacy and functionality of silver-coated textiles in AE.</p>	<p>A multicentre, double-blind, placebo-controlled trial – 68 patients diagnosed with AE.</p>	<p>Patients were instructed to wear either silver-coated (verum, 35 patients +2 dropouts) or cotton garments (placebo, 22 patients +9 dropouts) directly on the skin for 2 weeks. Only basic skin care and ongoing therapy with topical steroids or oral antihistamines was permitted.</p>	<ul style="list-style-type: none"> In the verum group, eczema improved significantly after 1 week with further enhancement until the end of study ($p=0.03$ and $p<0.001$). Silver-coated textiles were comparable to cotton in comfort and functionality. Pruritus and self-assigned skin condition improved significantly more than with placebo ($p<0.001$ and $p=0.003$). Silver-coated textiles can improve the symptoms of AE significantly within 2 weeks, showing a good wearing comfort and functionality comparable to cotton. 	18	
<p>Composition of therapeutic textiles</p> <p>Silver-coated textiles</p> <p>Aim: To evaluate the effects of silver-coated textiles in the treatment of hidradenitis suppurativa (HS).</p>	<p>A case report with a 14-year-old boy diagnosed with HS.</p>	<p>The patient was instructed to wear boxer underwear for a couple of successive nights to treat HS exacerbations.</p>	<ul style="list-style-type: none"> Improvement of inflammatory lesions after the use of silver-coated textiles. The patient was highly satisfied with this convenient treatment and declined a systemic therapy. 	3	

(Continues)

TABLE 2 (Continued)

Metal as active compound in the fabrics		Study design/Target population	Intervention	Main results	Reference
Composition of therapeutic textiles					
Silver-seaweed-cotton fibres	A prospective, randomised and double-blinded controlled trial	The children were divided in two groups with similar demographic and clinical characteristics: control group (7 children) wore placebo clothing and the trial textile group (12 children) wore clothing with the textile in test.			
Aim: To evaluate the efficacy and safety of clothing made of cellulose fibres with seaweed enriched with silver ions in the treatment of children with AD.	- 19 children with diagnosis of AD.			<ul style="list-style-type: none"> The SCORAD index improvement in the group with the fibre under study was statistically significant after the first 7 days of treatment ($p < 0.001$) and was reduced by about 45% after 90 days. There was also a statistically relevant reduction of the intensity of pruritus and an improvement in the sleep quality after the initial 7 days and at day 90. The results showed that the textile clothing with seaweed enriched with silver ions brings a quicker improvement of the patients in the first days in opposition to the use of standard all-cotton clothes. The results also reinforce the importance of non-pharmacological measures, like clothing, in the management of patients with a diagnosis of AD. 	19
Silver-loaded cellulose fabric SkinDoctor®	Randomised controlled trial - 12 subjects with mild to moderate atopic dermatitis.	The patients wore a two-piece garment (top and leggings), each piece of which was divided into two parts: one side was made of SkinDoctor® fabric and the other of 100% cotton.			
Aim: To evaluate the clinical effectiveness and biophysical properties of a newly developed silver-loaded cellulose fabric with incorporated seaweed in patients with AD.				<ul style="list-style-type: none"> Treatment efficacy was measured with the modified SCORing Atopic Dermatitis (mSCORAD) index, transepidermal water loss (TEWL) and the patients' subjective impressions. All three of these measures had significantly better scores on the side covered with SkinDoctor. These results suggest that SkinDoctor is a beneficial fabric that can improve the comfort of patients with AD. 	24
Zinc oxide-functionalized textiles: Benevit Zink+ (Benevit Van Clewe, Dingden, Germany), which consists of 74% Lyocell fibre, 19% SmartCell sensitive fibre and 7% spandex.	In this uncontrolled pilot trial, adult patients with moderate to severe AD - 5 women and 7 men with a mean age of 60.6 ± 15.1 years (range 28-78 years).	Three days after individualized topical treatment with corticosteroids, calcineurin inhibitors or coal tar, the ZnO textile was used for overnight underclothes with trousers and long-sleeve shirts for three subsequent nights.			
Aim: To investigate the effects of zinc oxide- functionalized textile in patients with AD.				<ul style="list-style-type: none"> A rapid improvement of AD severity, pruritus and subjective sleep quality when AD patients wore the ZnO textiles overnight on 3 consecutive days. This findings were correlated with is the high antioxidative capacity of the ZnO textile, and its strong antibacterial activity. Very good biocompatibility and well tolerated by the patients. 	20

TABLE 3 Characterisation of selected studies in which textiles incorporated with chitosan were used by patients with skin dysbiosis.

