Kaunas University of Technology
Faculty of Mechanical Engineering and Design

Comparison of End-use Properties of Linen and Hemp Woven Fabrics

Master’s Final Degree Project

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Kaunas, 2024

Kaunas University of Technology
Faculty of Mechanical Engineering and Design

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Master's Final Degree Project
Industrial Engineering and Management (6211EX018)

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Comparison of End-use Properties of Linen and Hemp Woven Fabrics

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Task of the Master's Final Degree Project

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1. **Title of the Project**

Comparison of End-use Properties of Linen and Hemp Woven Fabrics

(In English)

Lininių ir kanapinių audinių galutinio naudojimo savybių palyginimas

(In Lithuanian)

2. **Aim and Tasks of the Project**

Aim: to investigate the pilling performance and abrasion resistance of linen, hemp, and linen/hemp woven fabrics before and after anti-pilling finishing.

Tasks:

1. to compare the structural and physical properties of hemp and linen fabrics;
2. to evaluate the pilling and abrasion resistance of linen, hemp, and linen/hemp fabrics;
3. to analyze and compare the end-use properties of investigated cellulose fabrics after anti-pilling treatment;
4. to overview the economic factors and possibilities of ecological manufacturing of linen and hemp fabrics.

3. **Main Requirements and Conditions**

For linen, hemp, and linen/hemp fabrics woven in plain weave, treated with the machine "BRONGO 100 (Italy)", dyed at 60 degrees, and softened at 40 degrees, Martindale's tester (MESDAN-LAR, code 2561E) is used to evaluate pilling and abrasion resistance.

4. **Additional Requirements for the Project, Report and its Annexes**

N/A

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Darshan Puttaswamy. Comparison of End-use Properties of Linen and Hemp Woven Fabrics. Master's Final Degree Project, supervisor assoc. prof. Eglė Kumpikaitė; Faculty of Mechanical Engineering and Design, Kaunas University of Technology.

Study field and area (study field group): Production and Manufacturing Engineering (E10), Engineering Sciences (E).

Keywords: hemp fabric; linen fabric; blended linen/hemp fabric; pilling performance; abrasion resistance; enzymatic treatment.

Kaunas, 2024. 63 p.

Summary

The purpose of this study was to thoroughly investigate the unique qualities, physical attributes, and end-use functionality of linen and hemp textiles. Although the fabrics have similar qualities such as breathability, durability, and moisture-wicking capabilities, their origin and structure are different since the fibres used in them are obtained from the stems of hemp and flax plants. The study evaluated their physical and structural features, indicating similarities in linear density but significant variances in surface roughness. End-use qualities, including pilling and abrasion resistance, were crucial in determining fabric durability. Martindale’s abrasion and pilling testing showed hemp fabrics had 30% higher pilling resistance and 33% higher abrasion resistance than linen. However, blending linen with hemp increased pilling resistance by 14% and abrasion resistance by 27%. Furthermore, the use of BEIZYM UL enzymes in treatments increased pilling and abrasion resistance across all materials. Hemp fabric was found to be the most durable, lasting far longer than other fabrics treated with the same enzyme. The research also investigated the economic and ecological elements of hemp fabric manufacture, emphasizing its revival in the textile sector. Growing hemp is environmentally friendly, needs fewer pesticides, and provides quick growth cycles, positioning it as a cost-effective and sustainable alternative. Market pricing comparisons showed that hemp materials were competitively priced, appealing to environmentally conscious consumers. The study emphasized the possibility of environmentally sustainable fabric manufacturing by replacing traditional raw materials with sustainable alternatives such as hemp. Also, the study encouraged manufacturers to use cleaner manufacturing techniques and certifications such as GOTS and OEKO-TEX to increase transparency and incentivize responsible industrial practices. In summary, this thorough investigation demonstrated hemp’s transformational relapse potential in the textile sector, displaying this fibre as a symbol of innovation and sustainability in terms of job creation potential, exceptional durability and eco-friendliness.

Darshan Puttaswamy. Lininių ir kanapinių audinių galutinio naudojimo savybių palyginimas. Magistro baigiamasis projektas, vadovė doc. Eglė Kumpikaitė; Kauno technologijos universitetas, Mechanikos inžinerijos ir dizaino fakultetas.

Studijų kryptis ir sritis (studijų krypčių grupė): Gamybos inžinerija (E10), Inžinerijos mokslai (E).

Reikšminiai žodžiai: kanapinis audinys; lininis audinys; mišriapluoštis lininis/kanapinis audinys; pumpuravimosi elgsena; atsparumas dilinimui; fermentinis apdorojimas.

Kaunas, 2024. 63 p.

Santrauka

Šiame projekte atliktas išsamus lininių ir kanapių audinių tyrimas, nušviečiant jų išskirtines ypatybes, fizines savybes ir galutinio naudojimo elgseną. Nepaisant panašių ilgaamžiškumo, laidumo orui ir drėgmės sugerties savybių, audiniai skiriasi savo prigimtimi ir sandara, nes pluoštai gaunami iš lino ir kanapės augalo stiebų. Tyrimo metu buvo palygintos jų fizikinės ir struktūros savybės, atskleidžiant ilginio tankio panašumus ir ženklius paviršiaus faktūros skirtumus. Galutinio naudojimo savybių, tokių kaip atsparumas pumpuravimuisi ir dilinimui, tyrimas pasirodė esąs labai svarbus siekiant įvertinti audinio ilgaamžiškumą. Atlikti bandymai, naudojant Martindale dilimo ir pumpuravimosi mašiną, parodė kanapinių audinių pranašumą – jų atsparumas dilinimui buvo 30 % didesnis, o atsparumas pumpuravimuisi – 33 % didesnis nei lininių audinių. Tačiau lino maišymas su kanapėmis žymiai pagerino lininio audinio atsparumą pumpuravimuisi 14 % ir atsparumą dilinimui 27 %. Be to, fermentinis apdorojimas naudojant BEIZYM UL pastebimai padidino visų audinių atsparumą pumpuravimuisi ir dilinimui, o kanapinis audinys pasižymėjo išskirtiniu ilgaamžiškumu, gerokai didesniu nei kitų ta pačia medžiaga apdorotų audinių. Projektas taip pat nagrinėja ekonominius ir ekologinius kanapinių audinių gamybos aspektus, pabrėžiant jų atgimimą tekstilės pramonėje. Kanapių auginimo ekologiškumas, reikalaujantis mažiau pesticidų, ir greitas augimo ciklas, yra ekonomiškai efektyvi ir tvari alternatyva. Rinkos kainų palyginimas parodė konkurencingas kanapinių audinių kainas, patrauklias aplinkai neabejingiems vartotojams. Tyrime akcentuojamos ekologiškai tvarios audinių gamybos galimybės pakeičiant tradicines žaliavas tvariomis alternatyvomis, tokiomis kaip kanapės. Be to, siekiant padidinti skaidrumą ir paskatinti atsakingą gamybą, propaguojami švaresni gamybos procesai ir tokie sertifikatai kaip GOTS ir OEKO-TEX. Apibendrinant, šis išsamus tyrimas parodė kanapių sugržimo į vartojimą potencialą tekstilės pramonėje, pavaizduodamas šį pluoštą kaip naujovių ir tvarumo simbolį. Dėl jų ekonominės naudos, darbo vietų kūrimo galimybių, išskirtinio ilgaamžiškumo ir ekologiškumo kanapių pluoštas yra perspektyvi alternatyva, atspindinti perėjimą link klestinčios ir aplinką tausojančios tekstilės pramonės ateities.

Table of Contents

List of Figures **8**
List of Tables **9**
Introduction **10**
1. Linen and Hemp Fabric in the Textile Industry **12**
1.1. Structural Characteristics of Linen and Hemp 14
1.2. Physical Properties of Linen and Hemp Fabric 15
1.3. End-use Properties and Factors Affecting 19
1.4. Methods of testing 21
1.5. Chapter Summary 24
2. Material and Methods **26**
2.1. Structural Parameters of the Fabrics 26
2.2. Finishing Process and Additional Technological Operations 29
2.3. Methods 30
2.3.1. Atmospheric conditions 30
2.3.2. Establishing of Pilling Resistance of the Fabrics 31
2.3.3. Establishing of Abrasion Resistance of the Fabrics 32
2.3.4. Statistical Analysis of the Experiments 33
2.4. Chapter Summary 34
3. Results and Discussion **36**
3.1. Analysis of Pilling Resistance 36
3.1.1. Pilling Resistance of Linen, Hemp and Linen/Hemp Blended Fabrics 36
3.1.2. Improvement of Pilling Resistance of Linen, Hemp, Linen/Hemp Blended Fabrics 40
3.1.3. Influence of Raw Material and Finishing Type on Pilling Resistance 42
3.2. Analysis of Abrasion Resistance 45
3.2.1. Abrasion Resistance of Linen, Hemp, Linen/Hemp Blended Fabric 45
3.2.2. Improvement of Abrasion Resistance of Linen, Hemp, Linen/Hemp Blended Fabrics 50
3.2.3. Influence of Raw Material and Finishing Type on Abrasion Resistance 53
3.3. Economic Factors Influencing Pilling and Abrasion Resistance 55
3.4. Chapter Summary 56
4. Economic and Ecological Friendliness of Hemp **57**
4.1. Market Price Comparison of Hemp Fabric and Linen Fabric 57
4.2. Possibilities of Ecologically Sustainable Manufacturing 58
4.3. Chapter Summary 59
Conclusions **60**
List of References **61**

