FLAX-LINEN & HEMP
TEX AND TECH

The impact of Flax-Linen on sleep quality: A textile performance study

by CETELOR Laboratory - University of Lorraine
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Alliance for European
Flax-Linen & Hemp

The impact of Flax-Linen on sleep quality

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1 The impact of Flax-Linen on sleep quality: Key Facts

European Flax-Linen and sleep quality, the perfect partner for peaceful nights.

Flax-Linen has a privileged place in the world of sleep thanks to the comfort properties of its natural fibers.

CETELOR – The French Technology platform dedicated to Textile has produced a literature review of the body of scientific works on sleep quality and textiles.

The aim is to highlight the main textile parameters that impact sleep quality and to compare them wih the performance of Flax-Linen.

Flax-Linen, with its well-proven comfort properties, reaffirms the impact of Flax-Linen textiles on sleep quality from both bed linens and sleepwear.

The textile parameters such humidity, temperature and air flow clearly make Linen as a strong contender for one of the wisest choices for bed linens. The different studies and tests clearly show that 100% Flax-Linen fabrics help regulate sleep patterns, especially in warmer climates.

Thermal environment and humidity are the most important factors impacting sleep quality.

When it comes to sleep quality, indoor climate has a great effect on human thermal regulation.

There are optimal levels of humidity and temperature that help body regulation to work properly, and if the conditions deviate from them **sleep is disrupted.**

The best quality of sleep is achieved when the thermoneutral temperature (temperature and humidity at which the body doesn't need to self-regulate to maintain at its normal temperature), when the conditions are neither **too warm, too cold, nor too humid**[1].

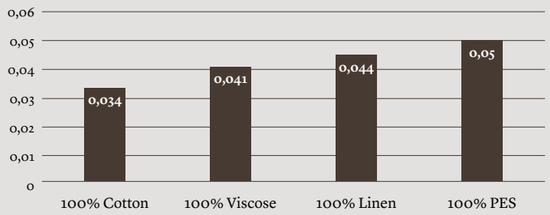
Thermal comfort is a complex sub-parameter, framed by a several values: thermal resistance of course, but also **air permeability, water vapour permeability and moisture management.**

Perspiration is indeed the main mechanism for regulating the body temperature, which helps expel excess heat out of the organism. If this perspiration remains trapped between the skin and the textile, the natural thermoregulation stops.

1. Flax-Linen maintains thermoneutrality for the human body with medium thermal resistance.

100% Flax-Linen ranks second in thermal resistance, which means that **it keeps a certain percentage of heat but is not fully insulating, helping the body to reach or maintain thermoneutrality.**

Taken together with its other parameters, Flax-Linen is a good option for **a restful sleep,** helping people cool off in warm climates but trapping enough heat in cooler climates.



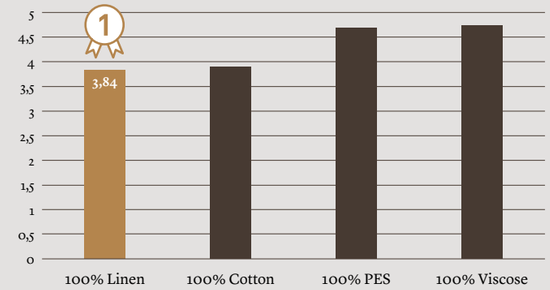
Insulation/Thermal Resistance Rct-m2 k/W
Skin Model ISO 11092 standard

2. Flax-Linen moisture management allows for natural body thermoregulation during sleeping – creating a dry and cool sleeping environnement.

Flax-Linen, with its strong moisture management properties, allows for the circulation between indoor air, the microclimate under the bed linens, and the body[2]. These moisture management properties are measured using 3 parameters, reflected in 3 tests:

A. FLAX-LINEN BREATHABILITY ALLOWS FOR THE NATURAL BODY THERMOREGULATION DURING SLEEPING

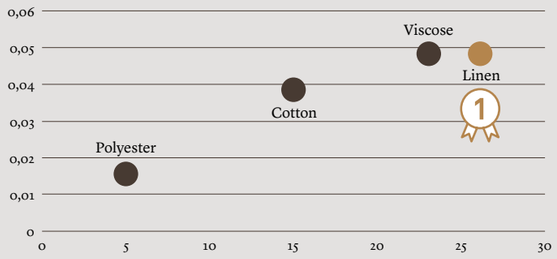
100% Flax-Linen textiles show the best breathability (permeability to water vapour), meaning they let perspiration pass through and favour **the natural thermoregulation of the body,** ensuring a **dry and temperate climate** between the skin and the fabric during **all stages of sleep.**



Permeability to water vapour
Water-vapour resistance Ret-m²Pa/W Skin Model ISO 11092 standard

B. FLAX-LINEN ABSORPTION OF LIQUID WATER KEEPS THE SKIN AND THE SLEEPING ENVIRONEMENT DRY AND THEN IMPROVES THERMOREGULATION

100% Flax-Linen absorbs the liquid instantly and diffuses it over a large surface area, there by promoting **better wicking. 100% Flax-Linen fabrics prevent moisture from accumulating** between the skin and the fabric during all **stages of sleep.**



Behaviour of dry fabrics with respect to water
- mm row and column - NF G07-165

C. MOISTURE MANAGEMENT TEST

100% Flax-Linen and 100% Viscose exhibited the best moisture management in the study = class 5 = medium to rapid wetting & absorption, rapid diffusion over a large diffusion surface. **100% Flax-Linen fabrics prevent moisture from accumulating between the skin and the fabric during all stages of sleep.**

Moisture Management Tester
classification scale 1 to 6 - AATCC 195 standard

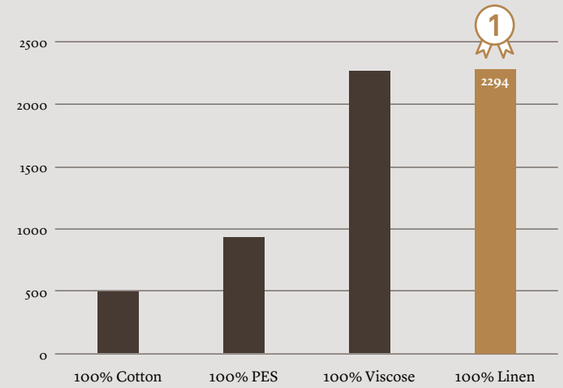
3. Flax-Linen air permeability improves sleep quality in warm and humid climates.

Slow airflow is more beneficial for the thermoregulation than still air, even with bed covers as it helps draw away perspiration.

The higher the air permeability of the bedsheet in a warm humid climates, the better the quality of sleep[3].

Flax-Linen, with its higher air permeability and breathability than cotton, viscose, and polyester, **allows for such exchanges between indoor air, the microclimate under the bed linens, and body.**

Flax-Linen fabrics are good candidate for bed linens and sleepwear as they will help dry away from the body.