Chitosan as active compound in the fabrics				
Composition of therapeutic textiles	Study design/Target population	Intervention	Main results	Reference
100% cotton coated with chitosan Aim: To evaluate the clinical utility of chitosan-coated garment use in AD.	Randomised controlled trial – 78 adults and adolescents with diagnosis of AD with age between 18 and 34 years.	The patients were randomly allocated to overnight use of chitosan-coated or uncoated cotton long-sleeved pyjamas (tops and pants) for 8 weeks.	<ul style="list-style-type: none"> The proportion of individuals with a clinically meaningful improvement in SCORAD was 67% in the chitosan group and 63% in the placebo group. No significant effect was observed either on daily pruritus or sleep loss scores. Chitosan-coated garments had no effect on the skin <i>S. aureus</i> counts, but had a significant increase in the coagulase negative staphylococci species. 	25
1. DermaCura® antimicrobial clothing (D&M): 98% TENCEL® C containing 1% chitosan and 2% elastane. 2. Binamed antimicrobial therapeutic clothing (BAP Medical): micro-modal lycra and woven silver filaments. Aim: To investigate the effectiveness of antibacterial therapeutic clothing (based on silver or chitosan) as compared to therapeutic without these agents on reducing AD severity.	Randomised controlled trial – 165 patients aged 0–80 years, diagnosed with moderate to severe AD.	The intervention groups received either DermaCura® antimicrobial clothing and Binamed antimicrobial therapeutic clothing while the control group received Binamed® therapeutic clothing without antimicrobial agents.	<ul style="list-style-type: none"> The results are not available yet. 	23

evidence of any clinical or economic benefit from the use of standard care or standard care plus silk garments made from DermaSilk or DreamSkin in the management of AD.^{12,14,15} In this case, only limited symptomatic relief of eczema was reported in both children and adults. Similarly, the use of chitosan-coated textiles did not show any significant effect on pruritus over time and in comparison to the placebo group²⁵

Furthermore, from the 18 selected therapeutic textiles, only four clinical studies evaluated the sleeping quality of patients. In these studies, better sleep was reported in only one study using pure silk as clothing-based therapy, namely after 2, 4 and 8 weeks of intervention.¹⁰ Intriguingly, no studies involving silk fabrics with the incorporation of any antimicrobial compound evaluated such parameter. Concerning the metal group, only one study using silver-seaweed-cotton fibres reported a significant improvement in sleep quality after 7 days of intervention,²³ and the use of another zinc oxide-functionalized textile resulted in better sleep quality after three consecutive days of evaluation.²⁰ On the contrary, no significant effect was observed on sleep loss scores for the chitosan-coated garment study²⁵

4.1 | Antimicrobial properties

In dysbiotic skin, noticeable differences in skin microbiota composition are reported when compared to healthy skin.²⁷ For instance, more than 90% of patients with AD are colonised with *Staphylococcus aureus*, whereas the percentage in healthy individuals is less than 10%.^{20,28} Besides, it is known that an over-infection of *S. aureus* plays an elevated impact on the course and intensity of AD, while a reduction in colonisation is usually correlated with a decrease in skin inflammation and an improvement of SCORAD index and symptoms.^{13,17,20}

Despite such importance, among the 18 selected studies, only six evaluated the antimicrobial activity of the therapeutic textiles.^{12,13,17,20,21,25} Within them, one study (CLOTHES trial) enrolled two different kinds of silk therapeutic garments (a 100% silk made from antimicrobial-protected knitted sericin-free silk (DermaSilk) and DreamSkin),¹² one study using a silk fabric (MICROAIR DermaSilk) coated with alkoxysilane quaternary ammonium and this same formulation coated with durable antimicrobial properties (AEGIS AEM5572/5),¹³ two studies with the incorporation of

TABLE 4 Characterisation of selected studies in which textiles incorporated with other active compounds were used by patients with skin dysbiosis.