List of Figures

Fig. 1. Schematic diagram of various applications of hemp……………………………………..13
Fig. 2. Bast fibre in hemp……………………………………………………………..…...14
Fig. 3. Abrasion resistance graph of linen, hemp, linen/silk fabric………………...……..……...16
Fig. 4. Ring, compact suiting, and shirting fabric's total hand value by fiber blend…………..…..17
Fig. 5. Formation of pills on fabric woven from ring-spun……………………...………………20
Fig. 6. Scheme of algorithm used in OCT………………..……………………………………...22
Fig. 7. The integration of the optical coherence tomography method……………………...……23
Fig. 8. Plan of weave……………………………………………………………………………26
Fig. 9. Weaving loom Itema 9500…………………………………………………………….....27
Fig. 10. Investigated fabrics..……………………………………………………………….....28
Fig. 11. Schematic diagram of finishing process and additional technological operations………....29
Fig. 12. Air-conditioning panel showing air temperature and humidity…………………..……….30
Fig. 13. Horizontal air-permeable surface for specimen conditioning..31
Fig. 14. Sample pairs on the holders and pilling tables..31
Fig. 15. Martindale abrasion and pilling tester MESDAN-LAB, Code 2561E (SDL AT-LAS, London, England)...32
Fig. 16. Holder of Martindale abrasion and pilling tester...33
Fig. 17. Load of 9 kPa in Martindale abrasion and pilling tester...33
Fig. 18. KERN EW 150-3M (KERN & Sohn GmbH, Wurtenberg, Germany)...............................33
Fig. 19. Graph of pilling performance of investigated unfinished and finished fabrics…………….39
Fig. 20. Graph of pilling performance of investigated finished fabrics before and after treatment...42
Fig. 21. ANOVA table for the influence of pilling resistance on raw material and type of finishing………………………………………………………………………………………..43
Fig. 22. Confidence intervals for different raw materials in pilling resistance: (1) linen; (2) hemp; (3) blended linen/hemp……………………………………………………………………..44
Fig. 23. Confidence intervals for different types of finishing in pilling resistance: (1) unfinished fabric; (2) finished fabric; (3) fabric after enzymatic treatment…………………….………………44
Fig. 24. Graph of mass loss versus abrasion cycles in unfinished fabrics……….…………………48
Fig. 25. Graph of mass loss versus abrasion cycles in finished fabrics………….…………………49
Fig. 26. Graph of mass loss versus abrasion cycles after treatment……….………………………52
Fig. 27. ANOVA table for the influence of abrasion resistance on raw material and type of finishing………………………………………………………………………………………..53
Fig. 28. Confidence intervals for different raw materials in abrasion resistance: (1) linen; (2) hemp; (3) blended linen/hemp……………………….………………………………………………..54
Fig. 29. Confidence intervals for different types of finishing in abrasion resistance: (1) unfinished fabric; (2) finished fabric; (3) fabric after enzymatic treatment……………………………………54

List of Tables

Table 1. Structural parameters of the examined fabrics……………………………………………27
Table 2. Visual evaluation of the pilling test……………………………………………………..32
Table 3. Samples of unfinished and finished fabrics during pilling resistance test after a specific number of cycles………………………………………………………………………………36
Table 4. Grade of pilling for both unfinished and finished fabrics…………………………………38
Table 5. Samples of chemically treated finished fabrics during pilling resistance test after a specific number of cycles………………………………………………………………………………40
Table 6. Grade of pilling for finished fabrics before and after enzymatic treatment……………....41
Table 7. Raised hypothesis for pilling resistance………………………………………………...43
Table 8. Samples of unfinished and finished fabrics after a specific number of abrasion cycles…..45
Table 9. Statistical values and average mass loss of unfinished and finished linen, hemp, and linen/hemp blended fabric sample………………………………………………………………..47
Table 10. Samples of chemically treated finished fabrics after a specific number of abrasion cycles……………………………………………………………………………………….…50
Table 11. Statistical values and average mass loss of finished linen, hemp, and linen/hemp blended fabric samples after enzymatic treatment…………………………………………………………...51
Table 12. Raised hypothesis for abrasion resistance……………………………………………..53

Introduction

Recently, as human activities and emerging economies lead to global warming and other ecological problems, efforts are being made to return to the natural use of natural biodegradable fibres, low-aggressive chemicals, and green energy resources. Linen is one of such ecological natural fibres that are biodegradable, antibacterial, antiallergic, strong, shiny and has high comfort and end-use properties. Due to the flax plant's intrinsic resilience to pests and diseases, the cultivation of linen fibers does not require the use of a lot of fertilizers and other chemicals. However, there are a few drawbacks to linen as well; for instance, the fiber itself is not elastic, it wrinkles easily and can be challenging to smooth. Nevertheless, according to present fashion developments, this disadvantage is minimal and may even be preferable.

Nowadays, hemp fibre is used for clothing and other purposes. It's properties are similar to those of linen, but its mechanical, and end-use properties are even higher than those of linen. The appearance of both hemp and linen fibres is similar, but linen is shinier. The dyeability of hemp is worse, and the colours are not as bright as those of linen. Nevertheless, the utilisation of hemp fibre has been largely unused for an extended period. In recent times, there has been a gradual increase in the widespread utilisation of this material. This can be attributed to its favourable mechanical and end-use properties, its environmentally friendly nature, and its exceptional durability. Also, the growing demand for ecologically friendly products throughout the world has led to an increase in the popularity of hemp fiber which fits well with the global drive for sustainable alternatives.

Pilling and abrasion resistance are two of the most important end-use properties of textile fabrics, influencing their durability and wearability. The improvement of these two end-use properties of textile fabrics is very important. There are different methods available for improving this process, such as utilising blends of various textile fibres, employing various finishing technologies, considering structural parameters, etc. Blends of different fibres and chemical treatments are commonly used to improve the end-use characteristics of any fabric. In this final project, an investigation is conducted on a blend of two natural cellulose fibres, namely linen and hemp, with the aim of improving the pilling performance and abrasion resistance of linen fabric. The properties of hemp fabrics have not been thoroughly investigated, which adds additional novelty to this final project.

Another way to improve fabric's pilling and abrasion resistance is by using different chemicals and treatments. Various types of finishing technologies and chemicals are analysed in the scientific literature, but one of the easiest and most effective ways to improve the fabric's properties is to treat it with enzymes. This method is used for the development of end-use properties of fabric. In addition, the economic and environmental issues, prices, costs, etc. of hemp fabrics in comparison to those of linen fabrics are analysed in the final project, as hemp fibre returns to the market after a long period of time. As a result, analyzing the economic aspects of hemp fabrics is critical to understanding their viability and influence.

Aim: to investigate the pilling performance and abrasion resistance of linen, hemp, and linen/hemp woven fabrics before and after anti-pilling finishing.
Tasks:
1. to compare the structural and physical properties of hemp and linen fabrics;
2. to evaluate the pilling and abrasion resistance of linen, hemp, and linen/hemp fabrics;

3. to analyze and compare the end-use properties of investigated cellulose fabrics after anti-pilling treatment;
4. to overview the economic factors and possibilities of ecological manufacturing of linen and hemp fabrics.
Hypothesis: hemp fabrics have higher end-use properties than linen fabrics, which can be improved using anti-pilling treatments and result in more economical and ecological fabrics.

1. Linen and Hemp Fabric in the Textile Industry

Linen is a fabric made from flax which is widely used due to its durability, endurance, lustrous appearance, and ability to maintain coolness in humid climates. Additionally, it is antibacterial, antifungal, as well as environmentally sustainable, making it an ideal choice for individuals with allergies or sensitive skin, it also provides protection against UV rays. It has a wide range of applications, including clothing, home textiles, and technical textiles. Linen fabric in the textile industry has excellent characteristics, but it also has some drawbacks. Linen materials are susceptible to wrinkling and also have a high flame velocity, making them easy to burn. With a focus on improving qualities like softness, durability, breathability, and wrinkle resistance, linen fibres have been blended with other materials like cotton, protein fibres, tencel fibres, and silk [1].

In comparison to linen, hemp is an environmentally friendly and sustainable textile solution with numerous advantages in the textile industry. Hemp is an excellent choice due to its sustainable nature, biodegradability, and adaptability to a variety of applications; its eco-friendly attributes guarantee a steady supply; its biodegradability ensures environmental friendliness at the conclusion of its life cycle; and its versatility permits its utilization in numerous industries, including construction, nutrition, and textiles. Hemp is a more ecologically friendly crop than cotton since hemp growing uses substantially less water and fertilizer; it is also heat and static electricity resistant, which makes it perfect for textile applications. In addition, hemp inhibits the development of weeds, prevents soil erosion, and removes toxic substances and heavy metals from the soil. Due to their tall stature, thick leaves, and ability to be grown densely, hemp plants are able to eradicate even the most tenacious weeds. In the textile industry, hemp fabric has several desired physical features, including a pleasant hand feel and high drapability; it is also cool and comfortable to wear. The thermal properties of hemp fabrics are determined by capillary structure, surface properties of the fibre, and distribution of air volume within the fabric [2].

Hemp fibre could be a sustainable and renewable alternative to synthetic fibre in the textile industry, according to Miranda [3]. In the study, hemp fibres were examined for their suitability as furnishings, a growing trend in the market. In addition to laboratory studies, the research examines the performance of hemp fibre compared to synthetic fibres. Further, the study investigates the economic potential as well as job-creating possibilities associated with hemp production in the US. According to the research, hemp fibre has excellent textile properties and can perform better than synthetic fibres. Hemp fibre has the potential to replace synthetic fibres as an environmentally friendly and renewable material for furnishings. The research indicates that hemp fibre is a viable option for the textile industry, but more study is required to fully understand its potential [3].

Hemp fabric is a feasible replacement for cotton textiles, as comparing hemp and cotton fabrics demonstrates hemp's potential as a durable and sustainable alternative to both cotton and flax. It is important to emphasize that hemp processing and production have positive environmental effects, such as using fewer or no pesticides and consuming less water. Although hemp textiles do have some disadvantages, they can be minimized by utilizing blended yarns like hemp/organic cotton or hemp/recycled polyester. Tensile and tear strength are dramatically enhanced, pilling and crease development are significantly decreased, and abrasion resistance is virtually excellent as a consequence of this smart mixing. Overall, hemp fabrics have great potential as a sustainable and robust alternative to cotton textiles; the environmentally friendly nature of hemp cultivation and processing, combined with the possibility of improving hemp fabric qualities through treatments such as liquid ammonia, underscores its promise as an eco-friendly textile choice [4].

In recent decades, Cannabis sativa L. has gained significant popularity as a trendy plant. Understanding the impact of the processes that create the hemp value chain on fiber characteristics is essential to utilizing hemp's potential for the growth of a sustainable textile bio-product industry. Furthermore, the hemp industry is experiencing substantial growth in Europe, a continent that has yet to completely exploit the potential of hemp. Between 2013 and 2018, the area dedicated to hemp farming in Europe expanded by 70%. Hemp has a broad range of applications, including the provision of raw materials for numerous economic sectors. In Fig. 1, the various applications for the hemp plant are outlined [5].