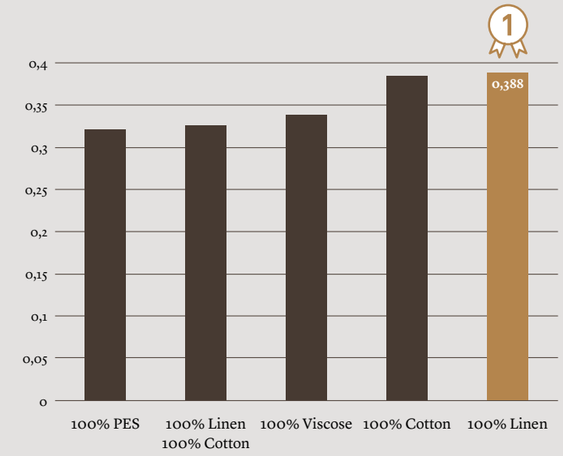
Permeability to air/thickness - mm/s - NF EN ISO 9237 (1995)

4. Global comfort index: Flax-Linen is the most comfortable textile for sleeping.

The IMT Comfort Index is a ratio between insulation (RCT) and breathability and is used to rank fabrics that are most comfortable for sleeping.

This index generates a single, general comfort value , reflecting or how comfortable a fabric would be under normal circumstances.

Here, **100% Flax-Linen ranks first,** which makes sense as it ranked first in RET value and second in RET value. It means that whether the fabric is **used for night clothing or bedsheets, Flax-Linen will be advantageous and usually the best choice[3].**



IMT water vapour permeability index / Confort index

Conclusion

Top sleep quality is achieved at the thermoneutral temperature (the temperature and humidity at which the body doesn't need to self-regulate to maintain its normal temperature), when conditions are neither too warm, too cold, nor too humid[1].

Flax-Linen is an excellent partner for sleep quality thanks to its thermoregulation, moisture management and ventilation properties.

"Of course, it depends on the individual, but various studies and tests clearly show that 100% Flax-Linen fabrics help regulate sleep patterns, especially in warmer climates."

1. Zhang, N., Cao, B., Zhu, Y., 2019. Effects of pre-sleep thermal environment on human thermal state and sleep quality. Building and Environment 148, 600–608.
2. Canelle Vibert Clement – CETELOR – 2021 – The impact of the properties of Flax on sleep
3. Tsuzuki et al, 2008 – Effects of airflow on body temperature state a,d sleep stages in a warm and humid climate

2 Quality of sleep and Flax-Linen properties: Literature review and analysis

a. Quality of sleep and textile parameters: a scientific literature review - CETELOR

INTRODUCTION

In the context of today's fast paced lifestyle and current events, including the pandemic-, people have been finding it harder and harder to sleep (Baghera et al). But sleep quality is necessary in maintaining a healthy lifestyle, as it has impacts on nearly every aspect of life: energy levels, physical and mental performances, concentration, memory, mood regulation, irritability, even hormone regulation (Pilcher et al)... Poor sleep quality can be harmful for anyone; now, more than ever, it is crucial for us to get the best sleep we can get.

Some factors impacting sleep quality are obvious: noise, light, temperature, the general sleeping environment, and personal habits/lifestyle; and many of these factors have been thoroughly tested. However, an often - overlooked part of sleep quality is the products that we use - the mattress, but also the bedding.

Nowadays, the most common materials used for bedsheets are cotton, polyester, or a blend the two. Both are widely available materials with clear advantages: strength for polyester fibers, and comfort for cotton fibers. But other materials are available, most of them being natural fibers: silk, wool, Flax-Linen, etc...

On the other side of the market, there is increasing tension when it comes to synthetic materials, especially ones made from petrol. While their usefulness no longer needs proving, the resources used to make them are finite and diminishing every day. Other sources of material are already being developed, but they need to be used and promoted even more in order to replace non-renewable materials. Local sourcing is also being encouraged, as it helps reduce the cost of transport.

This article is meant to review the major factors affecting sleep quality and link them to the composition of the bedding, especially bedsheets.

THERMAL ENVIRONMENT AND HUMIDITY /AIR PERMEABILITY

The thermal environment is one of the most cited and studied factors impacting sleep quality, especially inwarmer climates. In 1988, Libert et al studied the duration of each sleep phase under particular temperature and humidity conditions and found that *''Compared with the 5 nights of the baseline period at 20°C, sleep patterns showed disturbances at 35°C. Total sleep time was significantly reduced, while the amount of wakefulness increased. The subjects exhibited fragmented sleep patterns. The mean duration of REM episodes was shorter at 35°C than at 20°C of Ta (thermoneutral temperature, i.e. the temperature and humidity where the body doesn't need to self-regulate to maintain its normal temperature), while the REM cycle length shortened.''*

	29/50	29/75	35/50	35/75	
	Total duration of (min)				
Sleep onset	11.5 ± 5.8	11.9 ± 8.3	11.8 ± 10.2	13.3 ± 9.9	
Stage W	32.5 ± 13.4	52.1 ± 41.1	76.8 ± 54.3	123.5 ± 52.5	ab
Stage[1]	33.9 ± 8.0	34.5 ± 10.8	49.3 ± 16.4	64.4 ± 25.0	
Stage[2]	207.2 ± 17.2	204.6 ± 27.0	181.0 ± 47.3	172.9 ± 50.8	
Stage[3]	41.1 ± 9.6	32.7 ± 10.7	34.9 ± 17.8	16.7 ± 9.6	ac
Stage[4]	40.8 ± 15.5	36.4 ± 16.6	26.8 ± 10.3	21.8 ± 16.0	
SWS	81.9 ± 18.1	73.4 ± 15.6	61.7 ± 27.3	38.5 ± 20.3	ab
REM	105.5 ± 18.2	89.0 ± 31.1	96.0 ± 16.0	63.6 ± 11.6	ac
MT[1]	2.6 ± 1.3	0.9 ± 1.0	2.9 ± 3.7	1.4 ± 1.5	
TST[2]	428.7 ± 17.3	415.7 ± 46.5	388.1 ± 56.9	339.5 ± 51.3	
EMA[3]	5.6 ± 8.7	0.0 ± 0.0	0.5 ± 0.9	3.1 ± 4.8	
SEI%[4]	92.6 ± 2.6	88.7 ± 8.7	82.9 ± 11.4	73.1 ± 11.0	ab

1) moving time, 2) early morning awake, 3) total sleep time, 4) sleep efficiency index: SEI=TST/Time in bed. a=differs from 29/50, b=differs from 29/75, c=differs from 35/50 by at least P < 0.05 by post-hoc test (Fisher's PLSD)

Table 1: Sleep parameters under four conditions (from Shaikh et al)

In addition, Back et al and Karacan et al found that Sleep deprived people usually are more restless during sleep at 35°C than at 20°C. Real world results concur with lab results: Xu et al conducted a field study showing that higher air temperatures lead to poorer sleep quality. On the other side, Song et al showed that heating is necessary when sleeping in cold environments.