Other active compounds in the fabrics	Study design/Target population	Intervention	Main results	Reference
<p>Composition of therapeutic textiles</p> <p>Anion textile constructed from pure polyester filaments containing nano-sized fine-crustrated tourmaline powder.</p> <p>Aim: to evaluate the effectiveness and safety of an anion textile in patients suffering from AD.</p>	<p>A prospective, randomised and placebo-controlled – 52 patients between 2 and 30 years with diagnosed AD.</p>	<p>The patients were divided into two groups: 25 patients in test and 19 control wore undergarments made of an anion textile or pure cotton, respectively, for 4 weeks.</p>	<ul style="list-style-type: none"> • A significant decrease in the SCORAD index was observed among the patients with AD in the test group (mean SCORAD decreased from 47.2 to 36.1). • Improvements in the mean transepidermal water loss, skin erythema and stratum corneum hydration were significantly greater among the patients with AD in the test group compared to the control group. 	26

silver,^{17,21} one zinc oxide-functionalized (ZnO) textile,²⁰ and one presenting chitosan as bioactive compound²⁵

The CLOTHES trial demonstrated a slight decrease in skin infection for the silk clothing group in comparison to the standard care group. Although this trial indicates that silk garments may possess some antimicrobial properties, there was no evidence suggesting a reduction in the number of skin infections correlated with *S. aureus* colonisation by those using Dermasilk or DreamSkin compared with children who received standard care alone.¹² However, both fabrics of MICROAIR DermaSilk coated with antimicrobial compounds tested in children demonstrated a reduction in the mean number of colony-forming units per squared centimetre in both skin areas covered.¹³ In this case, more specifically, microbiological cultures were positive for *S. aureus* in 5/12 children (42%) at baseline and in 3/10 children (30%) at the end of the study. However, no statistically significant difference for the use of silk fabric coated with the antibacterial agent AEGIS was observed. On the other hand, two studies incorporating silver showed a significant reduction in *S. aureus* colonisation^{17,21} at the initial time point control.¹⁷ Furthermore, no changes in non-pathogenic surface bacteria were found.²¹ Moreover, ZnO textiles showed strong antibacterial activity against both *S. aureus* and *Klebsiella pneumoniae*, yielding log reductions >7.0 and >8.0, respectively.²⁰ Although the authors correlate the antibacterial activity of the ZnO textiles with an improvement in clinical settings, such antibacterial property of ZnO textiles were only evaluated using in vitro assays. In this case, it was shown that the ZnO textile was able to inhibit bacterial growth after 24h of incubation. Regarding chitosan, there was a decrease in the percentage of patients with identification of *S. aureus* from 68% to 55% in the chitosan group in contrast with an increase in the placebo group (from 53% to 64%).²⁵ Despite not having statistical evidence regarding the use of chitosan-coated garments and uncoated garments, a significant increase in total staphylococci counts, corresponding mainly to coagulase-negative staphylococci, was reported. According to the authors, chitosan-coated textiles may impact disease severity by modulating skin microbiota members, namely the staphylococcal profile.

4.2 | Antioxidant and anti-inflammatory properties

Oxidative stress is a key feature in inflammatory skin conditions correlated with dysbiosis. In this scenario, the presence of reactive species, mainly reactive oxygen species (ROS), reactive nitrogen species (RNS) and reactive sulphur species (RSS), is elevated and may induce DNA damage and cell death.²⁹ Consequently, these effects negatively impact skin inflammation. The overproduction of ROS plays a crucial role in the pathogenesis of AD, psoriasis and vitiligo.³⁰ In this context, antioxidant and anti-inflammatory properties become essential parameters to be evaluated and incorporated into therapeutic textiles.

However, the capability of fabrics to scavenge ROS was evaluated only in two studies.^{20,21} Interestingly, Fluhr et al.²¹ demonstrated

a dose-dependent scavenging of induced ROS by silver-loaded seaweed-based cellulosic fibres. Likewise, ZnO textile exhibited a significant dose-dependent antioxidant capacity not only for ROS but also for RNS.²⁰ On the contrary, despite some studies that have demonstrated an improvement of inflammatory lesions after the use of therapeutic textiles,^{3,13,16} only one study showed that dermal exposure to silver did not alter the expression of inflammatory cytokines.²² However, this study was limited to the detection of interleukin 1 (IL-1), a pro-inflammatory cytokine, in the stratum corneum.