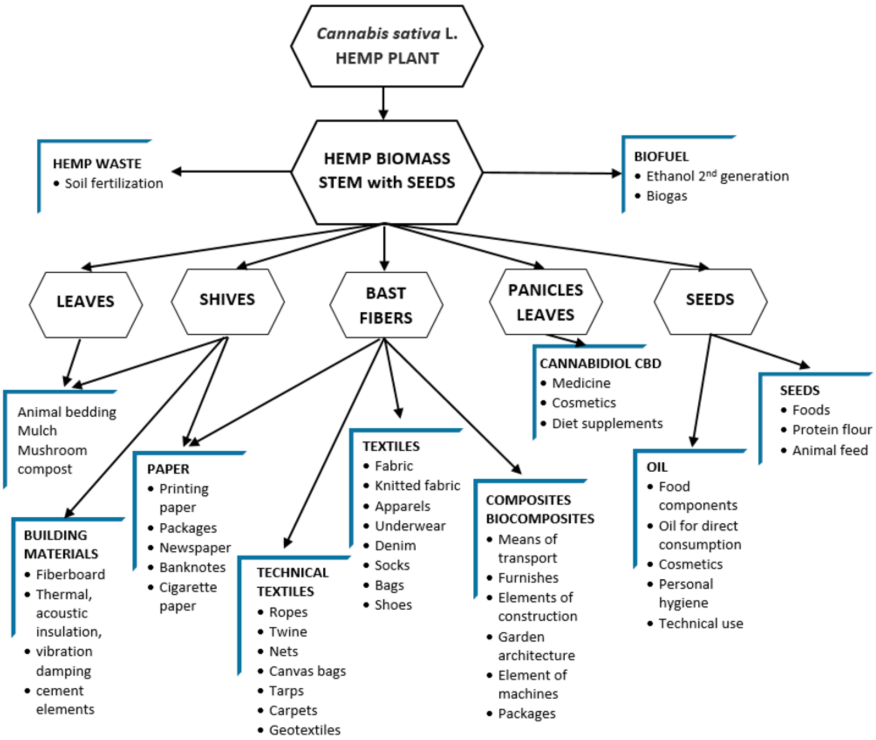


Fig. 1. Schematic diagram of various applications of hemp [5]

The study examines industrial hemp as a source of textile fibers from a variety of angles. In order to illustrate the difficulties and possibilities pertaining to Cannabis sativa L., the study delves deeply into the present advancements in hemp fiber processes, covering techniques for fiber extraction and processing as well as overall fiber qualities. Additionally, the study highlights the findings that are most relevant to how the retting procedures influence the composition of chemical fibers, ultimately resulting in specific fiber qualities. In order to extract fiber from the stem with varied degrees of success, techniques such as steam explosion, enzymatic retting, osmotic degumming, dew retting, water retting, as well as mechanical decortication are used to break down pectin, lignin, and hemicellulose. By using various spinning systems, such as linen, cotton, and wool spinning technologies, with or without the use of the decortication process, establishes subsequent procedures and demonstrates the variety of ways to make yarn [5].

Gabriela, et al [6] compare the price and environmental effects of cotton with industrial hemp fibre. It was discovered that the cost of growing hemp was cheaper than that of growing cotton, coming in at only 65.48 per cent of cotton's price. In the beginning, hemp fibre is less expensive than cotton, which may encourage clothing manufacturers to use hemp fibre in their products. This is due to the fact that hemp grows more quickly than cotton and doesn't need fertilizers, pesticides, or herbicides. Its fibres are also longer than cotton’s, needing less processing to make fabric. In addition to being stronger than cotton, hemp fibre is more resilient and suited for a wider range of goods. The potential advantages and difficulties of industrial hemp fibre are also addressed in the study. It demystifies the stigma associated with hemp and provides decision-makers with information on agricultural costs in order to facilitate a sustainable agricultural investment and the development of new technology to extract and manufacture the fibre. In addition, it equips decision-makers with the means to assess hemp’s viability as a viable alternative in their operations, enabling clearer garment production. Industrial hemp fibre, in the textile business, has the potential to be a more affordable and environmentally friendly material than cotton [6].

1.1. Structural Characteristics of Linen and Hemp

Natural fiber textiles, such as cellulosic fiber, are preferred for comfort, while wrinkle-free and pill-free fabrics are typically desired for aesthetic reasons. Linen, obtained from the flax plant’s stem, is one of the most widely used cellulosic fibers in textiles. When compared to cotton, it has higher durability, absorbency, and drying speed, making it a good choice for clothes, especially in warm weather. The major components of linen are cellulose, lignin, pectin, and wax. Fibres have primary cell walls that are approximately 0.2 microns thick and are composed of hemicelluloses and cellulose coupled with pectin and cellulose. Hemicellulose, a polysaccharide composed of short chains of glucose molecules, is amorphous and weaker than cellulose, which is composed of longer chains. The lumen in linen fibers is a hollow area made mostly of cellulose found in the secondary cell wall. This cellulose-rich composition contributes to linen’s excellent resilience. Furthermore, microfibrils, small fibers occurring in numerous levels of the secondary cell wall, improve the structural integrity of linen fibers [7].

Hemp has been extensively used as a form of fibre for millennia due to its flexible nature followed by sustainability. These fibres, additionally referred to as bast fibres, typically develop in the outermost stem tissues of hemp plants (Fig. 2). In contrast to cotton, which originates from the boll or fruit of the plant, fabrics can be made from hemp’s bast fibres. Bast fibres have been separated into two distinct categories, they are primary as well as secondary fibres. Primary fibres are often longer and larger, making them ideal for textile applications [8]. In contrast, secondary fibres are better adapted for cordage, pulp, as well as recycling additives due to their shortened length, and thinner diameter, along heavily lignified cell walls [9].

Fig. 2. Hemp fibre [8]

A hemp plant has a non-uniform distribution of main and secondary fibers, with secondary fibers rising as the plant ages and decreasing along the stem. In order to maximize fibre production, the harvesting season of hemp plants becomes an important factor. Textile-quality fibres can only be produced when hemp is harvested at the right stage when primary fibres dominate and secondary fibres are minimized [10]. Industrial hemp fibre processing has traditionally presented challenges in separating secondary fibres from primary fibres. However, advances in biological and physicochemical processing techniques offer promising solutions [11].

The cultivation period plays an important role in optimizing primary fibre development over secondary fibres and should be tailored to local weather and geographical conditions. Hemp cultivation from late April through early May has been found to increase primary fibre content in regions of the North Western Hemisphere. As a result, this insight points out the critical importance of timing in hemp cultivation practices, which in turn ensures the production of good-quality fibres that can be used in textiles. Within the textile industry, hemp fibre cultivation and processing continue to be areas of interest and innovation as sustainable and eco-friendly textiles become more and more popular [12].

1.2. Physical Properties of Linen and Hemp Fabric

In recent years, extensive investigation has been carried out on the distinctive properties of linen fibres, such as strength, breathability, as well as moisture absorption. Fabrics made of linen are excellent for dressings since they are hypoallergenic, antimicrobial, and wound healing. Biomaterials as well as wound treatment are two of the areas where linen fibres are being investigated more and more. Linen fibres have unique characteristics and functions that can contribute to the development of better dressings that will encourage efficient wound healing and patient comfort [13].

The natural state of linen poses several problems, yet it is still an important textile for the textile industry, despite its excellent properties. The fabric of linen is highly susceptible to wrinkles and burns quickly. Studies have been conducted on functional finishing techniques, such as for apparel, home textiles, and composite materials, to reduce these problems. A linen fabric's viscoelastic quality causes wrinkles, which are a crucial indicator of linen fabric quality in clothing and home textiles. Compared to cotton, linen is less susceptible to wrinkle-resistant chemical agents. It is therefore essential to develop functional finishing techniques for linen fabrics to reduce wrinkles without compromising their quality. In this process, cross-linking agents, starches, and similar chemicals can be used. These chemicals are added to the fabric during manufacturing to bind the fibres together and prevent wrinkles [14].

Hemp and flax are both natural fibres with differing qualities. In comparison to flax, which particularly stands out with its outstanding dyeability, hemp's dye absorption capabilities are somewhat worse. According to structural studies, hemp fibres are more amorphous while flax fibres are more crystalline. When silk is added to flax-based textiles, various structural characteristics can be achieved, resulting in reduced crystallinity. Depending on the washing process, different textiles that have various weaves and compositions keep colour in different ways. The importance of fabric selection is further highlighted by the fact that unwashed flax cloth has superior lightfastness over flax/silk or hemp textiles. The finishing procedure has an impact on fabric durability and abrasion resistance as well (Fig. 3). In addition, mechanical qualities and end-use features are influenced by yarn fibre composition and finishing methods, which complicates the production of fabrics.

Kumpikaitė, Varnaitė-Žuravliova, et al [15] examine the mechanical and end-use characteristics of cellulose and cellulose/protein woven fabrics. The authors tested the fabric's tensile strength, elongation at break, tear strength, abrasion resistance, and air permeability. The coloured fabrics were also tested for colour fastness, water resistance, and water vapour permeability. It has been found that fibre type, weave pattern, and dyeing technique all affect the mechanical and end-use properties of materials. These findings have significant consequences for the textile industry [15].

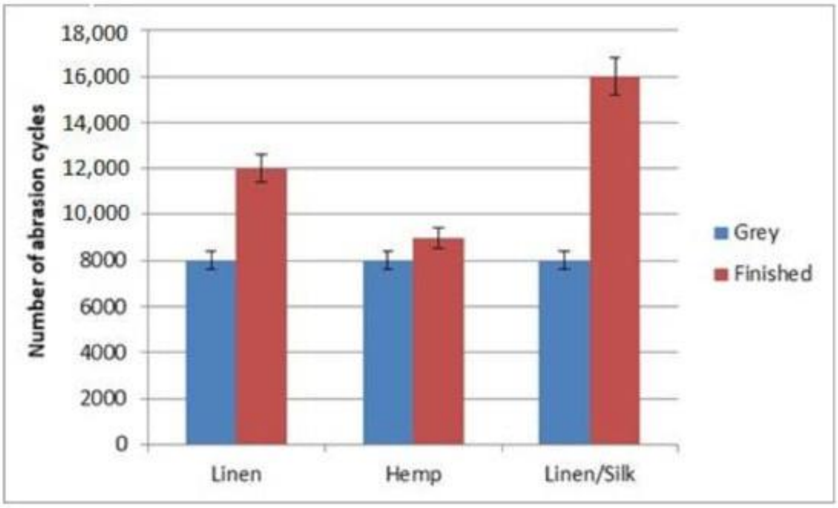


Fig. 3. Abrasion resistance of linen, hemp, linen/silk fabric [15]

The abrasion resistance of the fabric was shown to be significantly influenced by finishing. The grey fabrics experienced a breakdown after undergoing 8000 cycles of wear, while the finished fabrics exhibited a breakdown between 9000 and 16000 cycles of abrasion. Hemp fibers abraded first, and flax and silk fabrics had the highest resistance to abrasion; Fig. 3 illustrates this phenomenon. Based on the results of this research, coloured fabrics are more tensile and tear-resistant than grey fabrics, as well as water-repellent, abrasion resistant and vapour-permeable. Fabrics with these properties can be used to make outerwear or medical wear. In addition, the study emphasizes the importance of planning textile designs according to weaving patterns, dyeing methods, and fibre types. Overall, the study offers valuable insights into cellulose and cellulose/protein textile properties [15].