In addition, Back et al and Karacan et al found that sleep-deprived people are usually more restless during sleep at 35°C than at 20°C. Real-world results concur with lab results: Xu et al conducted a field study showing that higher air temperatures lead to poorer sleep quality. Conversely, Song et al showed that heating is necessary when sleeping in cold environments. Other researchers have studied each sleep stage in relation to the ambient temperature, and Ngarambe et al found that each sleep stage has its own peak temperature. Zimniewska et al found that *''The results of tests showed that clothing made from polyester fabric was a reason of changes in muscle electromyograph (EMG) records of the wearers, which indicated occurrence of desynchronization of motor units. The clothes made of fabrics composed of polyester and Linen fibers higher than 25% did not cause desynchronization of motor units in healthy muscles while providing the wearer with optimal comfort of using.''* The authors cited a higher core temperature as a probable cause.

Other studies have been conducted, and while some have varying results (for instance, Xia et al noted in 2020 that the elderly benefit more from a slightly warmer environment due to thermoregulation issues ; Park and Lee also found that when people sleep better, their skin temperature is slightly higher than someone who had a bad night in terms of comfort ; and Zhang et al found that a slightly higher pre sleep thermal environment can promote sleeping), the general consensus is that having a slightly cooler environment helps more with sleep duration and fragmentation more than a warmer environment. But the best sleep can be achieved when the conditions are neither too warm nor cold, and not too humid, either – In short, when the thermoneutral temperature is reached. Parmeggiani et al, along with nearly all the other scientists cited above, found that if sleep is disrupted without external factors, it's mainly due to the thermoregulatory response of the body. If the ambient conditions are too far outside the body's thermal neutral zone, the sleep's delicate balance of sleep will be disturbed:

> "But the best sleep can be achieved when the conditions are neither too warm nor cold, and not too humid, either"

"In conclusion, the experimental data show that sleep time peaks at thermoneutrality, wherever the placement of thermoneutrality may be in the temperature continuum, depending on the species and the adaptation. Sleep time declines above and below the thermoneutrality range as a function of ambient temperature. The rate of decline is smaller on decreasing than on increasing ambient temperature"

In addition, Dongmei et al found that bedding plays a major role in thermal comfort, since it sets the temperature and humidity at which the body will feel most comfortable, depending on which bedding is used (or not used). Shaikh et al found that a cool bed linen helps people feel as comfortable in warmer temperature as they would be in a cooler environment without this cool bed linen.

Shin, M. along with several researchers in the University of Sydney also studied the effect on sleepwear and bedding at several temperatures, and found that wool reduces the sleep onset latency (i.e. the time it takes for one to fall asleep) in cooler environments. This effect was even more pronounced among older people, who tends to have more trouble maintaining a satisfactory body temperature.

Thermal conditions are thus quite crucial to sleep quality, but temperature isn't the only factor affecting the thermal environment: air humidity also plays a major role in ensuring comfort.

Okamoto-Mizuno et al found that higher temperatures have a greater effect on sleep dysregulation when they are accompanied by high humidity (which may be linked to perspiration). High humidity is also not ideal for a good night's sleep.

> "As such, a fabric able to dissipate moisture and keep the body as its thermoneutral temperature would greatly help achieve these comfort parameters in beddings."

Fabric	Surface mass g/m²	Fabrics hygroscopicity (%)		Resistance Ω	Heat Resistance Km²/W
		65% RH	100% RH		
100% Linen	152.3	7.0	16.2	5.5 * 109	12.2
100% Cotton	141.4	6.4	15.1	1.2 * 109	10.6
100% PES	138.6	0.3	1.5	1 * 1012	7.5

Table 2: Properties of different fabric (From Zimniewska et al)

As such, a fabric able to dissipate moisture and keep the body as its thermoneutral temperature would greatly help achieve these comfort parameters in beddings.

Several papers analyze Flax and other fibers in relation to these properties.

First, Zimniewska et Kozłowski, 2004, studied some common thermal properties of Flax-Linen, Cotton and polyester (PES) together:

Table 2 shows that PES isn't hygroscopic like cotton or Flax-Linen – it's moisture content does not change depending on its surrounding temperature and air humidity. Its resistance is also higher, meaning that the current flows less easily through it. But it's heat resistance is lower, meaning that it tends to dissipate heat more quickly.

In 2006, Skomra et al studied the comfort of athletic wear depending on their moisture capabilities: *''Regarding comfort, for air permeability results, Polyester/Flax fabric is superior to all other fabric blends. In addition, Cotton/Flax has better air permeability than Cotton fabric.*

Regarding comfort, for wicking results, Polyester has the quickest wicking rate, followed by Polyester/Cotton. Regarding comfort, for wicking results, Polyester has the quickest wicking rate, followed by Polyester/Cotton Cotton/Flax has the highest absorptive capacity followed by Polyester/Flax. Cotton/Polyester has the lowest absorptive capacity.''

In short, natural fibers have better air permeability, likely due to their morphological appearance: natural fibers are not perfectly smooth like synthetic fibers, which means that they let air go through, but also traps some of it inside of their hollow core (see figure 1). This results in a fiber that is more permeable to air but also more comfortable adding Flax seems to have better air permeability compared with cotton.

When it comes to wicking and absorptive capacity, polyester draws moisture away nearly instantly, but since its absorptive capacity is very low, it becomes saturated very quickly, which would result in a very uncomfortable moist/wet feeling against the skin. Natural fibers take slightly more time to remove the excess moisture from the skin, but they are able to store more due to their cellulosic nature, which is hydrophilic.

Of course, since synthetic fibers are man-made, their porosity/density/appearance can be modified, and Kaleem et al found in 2021 some novel modified PET textiles with better air permeability and air transmission than cotton. But those textiles are still novel and not readily available on the market. And as they say in their paper, *"To achieve satisfactory thermal comfort, a textile must display a shorter moisture absorption time and higher rate of moisture transmission through the textile from wetted skin to*

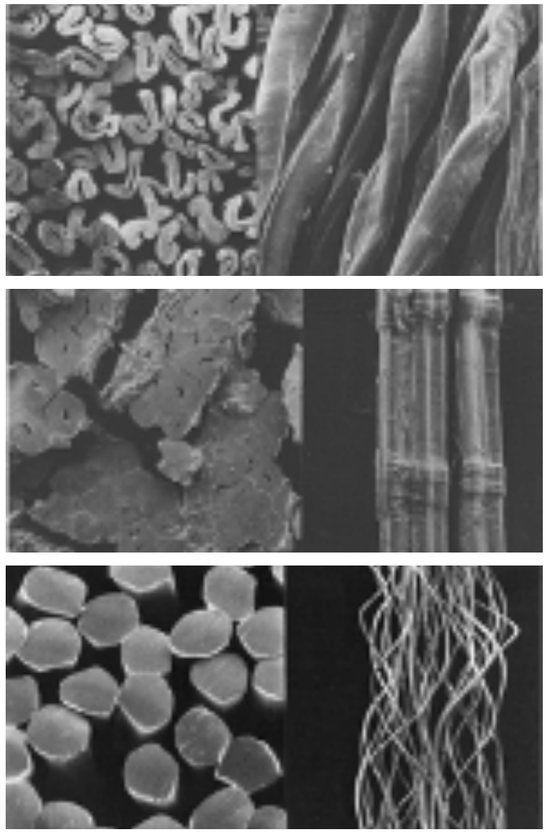


Figure 1 - Longitudinal and cross-sections of cotton (left), Linen (middle), and polyester (right), from ISO/TR 11827 standard

the atmosphere." Thus, currently, it's more likely to find regular PET textiles in beddings, which have lower thermal comfort, and which makes people sweat much more than cotton due to their inherent hydrophilic and hydrophobic natures (according to Ha et al).