4.3 | Safety and adverse effects

In general, most studies have revealed a good safety profile of therapeutic textiles both in children and adults.^{11,13,21,22,25,26} However, the safety of such products can also be correlated with good biocompatibility and tolerability rate,^{10,13,16,20,25} no systemic absorption^{11,21,22} or any adverse and side effects^{10,11,22,25}

Taking systemic absorption into consideration, the percutaneous penetration of bioactive compounds from therapeutic textiles was evaluated only in three clinical trials involving the impregnation of silver.^{11,21,22} In this sense, blood parameters (GGT, ALAT, ASAT, Crea, WBC, RBC, Plt, Hb, MCV, MCH and MCHC) of all patients were regular and not affected during the period of study.¹¹ In addition, the excretion of silver in urine revealed that dermal absorption of silver after wearing a garment containing 13% silver is low and does not cause any systemic effects.²² Besides, no detectable release of silver ions was found in any in vitro or in vivo tests, including in serum analysis²¹

When reported, the main adverse effects related to the wearing of therapeutic textiles were pruritus and some irritability during the study period.²⁶ AD flare with no causal link was reported in one patient who wore chitosan-coated pyjamas.²⁵

5 | DISCUSSION

While the topical use of steroids and antimicrobials in patients with skin dysbiosis has become a significant health concern due to its prolonged usage and long-term side effects,²⁷ textile materials have gained particular interest as a non-pharmacological approach due to its direct contact and ability to induce specific changes in the skin microbiota with no side effects.²³ For instance, dermatologists and patients who suffer from skin dysbiosis have carefully chosen suitable fabrics and textile materials that increase comfort levels and well-being and improve patients' life quality.^{9,10} Despite these properties supported by certain fabrics, namely silk and cotton, adding bioactive compounds has emerged as a top priority towards therapeutic textiles.

In this sense, a range of therapeutic textiles, namely those with antimicrobial activity, have been developed.³¹⁻³⁶ However, most of them are still limited to in vitro evaluation, and only a small portion effectively translated to clinical trials. But when translated to clinical

studies, the macroscopic evaluation has received special consideration, while the microscopic effects have been poorly investigated.³⁷ Therefore, little is known about the impact of therapeutic textiles, that is, fabrics with the incorporation of bioactive compounds as antimicrobials, on the human skin microenvironment, namely on the skin microbiota of patients with skin dysbiosis.

Most of the studies involving therapeutic textiles included in this review focus on their effects on disease severity and in the alleviation of symptoms, aiming at providing a better quality of life for patients.^{3,10,11,13-20,24-26} Hereupon, despite some studies demonstrating that the use of therapeutic textiles, namely those with the incorporation of metals might add some benefits in disease severity and symptoms of AD^{11,17-20,24} and HS,³ the heterogeneous methods for textile design/development/composition and analysis have led to different outcomes and results. As a consequence, this heterogeneity hinders the understanding of their real performance, both in comparison to the baseline and to control groups.

Although skin dysbiosis presents multifactorial aetiologies, these conditions share some pathological similarities, namely *dysregulation of the skin microbiota*, characterised by specific bacterial overgrowth and (*chronic*) *inflammation*.³⁸ Therefore, for the control, treatment and management of skin dysbiosis, it is necessary to specifically target the skin microbiota imbalance and restore the commensal species. This property is considered a key feature to modulate the host inflammatory response and improve the symptoms of the disease by supporting a healthy skin environment.³⁹ Surprisingly, most studies did not evaluate the anti-microbial activity of the therapeutic textiles, particularly their impact on skin microbiota as well as their ability to modulate skin microbiota. While the overgrowth of *S. aureus* in AD-affected patients should be (deeply) investigated in this kind of study, only six studies evaluated such property. In this sense, the CLOTHES trial demonstrated a slight decrease in skin infection for the group using silk in comparison to the standard care group.¹² However, the antimicrobial potential of such fabric was not correlated with the colonisation by *S. aureus*. In contrast, one silk fabric coated with the antibacterial agent AEGIS (DermaSilk)¹³ and cotton coated with chitosan²⁵ demonstrated the ability to decrease the colonisation of *S. aureus* when compared to the baseline and placebo groups, respectively, for DermaSilk and chitosan-coated garments. Nevertheless, the differences were not statistically significant in both cases. In addition, fabrics impregnated with metals, namely silver, have demonstrated a better performance showing a significant reduction in the colonisation by *S. aureus* when compared to the placebo at the initial time point.^{17,21} Furthermore, the antimicrobial effect of ZnO textile against *S. aureus* was only demonstrated using in vitro assays through the contact of the textile with bacteria for 24h.²⁰ However, a valid evaluation of the antimicrobial effect on *S. aureus* infection in human skin was not performed. Together, these studies are not enough to determine the antimicrobial effect of such products on dysbiotic skin, particularly their impact on the reduction of *S. aureus* colonisation, in the case of AD.