Flax, hemp, and cotton blend fabrics are investigated for their dyeability and performance properties. The objective of the research conducted by Riza Atav, Durul Busru, et al [16] is to develop an eco-friendly, appealing replacement to cotton fabrics. Fabric blends made of flax, hemp, and cotton are contrasted with cotton yarns and flax, hemp, and cotton yarns. Besides that, the comfort ratings of these materials have been contrasted with those of 100% cotton fabrics. In addition to cotton/linen and cotton/hemp blends, flax and hemp fibres in production-scale knitted fabric production are considered to be new materials for research. It is recommended that future studies focus on the detailed study of the handle and thermal comfort properties of these fabrics in order to make an important contribution to the literature on these topics. Overall the research provides valuable insights into the potential for flax and hemp fibres as affordable and sustainable alternatives. The process of creating fabrics is complex and requires careful consideration in order to optimize their properties. The composition and finishing methods of yarn affect its mechanical properties and end-use characteristics as well [16].

The characteristics of a fabric, including pilling and abrasion, are determined by both the structure and the basic material, as explained by Ahiwar and Behera [17]. Blends of cotton and hemp in ratios of 70/30 and 50/50 were utilized as examples. Hemp fibers varied in length by 15 to 25 mm, while cotton fibers varied in length by 28 mm, suggesting a higher concentration of short fiber. Short-staple length fibers pill more because fewer bindings are required to make the yarn while spinning, resulting in a loosely bound fibre. As a result, 100 per cent cotton fabric shows light surface fuzzing and partially produced pills in both shirting and suiting fabric types. In textiles with a ratio of 70/30 cotton to hemp, there was minimal surface fuzziness and pill formation. Blended cotton-hemp fabrics are more resilient than other fabrics, possessing superior tensile, bending, and shear strengths as well as increased abrasion and friction resistance. The study also examined the inherent qualities of summer shirting materials, finding that fabrics made entirely of cotton exhibit greater fullness, whereas fabrics composed of 70% cotton and 30% hemp, as well as fabrics with a 50% cotton and 50% hemp blend, are capable of being compressed [17].

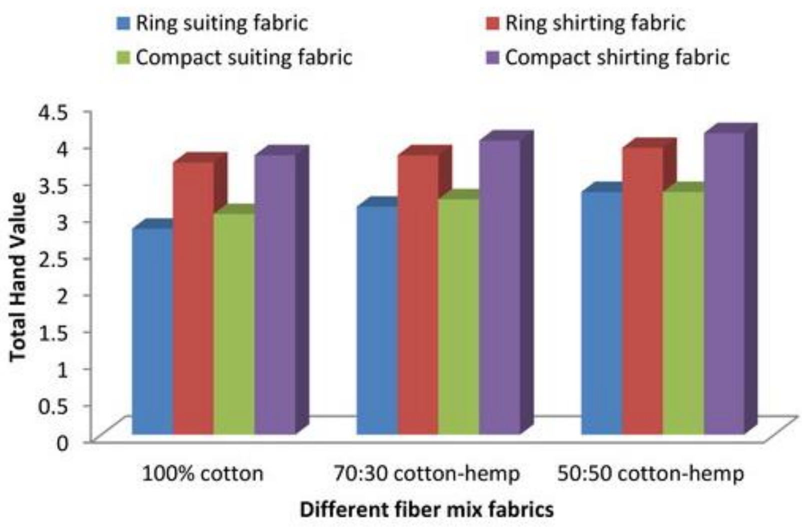


Fig. 4. Ring, compact suiting, and shirting fabric's total hand value by fiber blend [17]

Cotton-hemp blended textiles exhibit greater stiffness and crispness, whereas compact yarn fabrics demonstrate superior overall hand value. The total hand value of 50% cotton and 50% hemp fabrics was greater than that of 100% cotton and the same is depicted in Fig. 4 [17].

The utilization of hemp as a raw material for industrial textiles will yield significant benefits due to its eco-friendly composition. As a result, research was done on the bleaching of hemp fabric. This study examined the effects on hemp fabric using reagents made from chemicals and biochemical-enzyme combinations. The chemicals employed were the following: hydrogen peroxide, a solution of sodium hypochlorite, and sodium hydroxide. These compounds were mixed with the laccase enzyme in six distinct ways. The hemp fabric was evaluated for eleven physical traits both before and after treatment. The hemp fabric that had been bleached by a chemical reagent showed very little discoloration. Further testing was carried out with the chemical and enzyme combination samples. Using spectrophotometer measurements, the bleaching effect of each sample was ascertained. As a result, the treatment improved pilling and abrasion performance. [18]

According to Zhang's research, treating hemp with chitosan can improve its color production as well as its soft handle and resistance to pilling. Hemp fibers were treated with chitosan, which has a molecular density of 4200 and a degree of degradation of 0.90. Subsequently, Remazol Brillant Blue R was employed as the dye, while different volume proportions of silicone oil combined with epoxy-modified chitosan were used to obtain distinct colors. A variety of analytical techniques were employed to examine the structural changes in hemp fibers, including X-ray diffraction, thermal gravimetry, differential scanning calorimetry, and scanner electron microscopy. Furthermore, an investigation was conducted into the tensile, bending, dyeing, and colorfastness features of hemp cloth. The study showed that the percentage of residual weight increased over the temperature range of 25–550°C and that the thermal performance of the chitosan/silicone oil-modified hemp fiber changed as compared to untreated hemp fiber. The crystal grain size decreased while the degree of crystallization increased. Hemp fabric treated with silicon oil and chitosan showed a reduction in both tensile and flexural stiffness. Using a 2:1 volume ratio between the dyeing solution and silicone oil produced the best color yield. The color fastness against rubbing and wet cleaning was improved further [19].

An investigation of the end-use properties of woven fabrics using synthetic fancy threads is presented by Ragaišienė and Kumpikaitė [20]. Several fancy yarn structures are used for evaluating the abrasion resistance, mass loss, as well as air permeability of fabrics. The yarns were tested at 20°C ± 2°C and 65% ± 2%, and the fabric was conditioned at 20°C ± 2°C. A regression analysis and statistical analysis were performed using Microsoft Excel Analysis Tool Pak. According to the results, fabrics with loop fancy yarns have the highest abrasion resistance, while fabrics with slub fancy yarns have the lowest. Fabrics with spiral structure fancy yarns have a 5% higher abrasion resistance than fabrics with slub fancy yarns. In summary, this study provides valuable insight into the end-use properties of woven fabrics with synthetic fancy yarns. Moreover, the results may be utilized in the development of outerwear textiles with enhanced levels of comfort and durability. Additional factors, such as the processes of washing and ironing, have the potential to impact the end-use properties of these textiles; however, more investigation is necessary to ascertain their precise effects [20].

Asanovic, Ivanovska, et al [21] investigated the impact of pilling on the quality of four plain weft-knitted flax single jersey textiles. Compression, comfort, and strength characteristics of materials both before and after pilling are examined in the study. According to the findings, for the same number of rubs, there were no discernible variations in the grade of pilling between samples, and the grade of pilling declined when more rubs were applied. The knitted material with the highest stitch density, weight, and thickness had the maximum compressive resilience, water retention, bursting strength, and ball traverse elongation but the least compressibility, thickness loss, and air permeability. In order to improve the durability of knitted textiles during regular usage, it is necessary to carefully choose the most effective combination of their structural characteristics. According to the study, the quality of textiles may be evaluated before and after pilling based on their compression, comfort, and strength attributes, and more research is needed to investigate the impact of pilling on various types of materials [21].

Jiahao Feng, Jun Li, et al [22] investigated the effects of liquid ammonia pre-treatment and crosslink finishing on the appearance, comfort, and mechanical qualities of hemp, ramie, and linen textiles. According to the study, crosslinked textiles exhibited less shrinkage in the warp and filling directions than untreated materials. In contrast to resin treatment, liquid ammonia treatment improved cantilever bending stiffness and moisture retention in hemp, ramie, and linen textiles. Furthermore, the study discovered that hemp, ramie, and linen textiles keep their look better while wet than when dry. Fabrics treated with resin have more dimensional stability than untreated cloth. According to the study, NH_3

treatment enhanced the warp shrinkage of hemp fabric while increasing its extensibility in the filling direction. In addition to enhancing the fabric's ability to retain moisture, the NH_3 treatment increased the fabric's ability to lose moisture. Although the moisture re-gain of hemp fabric was reduced by crosslinking, hemp fabric treated with NH_3/crosslinked exhibited a higher moisture re-gain than hemp fabric that was not treated. After crosslink finishing and NH_3/crosslinking, the air and moisture permeability of hemp fabrics was reduced. Overall, the study sheds light on the impact of liquid ammonia pre-treatment and crosslink finishing on the characteristics of hemp fabric [22].

Saricam investigates the comfort properties of hemp and flax blended denim fabrics after being washed with common industrial processes. Hemp and flax blended denim fabrics are being studied for their comfort properties following industrial washing processes. Several industrial washing treatments were applied to hemp and flax blended denim fabrics as part of the research methodology. In addition to air permeability, water vapour permeability, thermal resistance, and water absorption tests, the comfort properties of the fabrics were evaluated. The industrial washing treatments influenced the comfort properties of hemp and flax denim fabrics. In conclusion, hemp and flax blended denim fabrics provide better comfort properties than traditional cotton denim fabrics [23].

1.3. End-use Properties and Factors Affecting

In the textile industry, pilling is a concern. It involves the formation of ball-like fabric surfaces. As fibres rub against each other, they break and form small balls on the surface of the fabric. These balls can stick to the fabric and create a rough texture. The protruding fibres tangle up over time, resulting in pills that affect the appearance, feel, and overall quality of the fabric. Generally, pilling occurs with fabrics made from cotton, wool, and polyester, although it can also occur with blends. In terms of quality, it gives fabrics a worn-out and aged appearance, which consumers find unattractive. Additionally, pilling can make fabrics feel rough and uncomfortable against the skin. Furthermore, it can negatively affect the fabric's drape and shine, which ultimately reduces its appeal [24].