Taken together with higher permeability, and since both air and moisture have an impact on human temperature, natural fibers - and especially Flax - make for a good thermoregulating fabric, and prevent sweating, which is essential to a good sleep quality.

The CELC, with the help of CETELOR, published a study in 2014 about the comfort level of several textiles, and Linen came first in nearly every category.

HANDFEEL/COMFORT AND SLEEP

While thermal comfort is the most studied parameter for sleep quality, general, non-thermal related comfort also plays an important role.

Indeed, it is widely reported that people with chronic pain and discomfort have more trouble sleeping than healthy people, and when those pains were alleviated, sleep quality improved (ex Taylan, S et al, who reported a significant increase of sleep quality in patients after a surgery that affected their nose and breathing).

Some papers have also studied the importance of mattresses, pillows (Gordon), and even earplugs (Röddiger et al) with respect to sleep quality, and all of them had and significant effect on sleep quality, whether positive for mattresses deemed as comfortable, or negative when it came to bulky, stiff plastic earplugs. With this, in mind, it seems that handfeel is important when it comes to sleep quality.

Handfeel, or handle, is the way a fabric feels under the hand, and since it is a mostly subjective parameter, it is trickier. Trying to find a fabric with the "best handfeel" for all circumstances is irrelevant, as everyone has their own preferences. Plus, as Barker and al found, different items of clothing serve different purposes and as such, people won't judge them in the same way. Civille and Dus attempted to characterize specific characteristics in 1990.

More recently, Ahirwar and al studied in 2020 the link between sleep, handfeel and fiber composition. They found that fiber composition is the most common criterion for choosing bedsheets (just via handfeel), over aesthetics or other physical characteristics.

Properties	Ranking	Weightage (Wi)
Fiber	1	42.8
Color	2	15.1
Smell	3	15.7
Feel	4	27.9
Design	5	10.2
Print	6	8.4
Compressibility	7	6.2
Luster	8	3.6
Drape	9	4.7
Stretchability	10	6.0
Wrinkle	11	8.6

Table 3 : Weight distribution and ranking of bed linen properties, according to a panel of 53 person

In parallel, they also modeled a Bed Linen Sleep Quality index, which includes handfeel, moisture management, air permeability, thermal resistance, etc, and rated several fabrics on these characteristics, as seen in table 4. They made a subjective quality index (made by individuals), an objective one (made by a panel of experts), and a computational one (following equations).

Fabric samples	Subjective BLSQI
100% Cotton	2.9
Viscose-cotton	1.8
Modal-cotton	4.6
100% Modal	4.5
Poly-Modal	4.0
Poly-Modal-Linen	3.5
100% Excel	2.0

Fiber mix	Objective BLSQI
100% cotton	3.04
100% PET	1.80
100% excel	2.64
100% modal	2.67
70/30 Modal/cotton	3.13
55/45 Cotton viscose	3.06
100% Excel	2.0

Table 4 : Subjective and objective bed linen quality index made of different fibers

To summarize their research, subjective handfeel seems like a good parameter to judge bedsheets and how they will perform during sleep, and while Flax-Linen is not in the study, natural fibers seem to have a better ranking than synthetic ones.

To summarize their research, subjective handfeel seems like a good parameter to judge bedsheets and how they will perform during sleep, and while Flax-Linen is not included in the study, natural fibers seem to rank higher than synthetic ones.

B. K. Behera et al also used the Kawabata hand, developed in the nineties, which places several factors into groups. They found that Flax-Linen can be made with a lower thread density due to its higher tensile resilience, which makes it more breathable. It's also a heavier fabric, which tends to give it a better handle. But it's also a tougher, fabric that bends less and creases very easily, lowering the handle. In this regard, there are many ways to interpreted handle value but Flax-Linen seems to have one of the highest ones at low weights and following proper preparation of the fiber.

Indeed, Meng et al found that while handfeel varies among people due to cultural variations, Flax-Linen often seems to be given preference over synthetic fabrics.

This is not to say that other fibers don't have a good handfeel, or that this is an absolute quality. Shin et al found that at lower temperatures, other fibers like wool seems better for comfort. But Flax-Linen is quite high on the list of fabrics, and as such should be taken into consideration when choosing bedsheets.

ANTISTATIC PROPERTIES

Antistatic properties are widely studied, but their effects on human biology are still not fully known.

Electric fields, or EF, are a natural occurring phenomenon that can be found anywhere, and whose intensity can vary with the weather. Static charges can also be generated via friction with textiles.

The international commission on non-ionizing radiation protection stated that *"Static electric fields do not penetrate the human body because of its high conductivity. The electric field induces a surface electric charge, which, if sufficiently large, may be perceived through its interaction with body hair and through other phenomena such as spark discharges (micro shocks). The perception threshold in people depends on various factors and can range between 10 - 45 kV/m. Furthermore, very high electric fields, such as from HVDC lines, can charge particles in the air, including polluted particles. There was a hypothesis that charged particles might be better absorbed by the lung than uncharged ones and so, raise people's exposure to air pollution. Current knowledge, however, suggests that an increased health risk from such charging of particles is very unlikely."*

Petri et al also studied in 2017 the effect of static fields on biology. They stated: *"The weight of the evidence from the literature reviewed did not indicate that static EF have adverse biological effects in humans or animals. The evidence strongly supported the role of superficial sensory stimulation of hair and skin as the basis for perception of the field, as well as reported indirect behavioral and physiological responses."*

With this information in mind, it seems that static electricity on the human body has no impact on health. However, everyone can feel static electricity through body hair with a high enough intensity– and static fabrics tends to stick to the skin due to their electrical charges. These statics charges thus have a significant impact on comfort – which, as stated earlier, does affect sleep quality.

Zimniewska et al, on the other hand, studied the static properties of both Flax-Linen and polyester: *"In the case of the Flax-Linen shirt, the level of electrostatic field potential difference was very low, close to 0 in both static (no exercise) and dynamic conditions (after 10 throws of the arms). The tests of the polyester shirt showed that electrostatic charges are accumulated on the shirt surface when worn in static conditions (no exercise). The electrostatic potential difference increases considerably in dynamic conditions (after 10 throws of the arms)".* And as seen in table 2, PES has a higher electric resistance, which could explain why it gets charged more easily.

Wool also seems to generate more static electricity, as Cerovic et al found. But the dielectric properties of fabrics are also greatly affected by humidity – dry air seems to make the detection threshold lower.

It then seems like natural, plant based fibers are a good option for their antistatic properties.

ANTIFUNGAL/ANTIMICROBIAL /HYPOALLERGENICITY

While the biggest factors have already been discussed, there is still the issue of the impact of micro organisms and allergies on sleep quality, as well as allergies.