Currently, it is known that the pathogenic effects of *S. aureus* on AD are correlated with the presence of superantigens, namely staphylococcal enterotoxin and toxic shock syndrome toxin-1, which activate basophils and cause T-cell-mediated inflammation.⁴⁰ Furthermore, staphylococcal modulins stimulate the release of pro-inflammatory cytokines from keratinocytes and other immune cells. While in this scenario the amount of ROS and pro-inflammatory factors is elevated, the majority of clinical trials did not evaluate the antioxidant and anti-inflammatory properties of those textile products. More specifically, only two such studies evaluated the antioxidant properties of fabrics impregnated with metals (silver and zinc) showing a dose-dependent antioxidant capacity of such products.^{20,21} Unfortunately, there is a lack of information about the anti-inflammatory potential of therapeutic textiles. Herein, only one study showed that dermal exposure to silver textiles does not alter the expression of inflammatory cytokines.²² However, this study was limited to the detection of IL-1, and there is no information about the presence of anti-inflammatory cytokines or the capacity of such products to modulate the host immune response towards an anti-inflammatory profile. Together, these results emphasise the need to explore such parameters in further clinical trials to clarify the antioxidant and anti-inflammatory potential of therapeutic textiles with the possibility to drive and increase their biomedical application scope.

The therapeutic textiles showed a good rate of safety with reduced side effects reported. Although the number of studies is still low to irrevocably conclude about the safety of therapeutic textiles when used by humans with skin dysbiosis, these results are promising and highlight the importance of performing more studies in such fields to inform the clinical practice.

From a macroscopic to microscopic point of view, more in-depth studies are necessary to explore and clarify (i) the influence of such textile products per phase of the disease (from an acute to a chronic state)/gender and age; (ii) how the clinical settings can be correlated with antimicrobial, antioxidant and anti-inflammatory properties of the therapeutic textiles; (iii) the real effect of such products in the skin microbiota and correlate specific changes per fabrics/bioactive compounds/ phase of the disease and (iv) the antioxidant and anti-inflammatory potential of such products as a strategy to reduce inflammation, modulate the host response and improve disease severity.

Additionally, another key point regarding the development of therapeutic textiles with antimicrobial activity to target skin dysbiosis is the composition of such products; unfortunately, most of them comprise synthetic or metallic antimicrobial agents, which, despite being very effective against a range of microorganisms and providing durable effects on textiles, are a concern due to health hazards, action on non-target microorganisms and environmental pollution.^{37,41} Consequently, the incorporation of natural bioactive compounds, such as fish oil, curcumin, chitosan, resveratrol and others, has emerged as safe alternatives due to their non-toxic, non-allergic and biodegradable nature combined with antimicrobial potential.^{32,42,43} Thus, the replacement by natural agents should be a

top priority during the design of therapeutic textiles providing innovative and sustainable products with antimicrobial, antioxidant and anti-inflammatory properties. Therefore, it is urgent to corroborate in vitro with in vivo assays to elucidate their clinical potential.

6 | CONCLUSION

This systematic review investigated, for the first time, the potential use of therapeutic textiles in patients with skin dysbiosis. Although such products have been thoroughly investigated in the pre-clinical and experimental literature, the translation of those studies into clinical practice is still limited and, in most cases, directed only at AD. Based on the reduced evidence that therapeutic textiles can be used as an advisable non-pharmacological therapy for controlling the severity of skin dysbiosis, deep characterisation of the effects, properties and standardization of evaluation of such products are crucial to determine how they contribute to symptom improvement while elucidating their real clinical applications. Therefore, further clinical trials prioritising therapeutic textiles incorporating natural bioactive compounds are imperative to further scientific knowledge and insight in this area.

AUTHOR CONTRIBUTIONS

CSO contributed with conceptualization, literature investigation, writing-original draft, writing-review and editing. FKT contributed with design, writing-review, editing and validation. All authors read and approved the submitted version.

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CONFLICT OF INTEREST STATEMENT

None.

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

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