There are numerous causes of fabric pilling. The composition of the fibres used in fabric manufacturing is among the most important factors. A fabric containing polyester tends to pill more easily than a fabric made with wool fibres that fluff but do not hold on to pills. It is also important to note that yarn count influences this phenomenon. A high-quality yarn with intersections promotes fiber stability and minimizes slippage, reducing pilling. A woven fabric's weave also affects pilling resistance. Satin weave fabrics, which have floating threads on the surface, are more susceptible to pilling than twill weaves or plain weaves. Fabrics with satin weaves tend to pill because of the floating threads. In contrast, twill and plain weaves have intersecting yarns, which improves stability and reduces friction that causes pilling. The prevention of pilling can be achieved by using various mechanical techniques, such as heat setting and singeing. In a heat setting, fabrics are heated to vacuum temperatures. In this process, the fibres on the fabric's surface are effectively stabilized, making it more pill-resistant. During singeing, the fabric is exposed to an open flame, which damages the fibres and prevents them from pilling [24].

Compact spinning is a novel process that enhances the efficiency of fibre use and improves the quality of fibres by fundamentally transforming the structure of yarn. Sunay Omeroglu and Sukriye Ulku [25] evaluated the characteristics of yarn produced by compact and traditional ring spinning, including tensile strength, elongation, and hairiness. As a result of these findings, compact spinning produces yarns that are stronger and longer elongated than ring-spun yarns. Furthermore, the present study aims to analyze the effects of compact spinning on several fabric qualities, such as air permeability, water vapour permeability, abrasion and pilling resistance. Fabrics woven from compact-spun and finer yarns have a lower pilling tendency whereas fabrics woven from ring-spun had extremely noticeable pills on the fabric surface as shown in Fig. 5 [25].

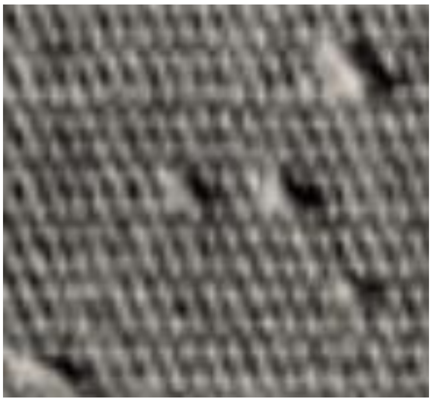


Fig. 5. Formation of pills on fabric woven from ring-spun [25]

In general, pill formation decreases as yarns become finer and less hairy. The abrasion behaviour of the fabrics was also examined, and the results show that compact yarn fabrics have the highest yarn breakage cycle numbers. In contrast to conventional ring spinning, compact spinning yields yarns and textiles that have enhanced characteristics. Compact-spun yarns possess desirable attributes such as increased tensile strength and reduced hairiness, rendering them highly suitable for textiles necessitating exceptional durability and smoothness. In addition, compact-spun textiles are well-suited for applications that necessitate breathability and comfort because of their enhanced permeability to air and water vapour [25].

Abrasion resistance is an essential feature in textiles that has a substantial influence on the performance and longevity of products such as apparel, upholstery, and industrial applications. Fundamentally, a fabric's resistance to abrasion depends on the type of fibre it contains. The choice of fibre is crucial in determining the performance of fabric since natural fibres, like cotton and silk, are more resistant to abrasion than synthetic fibres, like polyester and nylon [26].

The weave pattern which could be plain, twill, satin, or compound affects abrasion resistance. Plain weaves, for instance, are less resistant than twill weaves. A fabric's resistance to abrasion and durability can also be increased by finishing and treatments applied to it, such as anti-pill or abrasion-resistant coatings. Weight, thread count, and yarn size are just a few examples of fabric manufacturing characteristics that have an impact on abrasion resistance. Higher thread counts and bigger yarn sizes tend to make heavy textiles more durable and friction-resistant. Blends made of several fibre types may have varying abrasion resistance profiles, which enhances the complexity of a fabric when it contains many fibre types. It's important to understand these interconnected factors so textile industries can make informed decisions, ensuring fabrics meet their intended purposes and durability requirements, and ultimately advancing the textile industry [26].

An analysis of factors affecting the abrasion resistance of socks is conducted by Arzu and Nida [27]. In the study, the effects of yarn parameters and finishing processes on abrasion resistance in socks are discussed. The statistical analysis was conducted with the Modified Martindale method in SPSS 10.0 for Windows. For evaluating the abrasion resistance of yarns as well as fibres, the Modified

Martindale method is a prominent and reliable technique. In addition to testing different fibres and blends, yarn counts, twist coefficients, and plies, combing, softening, and mercerizing techniques were also evaluated. According to the investigation, abrasion resistance is influenced by a variety of elements. Improved abrasion resistance can be observed in coarser yarns and plies, although combing has no effect. Synthetic fibres like polyester or polyamide can be added to increase abrasion resistance, while natural fibres like cotton can get scattered during abrasion, losing thickness. Abrasion resistance can also be decreased by silicone softeners. Ultimately, this study provides important insight into the factors that impact abrasion resistance in socks [27].

The usage of accelerator abrasion testers was described by Ferguson and Elder [28]. In numerous plain-weave textiles, abrasion resistance varies depending on the fibre type. The resistance to abrasion of abrasives such as carborundum, rubber, metal, and plastic is graded in decreasing order. In contrast to cellulose-ester and regenerated protein fibres, polyamide fibres have excellent abrasion resistance. Because of its great strength and toughness, a polyamide fibre is more resistant to abrasion than a cellulose-ester or regenerated protein fibre. The degree of resistance displayed by synthetic polymer fibres, regenerated cellulosic fibres, and natural fibres varies depending on the nature of the abrasive, the linear density of the fibre, and the weave of the fabric. Overall, the results are consistent with the data that has been published, however, polypropylene-fibre textiles didn't perform as well as anticipated. Microscopical analysis reveals that detritus is made up of fragments of intact fibre, proving that abrasion results from fibre breaking. The specific strength and initial modulus of the fibre, or the energy of rupture of mechanically conditioned fibres, are connected to the fabric’s resistance to abrasion [28].

1.4. Methods of testing

According to Torsten Textor and Derksen, pilling performance and abrasion resistance can be evaluated using various methods. Martindale, Schopper, Einlehner, Wyzenbeek, Pilling Drum, Pilling Box, and Cylindrical Lighting System are among the test methods used to evaluate pilling and abrasion resistance performance [29]. Wyzenbeek’s and Martindale’s testing methods are similar where Martindale’s approach is strongly suggested for testing work clothes, Einlehner’s method for evaluating technical fabrics, and Schopper’s method for testing car seats [29].

Joanna, Jaroslaw, et al [30] presented a new approach for assessing the pilling tendency of textiles using Optical Coherence Tomography (OCT) and short-term abrasion tests. Traditionally, a standardized rating scale is used to assess pilling or abrasion through a subjective assessment. However, this new approach provides more accurate and detailed information about the pilling tendency of fabrics. The study additionally addresses the fundamental concepts of forced pilling and the use of a Martindale device for abrasion testing. The OCT technique maps the surface of knitwear by emitting infrared light, penetrating the material, and reflecting the light. With a resolution of roughly 5μm, this technology makes it possible to sensitively investigate surfaces and fibre configurations. In this technology, an algorithm was used that isolates the layer of fibers that form pills on the surface of the fabric and analyzes its texture to get quantitative indications of pilling. This software is specifically created to be compatible with the Python 3.6 and Windows 10 operating systems. Its main function is to remove the essential fabric layer while minimizing the appearance of apparent pilling fibers and the scheme of the technology is shown in Fig. 6 [30].

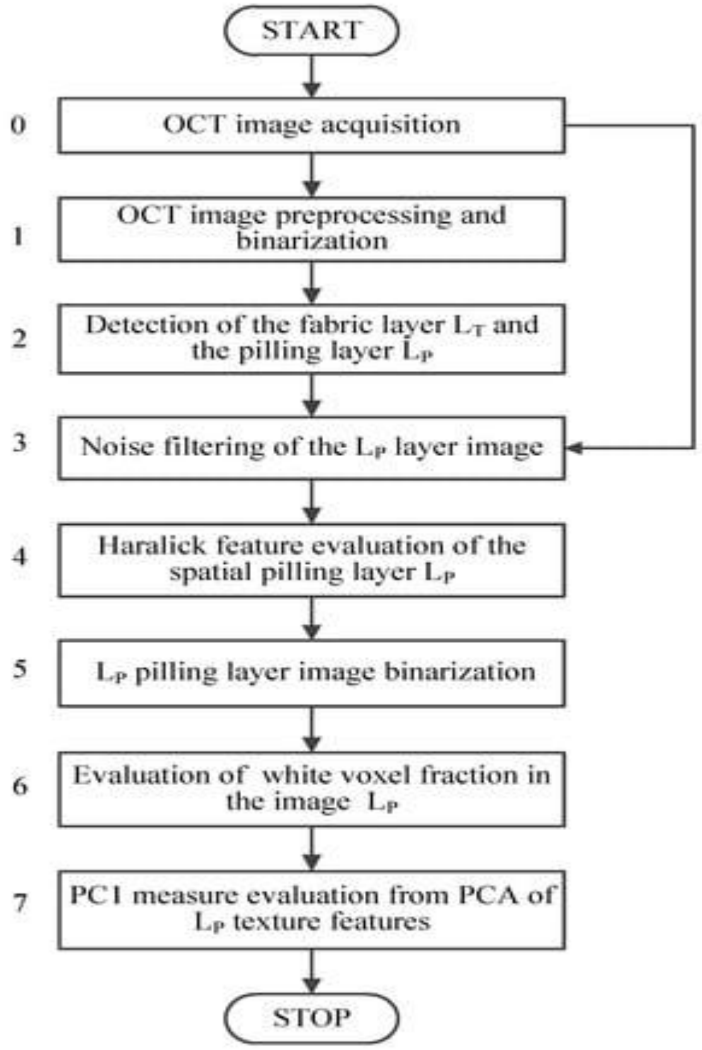


Fig. 6. Scheme of algorithm used in OCT [30]

Using this technology, a more precise and impartial method of evaluating pilling on fabrics can be established. OCT can also be used to assess quantitative and textural indications of pilling intensity. The validity of an innovative technique for estimating a fabric's propensity to pill has been established, suggesting that this is a promising area for study [30].

According to Rocco Furferi, et al [31] machine vision-based methodologies can also be used to measure pilling in textile fabrics. For picture segmentation and geometric property measurement, a new method based on a mix of image processing and machine learning techniques is suggested. In the study, the approach recommended is extremely useful for locating and classifying pills on fabrics. While evaluating pilling, machine vision technology has an advantage in improving objectivity and efficiency in the textile industry. Using this process, pills on fabrics can be located and classified with a high degree of accuracy. In comparison to more conventional methods, this one is more objective and requires less manual labour. Overall, the research offers insightful information about recent advances in non-intrusive and autonomous measuring techniques for pilling fabrics [31].