When it comes to microbes, bacteria, and fungal agents, their link with sleep quality appears to be a vicious cycle. Illness caused by these agents tend to decrease sleep quality (Drake et al, Tamm et al), and in return, degraded sleep quality tends to lower immune barriers (Majde et al).

One of the more studied diseases affecting sleep is atopic dermatitis (AD), or eczema, as it is a common disorder that affects many aspects of life, including sleep. Chang et al wrote in 2018: "Sleep disturbance is often viewed as one of the symptoms of AD and one of the measures of disease severity. [...] Sleep disturbance is reported in 47% to 80% of children with AD and in 33% to 87.1% of adults with AD." And as with microorganisms, sleep disorders can worsen AD. Edelman, a communication firm, even worked with doctors to build the world's most uncomfortable bed to help people not affected by this disease to better understand it. Ramirez et al found that around 50% of AD children have a worse sleep than non-AD ones, and depending on the severity, from 30 to more than 90% of adults suffering from dermatitis reported difficulties in sleeping.

Atopic dermatitis and allergies often go hand in hand but even then allergies on their own can be problematic. Allergies can be caused by pretty much anything, including microorganisms (Crameri et al). In the case of skin allergies, one common symptom a rash, an irritation of the skin. In this case, and like with AD, comfort and sleep quality are significantly altered.

Since fabrics remain in contact with the skin nearly every hour of the day, it's no surprise that studies put a focus on fabric composition in relation to these disorders, as textile have even been known to cause dermatitis (Mobolaji-Lawal et al). Reaction can vary (Fenton et al) depending on the fabric and person, the reactions can vary (Fenton et al).

Usually, smooth, soft fabrics are recommended for skin issues, which also do not retain moisture. In this regard, cotton and silk are usually recommended, and rough wool, coarse fabrics, and synthetic fibers are to be avoided. In the case of Linen, it would then need to be fine, thoroughly lignin-free fabric, as it tends to make fabric rougher. As chemicals can exacerbate skin problems, the use of dye-free fabric is recommended. Of course, the choice of fabric varies from one person to another. Ricci et al found that wool can be a minor irritant for people with already sensitive skin, but other sources cite fine wool as a good option. In addition, many novel textiles, including silk, were tested to see if they help reduce symptoms, including silk (Kurtz et al, Gauger et al, Hung et al).

On the other hand, many, if not most sites states that Linen is hypoallergenic. But as of today, there are no official guidelines for identifying a fabric as "hypoallergenic". How can this be explained?

Flax is a natural fiber (made of cellulose) that requires very little irrigation and chemicals during its growth, and none during its harvesting/yarn making (unlike cotton, for which uses magnesium salts are used during harvesting). Some products are still used, these can usually be washed out very easily. Linen has also been tested in medicine and is recommended for skin sensitive patients with sensitive skin, as they usually display no signs of allergy while wearing it.

Tests show that chemicals are more likely to result in allergies than plant-based materials. Therefore when it comes to allergens, they are more often caused ancillary products than the material itself. This means than an undyed Linen fabrics can indeed be considered hypoallergenic. However, a heavily dyed bedsheet is more likely to cause problems in the future, as it contains more chemicals that are in contact with the skin for long stretches of time.

In 1995, Gainsford identified some antifungal agents in the Flax roots, and usually, the Flax plant as a whole has some antibacterial and antifungal properties (Zimniewska et al).

But the molecules responsible for this behavior are mostly phenolic compounds and lignin, found in the roots and leaves. The fibers barely contain any, as Tian et al noted. Phenolic compounds are washed away by the treatment, and lignin is responsible for the fiber's stiffness, so it's eliminated to the extent possible for a maximally smooth feel. As such, the fiber has a very limited antifungal and antimicrobial activity. Some papers did find a slight resistance of the fiber to these issues (Chun et al, 2002; Qamar et al, 2015), but it was so minor that it is very unlikely to have a significant antifungal effect.

However, it doesn't mean that bedsheets will become moldy. If stored in normal conditions, they should not be affected by mold.

Moreover, Zimniewska et al identified antioxidants properties of Linen fabric. The compounds found in it are often associated with treatments for skin sensitivity. As with other compounds, they are only contained in small amounts, so Flax-Linen fabric won't cure any skin disease on its own, but it could be recommended in certain cases.

CONCLUSION

When it comes to sleep, thermal comfort seems to be the most influential parameter but also a complex one, since it depends not only on the climate the bed is in, but also on the individual. The best quality of sleep is achieved at a the thermoneutral temperature, when the conditions are neither too warm, too cold, nor too humid[1]. Thermal comfort is a complex sub-parameter, framed by a several values: thermal resistance, of course, but also air permeability, water vapor permeability and moisture management.

Non-thermal comfort (or handfeel) is also an important parameter, that comes into play when people purchase bed linen. Softness seems to be the most important parameter parameter determining a comfortable handfeel for bedsheets.

As of today, there is no direct link between sleep quality and static electricity fields, neither with antifungal & antimicrobial properties.

GLOSSARY

PES: Polyester

REM sleep: Rapid eye movement, or paradoxical sleep. It's the moment when people dream. Their body isn't moving but breathing, cardiac rhythm and core temperature change slightly.

Ta: Thermoneutral temperature

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b. The impact of the properties of Flax on sleep
CETELOR, 2022

INTRODUCTION

Sleep quality is a complex subject, in which many parameters can modify a person's sleep patterns in various ways. These can range from external parameters, such as temperature or humidity, to internal ones, like stress or general lifestyle, and even inherent parameters, such as health conditions, age, gender, etc. Additionally, populations may have different preferences depending on where they live and how they have been raised.

Some of these parameters can be hard to evaluate, and some simply cannot be changed (i.e. the inherent parameters). But the majority of external parameters can be measured and monitored, and links can be drawn between them and sleep quality can be drawn. For example, air temperature, humidity, etc.

Another important set of parameters that must be included in sleep quality studies is the fabrics one sleeps in. As they are in direct contact with the body for hours at a time, it is very important to understand their characteristics are, and how they impact the human body and subsequently, the sleep quality.

In 2014, the CELC (now the Alliance for European Flax-Linen & Hemp), the European agro-industrial organization specializing in all stages of Flax-Linen and Hemp production - partnered with the CETELOR Laboratory, a Lorraine textile center, to test different textiles on several crucial points: air permeability, breathability, absorption, moisture management, and balanced warmth and heat retention. These are the most frequently used parameters in the study of textiles in terms of comfort.

The result of these tests, displayed in the "Comfort Study: How Linen Performs" article, highlighted the fact that Flax-Linen nearly always came out on top, ranking higher than other natural fibers such as cotton, and artificial fibers.

In late 2021, a literature review on fabrics properties and comfort also emphasized the importance of fabric properties – and therefore their composition – when it comes to bedsheets and clothing.

The purpose of this article is to draw a more direct link between sleep quality and fabrics composition, using literature and the previous findings.