In order to predict textile pilling, Joanna, et al [32] also presented a new approach that makes use of a multivariate analysis of the surface layer above the fabric surface. A methodological approach for imaging fabric fuzz with increased sensitivity is provided by the use of infrared light in OCT (Fig. 7).

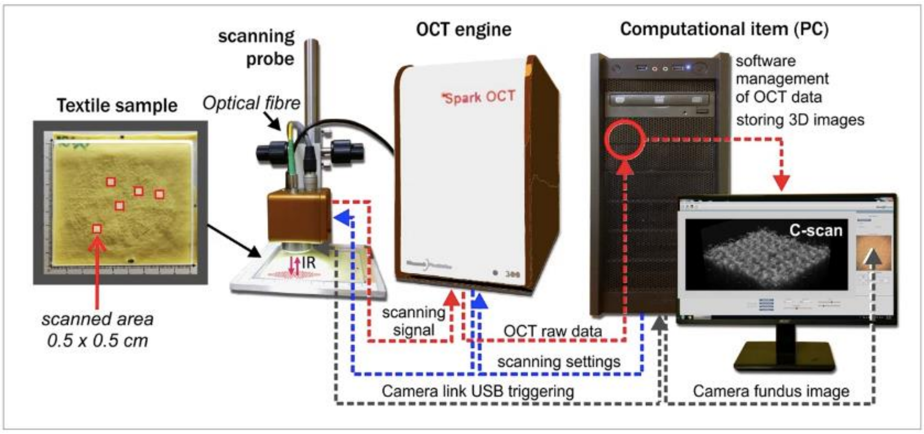


Fig. 7. The integration of the optical coherence tomography method [32]

The engine module of an OCT set contains a Fourier domain (FD) Michelson's interferometer, which generates interference utilizing a short coherence light scanning source. The OCT Scanning Probe has an infrared scanning head attached to its sample arm in the interferometer which is shown in Fig. 7. The pilling layer, which has a correlation with loose fibres and clusters, is investigated using this method at a resolution of 10×10×5.5μm to get textural information. The intensity of pilling is determined using supervised classification techniques using textual data. Both non-linear classifiers like Support Vector Machine (SVM) and linear classifiers like PLS-DA (Partial Least Squares-Discriminant Analysis) and LDA (Linear Discriminant Analysis) have been employed in this process. The outcomes of this study indicate that the procedure can be utilized for textiles that are subjected to brief periods of abrasion, which causes an increase in the amount of fuzz in the fabric layer that causes pilling. In such circumstances, the SVM model predicted pilling grades with greater than 98% accuracy, sensitivity, and specificity. However, validation accuracy after machine abrasion was lower for the evaluated models (up to 90.4% for the LDA model). This implies that the SVM model has superior performance in forecasting pilling grades specifically for short-term abrasion scenarios when the presence of fuzz is more conspicuous and hence more easily detectable. On the other hand, during the process of machine abrasion, the identification of tangled fibres inside the pilling layer becomes more difficult, resulting in a decrease in the accuracy of the model. Overall, this work shows the potential of OCT as a useful tool for evaluating the effects of abrasion on textiles by quantitatively monitoring fabric sample changes resulting from abrasion testing. The effectiveness of the OCT method in fabric analysis is highlighted by its capability to identify minute structural changes in fabric that are not visible to the human eye. This capacity eliminates the requirement for pre-processing procedures and streamlines the analysis process, hence improving the dependability of the results [32].

Mendes, Lucas, et al [33] propose a unique methodology for assessing pilling formation on textile materials. The amount of pilling on fabric samples is measured using optical scanning, and the results are then contrasted with assessments regarding the degree of pilling. As a consequence of the research, the method is demonstrated to be an advantageous substitute methodology for subjective evaluations due to its accuracy, robustness, as well as methodical identity. The most reliable indicator of subjective pilling grade categorization, in particular, was determined to be the total volume coefficient. The reliability of pilling assessments is improved by adopting this technique since it validates subjective assessments and indicates potential inaccuracies. In addition, the investigation examines the fabric properties and abrasion action that affect pilling on materials. The proposed methodology illustrated consistency along with dependability, eliminating the need for multiple evaluations. The analysis of 46 fabrics revealed that 43 exhibited no grade changes or only minimal half-grade variations, confirming the consistent relationship between the proposed method and subjective classification. The three fabrics have some uncertainties due to subjective evaluations. Nevertheless, the approach remained to be an effective tool for identifying potential problems and cross-validating results. Thus, this study provides crucial insights into the evaluation and quantification of pilling on textile fabrics, and the proposed methodology can improve fabric performance and quality [33].

The abrasion resistance of woven fabrics is investigated by Sara Asghari Mooneghi, S. Mohammad Hosseini Varkiyani, et al [34]. In the study, fabric surfaces are scanned using non-contact laser-based technologies, which are then utilized to compute a number of two and three-dimensional roughness metrics. A statistical investigation shows that surface roughness in 2D and 3D is influenced by both weft density and weave type. The 3D parameters give further information on surface roughness, which influences both the warp and weft directions. The study shows that the 3D roughness characteristics and abrasion resistance have a high correlation. Surface roughness is an important factor in determining the tactile characteristics of materials. The surface roughness of the fabric is influenced by both weft setting and weave type, and 3D characteristics provide additional information on how this impacts the fabric's overall tactile qualities. As a result, surface roughness is an essential component in estimating the fabric's abrasion resistance, which is an important consideration when developing materials for certain applications [34].

After analyzing various testing methods, it is clear that each testing method has its standards and specifications. Therefore, it is essential to select the most effective testing method. In terms of pilling and abrasion testing, various methods are adopted based on the investigated fabric type. Martindale's testing method is strongly considered for establishing end-use characteristics of work apparel or daily attire since it produces highly precise and accurate results. The Martindale method gives accurate results with its meticulous testing approach and is specifically developed to evaluate fabric abrasion and pilling. In this approach, the fabric is rubbed against a standardized counter to determine the degree of pilling and abrasion. In comparison to other approaches, Martindale's testing procedure is intended to be as feasible as possible to accurately analyze pilling and abrasion on fabrics.

1.5. Chapter Summary

This chapter examined the characteristics of linen and hemp materials used in the textile industry, as well as their physical and end-use characteristics and the various factors that affect these qualities. Additionally, it emphasised the properties that make linen and hemp suitable for usage in different contexts. Flax-based linen is well-known for being durable, absorbent, and quick to dry, making it an excellent fabric to use for apparel in warm climates. Hemp, on the other hand, is an eco-friendly alternative to linen that has similar properties but offers greater mechanical strength, end-use performance, and durability. As a result of its eco-friendly qualities, the popularity of hemp fibre continues to increase as a result of the increased global demand for environmentally friendly products.

In addition to investigating the characteristics of hemp and linen fabrics, this chapter also examines the effect of finishing techniques on the properties of these fabrics. Yarn size, weave pattern, and composition have all been investigated to determine their impact on abrasion resistance and pilling tendency in textiles. This chapter focuses on the challenges related to pilling in textiles, taking into account their end-use characteristics. It analyzes factors that influence pilling, such as fibre composition, yarn qualities, and finishing procedures.

Furthermore, the chapter discussed Martindale, Schopper, Einlehner, Wyzenbeek, Pilling Drum, Pilling Box, and the Cylindrical Lighting System as methods for evaluating pilling and abrasion resistance in textiles. Drawing on scholarly works, we found Martindale's approach to be strongly suggested for testing work clothes, Einlehner's method for evaluating technical fabrics, and Schopper's method for testing car seats. A new approach for assessing the pilling tendency of textiles, Optical Coherence Tomography, was also mentioned. This approach allows pilling and fabric qualities to be assessed more accurately and effectively as it utilizes machine vision and optical scanning. The chapter also covered the relationship between surface roughness and abrasion resistance, emphasising the need to select the appropriate testing method based on fabric type and application.

2. Material and Methods

The main objective of this study was to look at the pilling along with abrasion resistance of 100% linen, 100% hemp, and 50% linen/50% hemp blends before and after finishing. The pilling and abrasion resilience of linen and hemp fabrics are important factors to consider when selecting materials for clothing and other textile goods. The outcomes of this study will be useful in identifying the kind of materials that work best in items that need to be highly durable and resistant to abrasion and pilling. Under precise climatic conditions, Martindale's abrasion tester was utilized to determine the end-use properties of each sample. To enhance the end-use properties of the investigated samples, the same fabric was enzymatically treated. Following enzymatic treatment, the treated fabric's pilling and abrasion resistance were again evaluated. The results were compared in order to analyze the end-use characteristics of linen and hemp fabrics.

2.1. Structural Parameters of the Fabrics

The primary focus of the study was on investigating the end-use performance of unfinished and finished linen, hemp, and linen/hemp blended fabrics before and after anti-pilling treatment. The linen and hemp yarns used in these fabrics have a linear average density of 28 tex in both the warp and weft directions. Warp was drawn in by skip-draft into four harnesses. The reeding was two threads per reed dent. The plan of the weave is represented in Fig. 8.

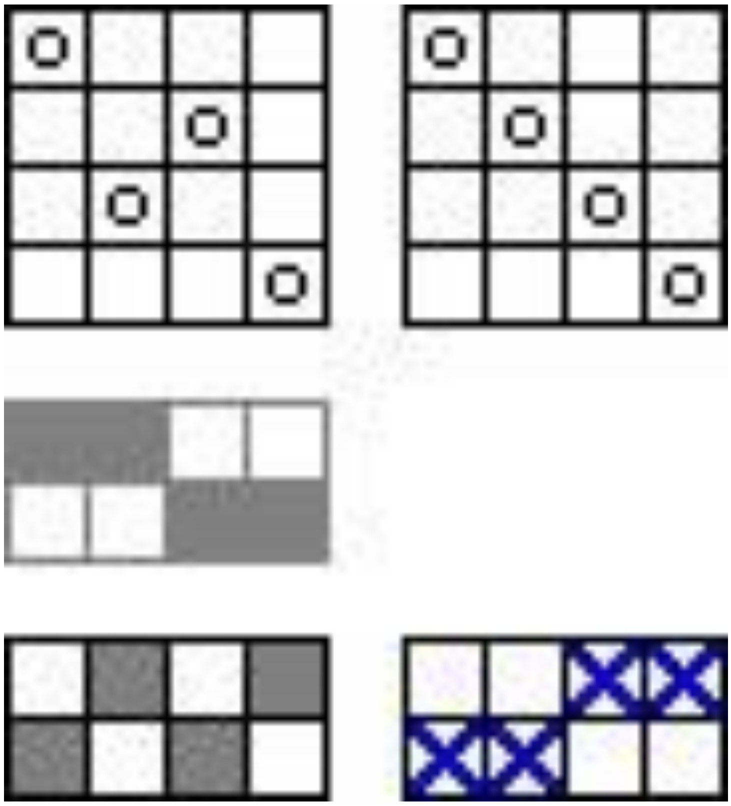


Fig. 8. Plan of weave

The materials were woven in plain weave on a rapier weaving loom Itema 9500 (Itema Group, Italy, Colzate) at the textile company Klasikinė tekstilė which is in Kaunas, Lithuania. The Itema 9500 weaving machine (Fig. 9) is a textile weaving apparatus that is known for its innovative features and great performance. With modern technology, it is possible to produce high-speed and versatile fabrics with complicated patterns and detailed designs.