HIGHLIGHTS

When it comes to sleep quality, indoor climate has a great effect on human thermal regulation. There is an optimal climate in terms of humidity and temperature to maintain for the body regulation to work properly, and if conditions deviate from it, sleep is disrupted.

These optimal conditions vary depending on how covered one is.

In addition, a slow airflow is more beneficial for the thermoregulation than still air, even with bed covers.

Flax-Linen, with its higher air permeability and breathability than cotton, viscose, and polyester, allows for such exchanges between indoor the air, microclimate under the bed linens, and the body.

Flax-Linen also ranks second in Rct, which means that it retains a certain percentage of heat but is not fully insulating. With this and all the other values in mind, Flax-Linen is then a good option for a restful sleep, allowing for a cool feeling in warm climates, but still suitable for mid-range climates.

There is less information on the effect of mild cold exposure on human sleep, and none involving a comparison with linens. As such, the impact of Linen bedsheets in cool environments cannot be discussed in details at this moment.

Bed linen composition doesn't seem to have an impact on sleep when it comes to static electricity exposure, except perhaps for a lower chance of experiencing uncomfortable sparks while moving in one's sleep; and their antimicrobial/antifungal properties are not significant enough to have any impact either on sleep quality.

However, natural fibers are always recommended for skin conditions such as eczema. But so far, no specific natural fiber has come out on top in medical recommendations.

That being said, 100% Flax-Linen is a sound choice for bedsheets and bedcovers in order to achieve thermal comfort and promote restful sleep.

Thermal environment

INTRODUCTION

Many studies cite the thermal environment as one of the most influential factors in sleep quality (Libert et al, 1988; Gilbert et al, 2004). Indeed, they have shown that the human body has optimal levels of relative humidity and air temperature, and deviating from this, such as with air that is too dry or too humid, and temperature that is too cold/too hot, , will disrupt sleep patterns and cause more waking up, shorter sleep times, more difficulties waking up, etc.

Indeed, Libert et al found in 1988 that changing air temperature and humidity changes the sleep stages durations significantly, and overall reduces overall sleep quality. Details for these studies can be found in the 2021 literature review. More studies show similar results, which proves the importance of having the best possible room conditions possible for a good, restful sleep, like for instance Strøm-Tejsen et al, who stated *"The results show significant negative effects of an increased bedroom temperature on subjectively assessed sleep quality and on the score from the Groningen Sleep Quality Scale. Significant negative effects were also found on assessed freshness of air, skin and lip dryness. The subjects felt significantly warmer in the room and under the duvet in the warmer condition."*

But regulating the air outside the bed has its limits, especially if the fabrics in which one sleeps do not allow for thermal regulation. In addition, Wang et al found in 2015 that: *"When a person sleeps with a covering quilt, the bedding system insulates the human body from the indoor thermal environment. Therefore, sleep quality and sleep thermal comfort are more affected by the bedding micro climate compared with the indoor thermal environment. If the indoor temperature is lower, then sleep thermal comfort can be satisfied by changing the thermal resistance of the clothes and quilts."* A significant percentage of studies focusing on indoor climates have the participants wear little to no covers, and minimal sleepwear. But in reality, people tend to sleep at least under bedsheet, and use regular sleepwear too; bed linens thus have a strong impact on thermal sensations on the body.

To find out which kind of fabric would be the best choice for bed linens, the 2014 Alliance for European Flax-Linen & Hemp/ CETELOR study tested four different fabrics: 100% Flax-Linen, 100% Cotton, 100% Viscose (reconstituted cellulose), and 100% Polyester (PES).

AIR PERMEABILITY

Thermal comfort is, as previously mentioned, a complex parameter that cannot be summed up in a single value. Having several parameters is important for having a general understanding of how a fabric behaves under certain circumstances.

One of the first parameters that can be evaluated is the air permeability: indeed, fabrics needs to let air through along with heat, in order to prevent an accumulation of perspiration, which would cause the air under the covers to become too moist, in addition to creating an uncomfortable sticky and chaffing sensation due to damp sleepwear and bed linens. Indeed, in 1982, Candas et al highlighted in 1982 that "[...] under the 32/80 [32°C and 80% relative humidity] with still air condition, a higher sweat rate, and additional clothing induced the increase in skin wettedness. The clothing interrupted the process of losing heat during sleep in the warm humid environment and increased the discomfort. Such discomfort along with stickiness might be perceived to be responsible for wakefulness during sleep; moreover, it may also prolong the period of wakefulness, or increase the number of episodes of wakefulness, as happens with thermosensitivity."

Not only this, but in 2008, Tsuzuki et al found the following: *"The increased airflow reduced the duration of wakefulness and did not impede sleep; rather, it facilitated sleep in a warm humid climate [...] The alleviated heat load due to the increased airflow reduced wakefulness."* Having a slight airflow seems to be beneficial, especially in warmer, humid climates, as it helps regulate body temperature and draw away excess moisture. This means that having a high air permeability would promote this kind ofairflow and allow for a better sleep overall.

> "Linen fabrics are a good candidate for bed linens and sleepwear as they will help moisture to be pulled away from the body".

The Alliance for European Flax-Linen & Hemp/ CETELOR study tested this parameter (see figure 1 for results) and showed that a 100% Flax-Linen fabric has the highest air permeability, at 2294 l/m²/s, well above cotton (499 l/m²/s) and PES (958 l/m²/s). A close match to Flax-Linen for this parameter is viscose, with a value of 2293 l/m²/s. This means that Linen fabrics are a good candidate for bed linens and sleepwear as they will help moisture to be pulled away from the body.

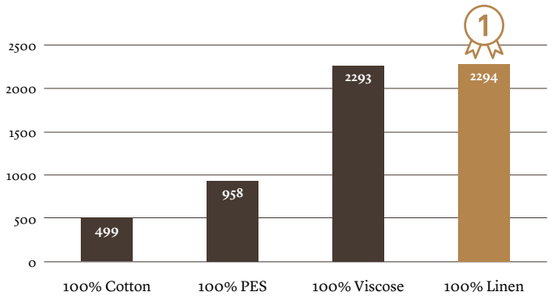

Figure 1 - Permeability to air / thickness - mm/s - NF EN ISO 9237 (1995)

MOISTURE MANAGEMENT

Another important feature of moisture management is the RET, or water vapor resistance (figure 2). This parameter helps to show how breathable the fabric feels on the body. Linen and cotton are fabrics are close contenders, but Linen is slightly better at 3,84 m².Pa/W, for 3,86 m².Pa/W. Polyester and viscose fabrics have a value of 4,7 and 4,73 m². Pa/W respectively, and to put things into a broader context, RET values below 6 are considered very breathable, and aren't considered breathable above 12 m².Pa/W. While all fabrics tested in this study are considered highly breathable, having a tighter weave or denser fabric would still make for a breathable Linen fabric.