Fig. 9. Weaving loom Itema 9500

The Itema 9500 with its user-friendly interface and automated controls, simplifies operation and decreases the possibility of error, making it a popular choice among textile makers. This weaving machine not only promotes increased production and great fabric quality but also establishes new industry standards.

An investigation of the structural parameters of unfinished and finished linen, hemp, and linen/hemp blended fabrics is carried out on the basis of the thread system, the raw material of the fibre, the linear density, and the warp setting and weft setting of the fabric.

Table 1. Structural parameters of the examined fabrics.

Fabric	**Thread system**	**Raw material**	**Linear density of yarn**	**Setting of unfinished fabric, dm^{-1}**	**Setting of finished fabric, dm^{-1}**
Linen	Warp	Linen	28 tex	220	251
	Weft	Linen	28 tex	203	234
Hemp	Warp	Hemp	28 tex	220	249
	Weft	Hemp	28 tex	203	237
Linen/Hemp	Warp	Linen	28 tex	220	252
	Weft	Hemp	28 tex	203	235

Table 1 presents the structural parameters of the studied fabrics. The linear density of all the investigated fabric's warp and weft threads was 28 tex. This is due to the fact that all of the textiles utilized were of the same weave type. The linear density of fabric measures its thickness, and in this situation, all fabrics were of the same thickness. The unfinished linen, hemp, and blended linen/hemp fabrics had warp and weft settings of 220 $dm^{-1}$and 203 dm^{-1} respectively. It ensured that the structure of all unfinished fabrics was identical. However, the warp and weft settings of the finished fabrics were a little different. The finished linen fabric's warp and weft settings were 251 dm^{-1} and 234 dm^{-1}, respectively. The warp setting in the finished hemp fabric was 249 dm^{-1} and the weft setting was 237 dm^{-1}. The warp setting in the finished linen/hemp blended fabrics was 252 dm^{-1} and the weft setting was 235 dm^{-1}. However, these differences are not significant and it can be said that the settings of finished fabrics are similar.

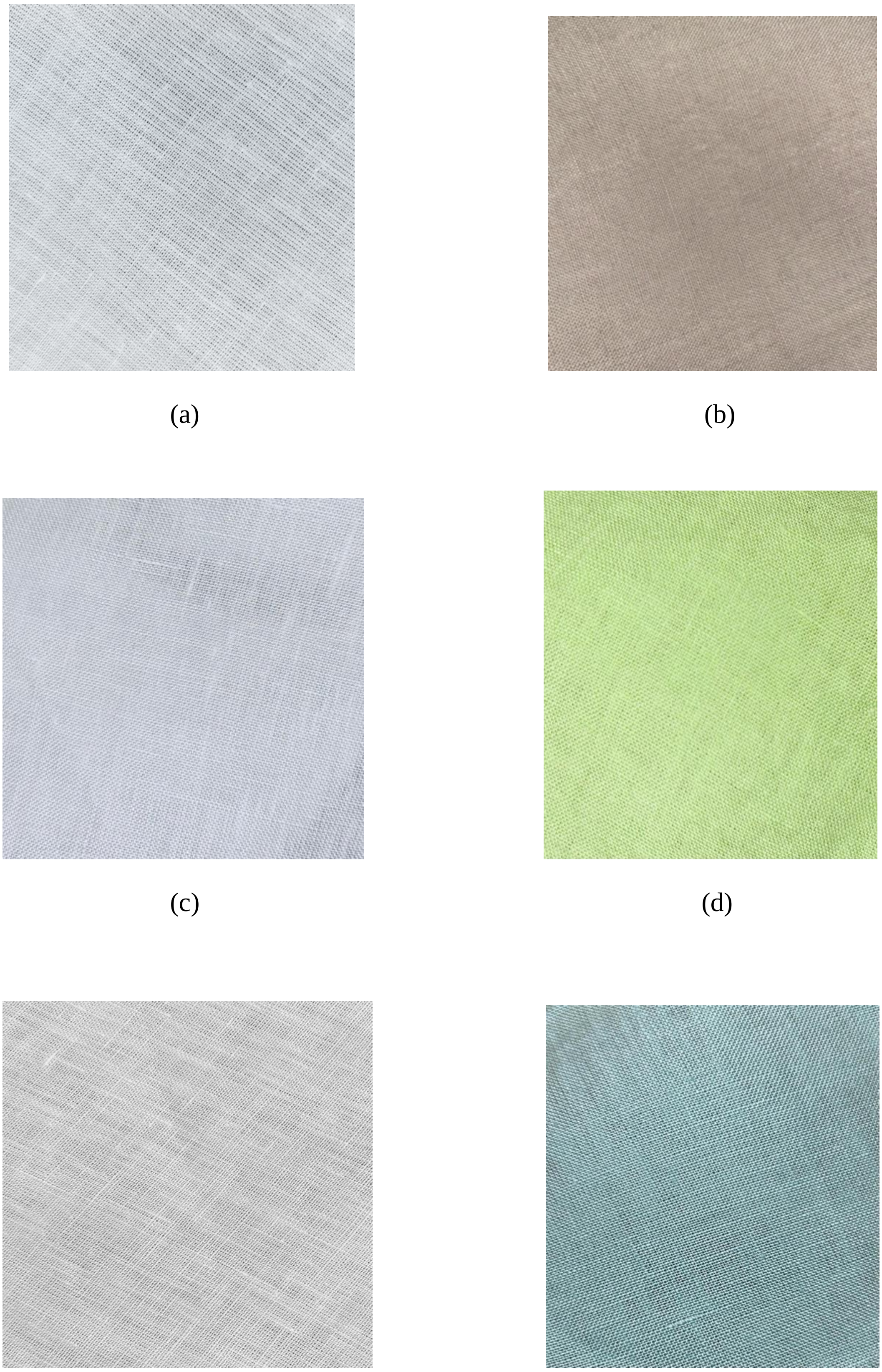


Fig. 10. Investigated fabrics: (a) unfinished linen fabric; (b) finished linen fabric; (c) unfinished hemp fabric; (d) finished hemp fabric; (e) unfinished linen/hemp blended fabric; (f) finished linen/hemp blended fabric.

All of the investigated materials, including unfinished and finished linen fabric, unfinished and finished hemp fabrics, and unfinished and finished linen/hemp blended fabrics are shown in Fig. 10.

2.2. Finishing Process and Additional Technological Operations

Unfinished fabrics went through washing, dyeing, and mechanical softening processes. As part of the finishing process, fabrics were washed, dyed, rinsed, softened, dried and treated with enzymes, and the schematic process is shown in Fig. 11.

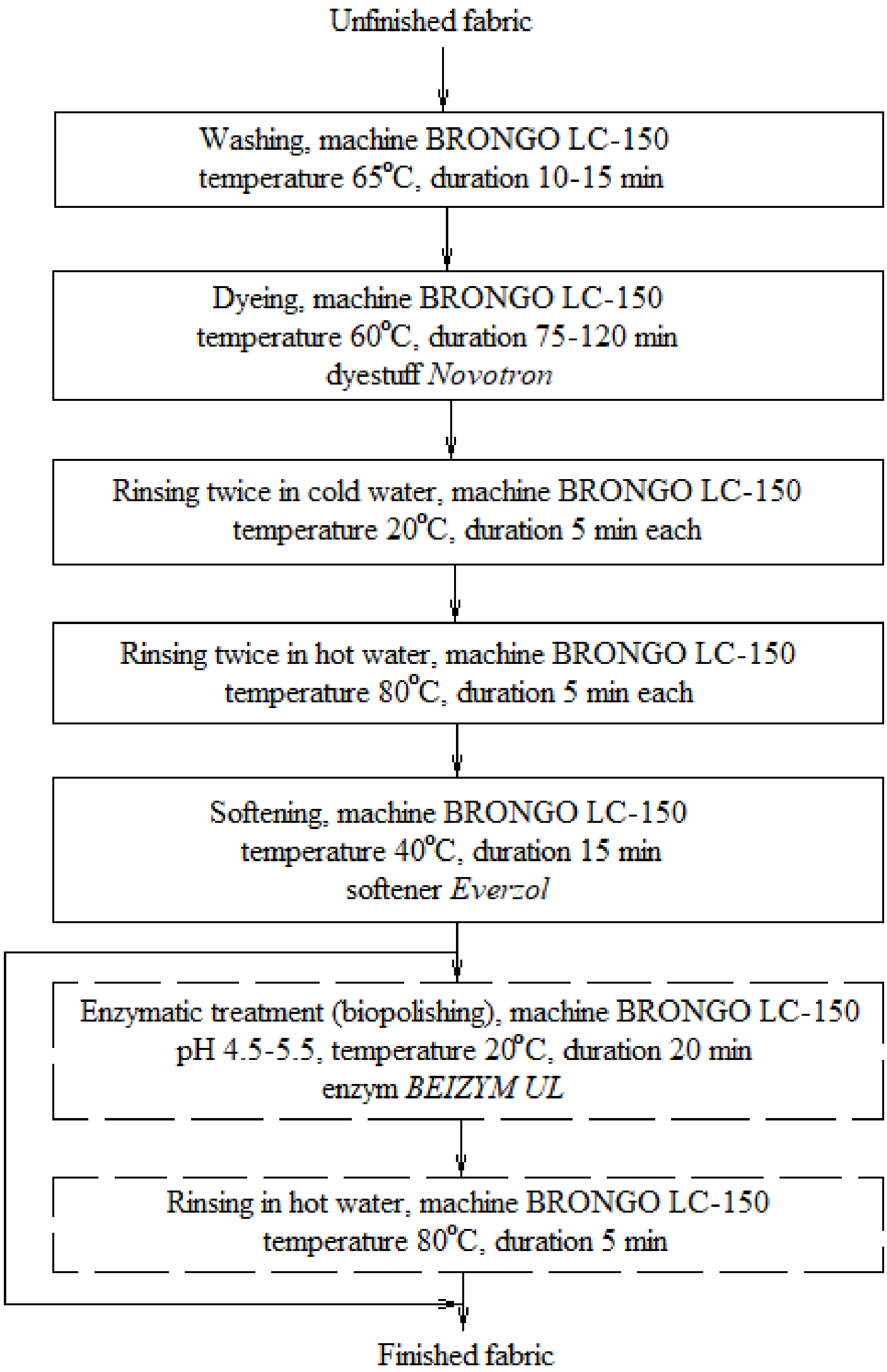


Fig. 11. Schematic diagram of finishing process and additional technological operations