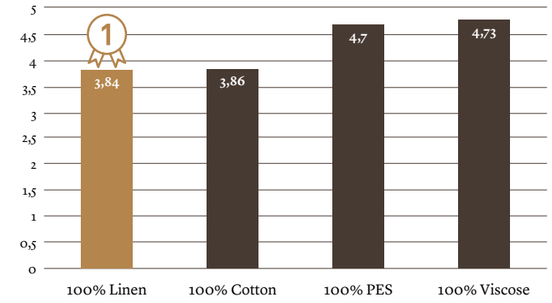

Figure 2 - Permeability to water vapor - Water-vapor resistance Ret- m²Pa/W Skin Model ISO 11092 standard

With all of this in mind, Flax-Linen should improve sleep quality in warmer climates, but it could also have an impact when the temperature is cooler, because Zhang et al showed that *"for conditions when the ambient temperature is below skin temperature, the air permeability of a textile has far more influence on rectal temperature than its moisture regain, and that in conditions where the skin temperature is higher than the surrounding temperature, it is vice versa"*. When cross analyzed with the previous results, namely the heat resistance, one could argue that while Linen fabrics aren't the best at retaining heat, they could still be used for mid-range climates, as they would promote airflow but also keep some measure of heat, maintaining good body temperature and, more importantly, dryness.

However, the literature heavily leans towards in warmer climates, and there is much less data to be analyzed when it comes to sleeping in cooler environments. Okamoto-Mizuno et al found in 2012 that *"Increases in wakefulness are greater in cold Ta [ambient temperature] than in heat, suggesting that the impact*

of cold exposure is greater than that of heat exposure. Ta higher or lower than the thermal neutral temperature (29°C) have been shown to increase wakefulness and decrease REM [Rapid eye movements, or paradoxical sleep] and SWS [slow wave sleep] in semi-nude subjects. However, these results are based on semi-nude subjects and exclude the effects of bed covers and clothing. In real-life situations where bed covers and clothing are used, sleep is actually disturbed during heat exposure rather than cold exposure in the young, as well as in the elderly", meaning that with a covering, cool environments could have less of an impact. But this remains to be proven by future studies focusing on this parameter in particular, and a study directly testing Flax-Linen and other fabrics could be beneficial to understanding its behavior in cooler indoor climates.

MOISTURE MANAGEMENT AND ABSORPTION

The previously discussed tests concerned heat and airflow, but humidity and perspiration quickly appeared in the discussion, as temperature and air humidity are closely linked: an atmosphere at the same temperature but at a different relative humidity will not be experienced the same way. Which means that moisture must be directly tested to gain a better understanding of its behavior in clothing upon contact with the skin.

Sweating in general helps with thermal regulation and preventing one from overheating. And it seems that this regulation changes with sleep cycles.

This phenomenon has been studied for quite some time, and Henane et al found in 1977 that "in neutral conditions (32 and 34 °C) body temperature and skin evaporation decreased during the night, following the circadian rhythm"

Two tests have been carried out in the 2014 study: First, the absorption test (figure 3), where the diffusion area of a droplet is measured, as well as the time needed for the diffusion to occur. Flax-Linen has the highest area of diffusion and there is no latency between the droplet touching the fabric and the diffusion taking place. Viscose once again comes in as a close second, and cotton is also relatively close behind, while polyester shows very poor results in this area.

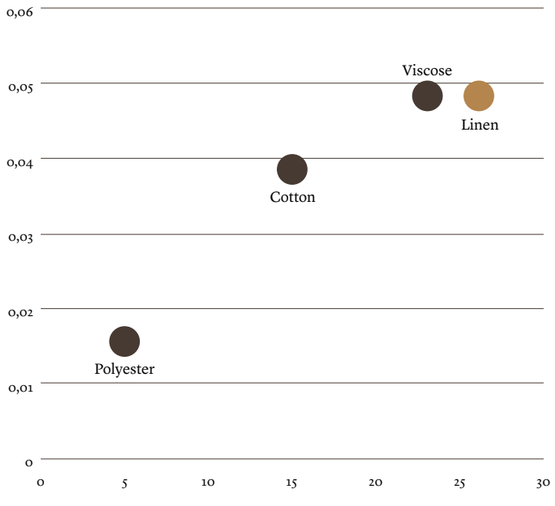

Figure 3 – Behavior of dry fabrics with respect to water - mm row and column - NF G07-165 (absorption)

This phenomenon can be explained by the nature of the fibers themselves – Flax-Linen, Viscose and Cotton are fibers made out of cellulose, a naturally occurring long molecule chain that is hydrophilic in nature. This means that the water can travel through the fabric much more quickly than through artificial fibers like polyester, which are hydrophobic in nature.

What this means in terms of fabric-skin behavior is that Flax-Linen can absorb the most water without feeling damp, as it will spread out and be diffused over a bigger area.

Another moisture test was conducted, the moisture management test (figure 4), which also analyses the diffusion of moisture over fabric, but it does this in terms of clothing-skin interaction, and ranks fabrics according to 6 classes, with 6 being the best.

100% Flax-Linen and viscose fabrics both ranked 5, while cotton ranked 3 and PES ranked 1. This result validates the previous test, as they behave similarly respect to with moisture, and confirms Flax-Linen as the best option for moisture management fabrics.

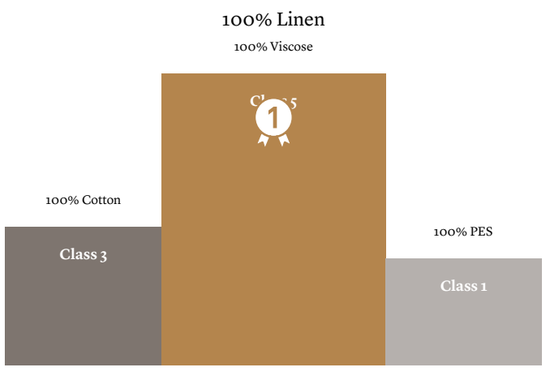

Figure 4 - Moisture Management Tester classification scale 1 to 6 - AATCC 195 standard

When analyzed with the previous results, notably the air permeability and the RET, and cross-referenced with sleep dates, Flax-Linen appears to be the best fabric to pick for bed linen and/or sleepwear, as it will stop moisture from accumulating on the body, and will pull it away through the sheets and out in the air. As Bliss wrote in his paper in 2005: *"Adding Flax to clothing fabrics helps keep skin cool partly because the Flax improves moisture wicking, which means channeling moisture away from the skin's surface."*

> "Flax-Linen as the best fabric to pick for bed linen and/or sleepwear, as it will stop moisture from accumulating on the body, and will pull it away through the sheets and out in the air"

It is important to note that in terms of wicking speed, PES seems to be fastest when the first drop falls, but then slows very rapidly as more condensation is formed and touches the fabric – as stated above, its hydrophobic nature means that water can pass very quickly through it but also that that there is zero diffusion, so the water saturates the fabric, creating damp spots.

THERMAL RESISTANCE AND COMFORT INDEX

Heat has been mentioned throughout this review, with the several studies showing that that high levels of heat are quite detrimental to sleep quality. To study these insulating properties, the 2014 CELC/CETELOR study performed an RCT test on the different fabrics, which gives insight on the insulating properties of the materials (figure 5). When compared to cotton, viscose, and polyester, 100% Flax-Linen fabric ranks second for insulation behind PES, which means that it traps some heat, but doesn't retain most of it in; this is consistent with its high permeability. In short, it allows for [Flax-Linen] a compromise between two extremes and allows for the person either wearing it or sleeping in to feel cool throughout.

> "Flax-Linen, a compromise between two extremes and allows for the person either wearing it or sleeping in to feel cool throughout."

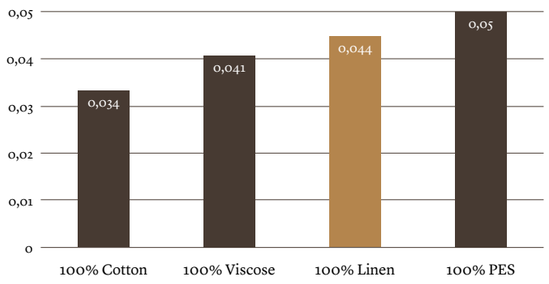

Figure 5 - Insulation / Thermal Resistance Rct– m2 k/W - Skin Model ISO 11092 standard

And lastly, the Alliance for European Flax-Linen & Hemp/CETELOR study calculated the IMT index for all the tested fabrics tested (figure 6). This index is determined using both the RCT and RET values, which indicate the thermal and vapor comfort of a fabric in relation to a skin model. This index then gives a single, general comfort value: or how comfortable a fabric would be under normal circumstances.

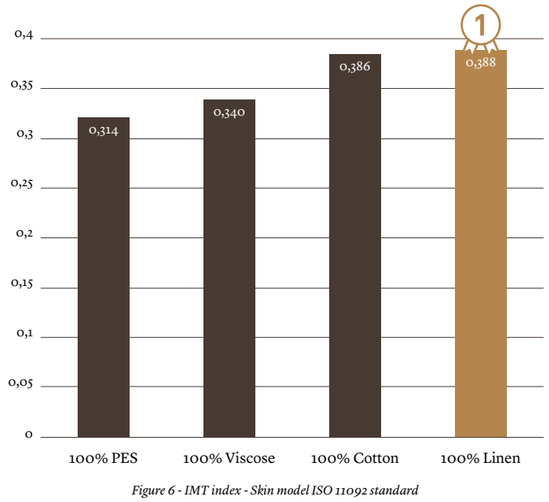

Figure 6 - IMT index - Skin model ISO 11092 standard

Here, 100% Linen ranks first, which makes sense as it ranked first in RET value and second in RET value. This means that whether the fabric is used for clothing or bedsheets, Linen will be advantageous and usually the best choice.

HANDFEEL COMFORT

B. K. Behera et al also used the Kawabata hand, developed in the nineties, which organize several factors into groups. They found that Flax-Linen can be made with a lower thread density due to its higher tensile resilience, which makes it more breathable. It is also a heavier fabric, that tends to improve the handle. But it's also a tougher, less bending fabrics which creases very easily, which negatively affect the handle. In this regard, there are many ways to interpreted handle value but Flax-Linen seems to have one of the highest one at low weights and following proper preparation of the fiber.

Indeed, Meng et al found that while handfeel varies from one perso to the next due to cultural variations, Flax-Linen always seems to be given preference over synthetic fabrics.

This is not to say that other fibers don't have a good handfeel, or that handfeel is absolute. Shin et al found that at lower temperatures, other fibers like wool seems better for comfort. But Linen ranks quite high on the list of fabrics, and as such should be taken into consideration when choosing bedsheets.

ANTISTATIC PROPERTIES & MICRO-ORGANISMS RESISTANCE

As of today, there is no direct link between sleep quality and static electricity fields. The latter doesn't seem to have any impact on human biology and health, and even when high enough, the only interaction it has in the human body is with the body hair, which will rises when charged.

Zimniewska et al, on the other side, studied the static properties of both Flax-Linen and polyester: « In the case of the Flax-Linen shirt, the level of electrostatic field potential difference was very low, close to 0 in both static (no exercise) and dynamic conditions (after 10 throws of the arms). The tests of the polyester shirt showed that electrostatic charges are accumulated on the shirt surface when worn in static conditions (no exercise). The electrostatic potential difference increases considerably in dynamic conditions (after 10 throws of the arms) ». And as seen in table 2, PES has a higher electric resistance, which could explain why it gets charged more easily.

As it stands, synthetic fibers like polyester tend to have a higher electrostatic charge, as Das et al highlight: "The phenomenon of static electricity has taken on a new importance with the advent of synthetic fibers, since these are more likely than the traditional ones to acquire an electrostatic charge of such magnitude that discomfort, or possibly even danger, is experienced." But the danger noted here is a spark that could ignite a highly flammable object or atmosphere. During sleep, this does not present a problem. Moreover, this charge builds up with repetitive movements, which are not frequent during sleep.

Wool also seems to generate more static electricity, as Cerovic et al found. But the dielectric properties of fabrics are also greatly affected by humidity – dry air seems to ower the detection threshold.

With the available data, only conjectures can be made on the topic of antistatic properties. Natural fibers diffuse charges better

and can prevent some uncomfortable sensations, which could potentially improve sleep comfort, but not direct link is available for now.

When it comes to antifungal and antimicrobial properties too, no direct link between these properties and sleep quality has been reported, either. Flax-Linen is a cellulosic material like cotton, and if left untreated in humid conditions with no airflow, microorganisms such as bacteria or mold will grow on it. But again, there is no risk of such growth under normal living and storage conditions.

However, natural fibers have been recommended by many doctors and medical boards like the eczema society to help manage skin issues such as atopic dermatitis of which one of the worst symptoms causes to the rashes is a decrease in sleep quality (and loss of sleep altogether). They recommend it for the reasons listed above: natural fibers help diffuse moisture and perspiration, which allows the skin to "breathe" better, and in doing so, it avoids rashes and itches. As it stands, Flax-Linen and cotton have been recommended alongside other natural fibers like silk, without preferring one over the other; which means that there is no clear distinction between them. One could argue that with the results of moisture management and RCT/RET, Flax-Linen could be a better candidate for bed linens, but as previously said, there is no study directly linking Flax-Linen, sleep, and skin issues in comparison with other natural fibers.

"Natural fibers have been recommended by many doctors and medical boards like the eczema society to help manage skin issues such as atopic dermatitis"

CONCLUSION

Some fabric-related variables are still not fully understood when it comes to sleep quality, but the more prevalent ones, namely the ones pertaining to humidity, temperature, and air flow clearly make Linen a strong contender for one of the top choices for bed linens. Of course, it will depend on the individual, but the different studies and tests clearly show that 100% Flax-Linen fabrics will help regulate sleep patterns, especially in warmer climates.

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Alliance for European
Flax-Linen & Hemp

About the Alliance for European Flax-Linen & Hemp

The Alliance for European Flax-Linen & Hemp is the only European agro-industrial organization federating all the stages of production and transformation for Flax-Linen & Hemp - 10 000 European companies in 14 countries -, leading this industry of excellence in a globalized context. This mission relies on the innovative and environmental values of these natural fibres, guaranteed by traceability labels EUROPEAN FLAX™ and MASTERS OF LINEN™.

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