All of the treatments were carried out using BRONGO LC-150 (Brongo, Valencia, Italy) equipment. This machine has a number of automated operations that allow it to handle all treatments rapidly and efficiently. The treatments increased the appeal and durability of the fabric, as well as its ability to withstand wear and tear. The textiles were washed for 10–15 minutes at 65°C, then dyed for 75–120 minutes at 60°C. For dyeing, Novotron reactive dyestuff (Hausmann, Zurich, Switzerland) was utilized. Reactive dyestuff is chosen for its ability to adhere to the fabric and create long-lasting colour. For each treatment, optimal temperatures and durations were maintained to ensure that the fabric was adequately treated. After dying, the fabrics were rinsed with cold water twice and with hot water twice. Each rinse took five minutes. Any extra dye will removed by rinsing with cold water, while the hot water rinse sets the colour. Softening was then performed in an acidic atmosphere at 40°C for 15 minutes. The softening agent utilized was Everzol (Eeverlight Chemical Industrial Corp., Taipei, Taiwan). A softening agent called Everzol made the fabric softer and smoother by neutralizing any alkalinity in the dye. Drying was done for 15 minutes at a temperature of 60 °C. Furthermore, the fabrics were also treated with enzymes to prevent pilling and improve end-use qualities and dried under the same conditions.

Enzymatic treatment (biopolishing) was carried out in the same universal machine BRONGO LC-150 using the enzyme BEIZYM UL (CHT, Tubingen, Germany) in an acidic environment (pH 4.5–5) and at a temperature of 20 °C. The treatment lasted for 20 minutes. It was required to rinse the fabric in hot water (80 °C) following enzymatic treatment.

2.3. Methods

The experiments were conducted at the Laboratory of Materials Research of the Faculty of Mechanical Engineering and Design at Kaunas University of Technology according to certain standards and atmospheric conditions.

2.3.1. Atmospheric conditions

In compliance with standard LST EN ISO 139:2006 "Textiles Standard Atmospheres for Conditioning and Testing", the samples were left for a whole day, and the experiments were performed under standard conditioning and testing environment with a temperature of (20 ± 2) ^{o} C and relative humidity of (65 ± 4) % (Fig. 12).

Fig. 12. Air-conditioning panel showing air temperature and humidity

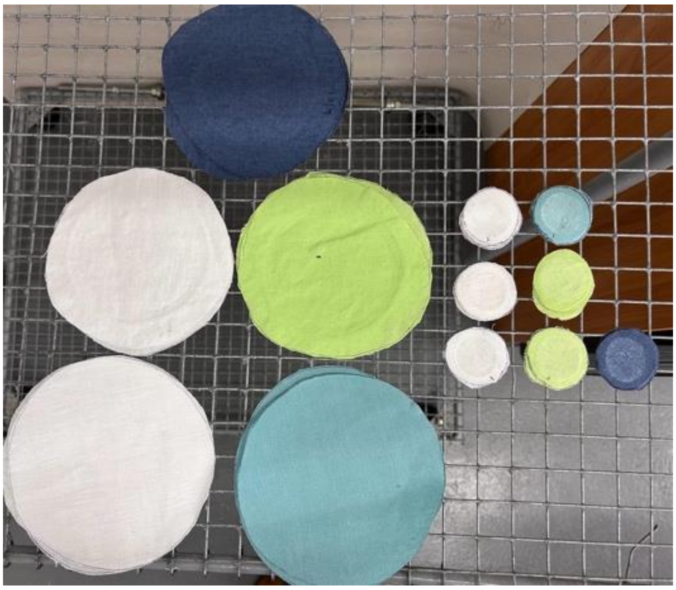


Fig. 13. Horizontal air-permeable surface for specimen conditioning

The samples to be studied were placed on the shelf, which has a level horizontal surface and is air-permeable (Fig. 13).

2.3.2. Establishing of Pilling Resistance of the Fabrics

The Martindale pilling and abrasion tester MESDAN-LAB, Code 2561E (SDL AT-LAS, London, England) was used to determine the pilling resistance of woven fabrics. The experiment was carried out in accordance with the standard LST EN ISO 12945-2:2000 “Textiles. Determination of fabric propensity to surface fuzzing and to pilling, Part 2: Modified Martindale Method”. Three pairs of circular samples were cut from the fabrics under investigation, three of which were placed on the holders and the other three on the pilling table (Fig. 14).

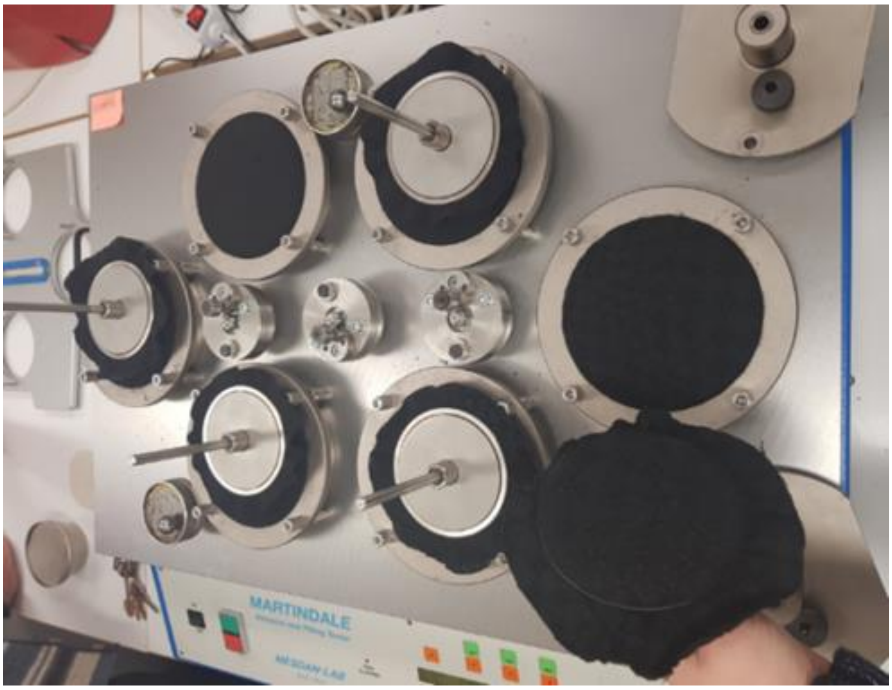


Fig. 14. Sample pairs on the holders and pilling tables

After passing a specific number of cycles outlined in the standard, two experts visually examined each sample. According to the standard, the number of cycles after which the tester must be stopped is 125, 500, 1000, and 2000 cycles. A total of 2000 cycles is considered sufficient if the abraded samples have an appearance grade of 4 or lower after 2000 cycles. All investigations using woven textile samples complied with this requirement. After evaluating each sample's appearance, the pilling grade was determined, and the average result was calculated. The pilling grades are described in Table 2.

Table 2. Visual evaluation of the pilling test

Grade	Description
5	Remains unchanged.
4	Partially formed or slightly fluffed-up pills
3	Moderate pilling or pills of various sizes covers a section of the sample's surface.
2	Prominent pilling or pills of various sizes cover a significant amount of the sample's surface.
1	Extremely noticeable pilling or pills of various sizes encompass the entire sample's surface.

The visual evaluation of the pilling test is performed using Table 2. The samples were evaluated based on the changes in the fabric's surface. The fabric with no surface changes will be graded as 5, indicating that it has excellent pilling performance. The lowest grade of 1 indicates that the fabric has minimal pilling performance, with highly noticeable pill formation on the fabric surface.

2.3.3. Establishing of Abrasion Resistance of the Fabrics

The abrasion resistance of the investigated specimens was established in accordance with the standard LST EN ISO 12947-2 "Textiles. Determination of the abrasion resistance of fabrics by the Martindale method, Part 2: Determination of specimen breakdown". The Martindale abrasion and pilling tester MESDAN-LAB, Code 2561E (SDL AT-LAS, London, England) (Fig. 15), was used to determine the fabric's abrasion resistance.

Fig. 15. Martindale abrasion and pilling tester MESDAN-LAB, Code 2561E (SDL AT-LAS, London, England)

Finished and unfinished fabrics under investigation were cut into 38 mm diameter circular specimens, which were then attached in holders (Fig. 16). A force of 9 kPa was applied to the samples during abrasion. (Fig. 17).

Fig. 16. Holder of Martindale abrasion and pilling tester

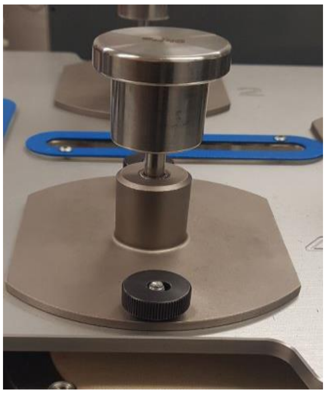


Fig. 17. Load of 9 kPa in Martindale abrasion and pilling tester

The abrasion tester was paused every 2,000 cycles throughout the entire experiment. After each abrasion cycle, the sample’s condition was evaluated. A sample is considered broken when two threads break on the surface of the fabric and holes appear. During the experiment, the change in sample mass due to abrasion was also determined.

Fig. 18. KERN EW 150-3M (KERN & Sohn GmbH, Wurtenberg, Germany)

An electronic balance, the KERN EW 150-3M (KERN & Sohn GmbH, Wurtenberg, Germany) (Fig. 18), was used to weigh abrasion samples both before and after the experiment, stopping the tester after each of the 2000 cycles.

2.3.4. Statistical Analysis of the Experiments

The statistical analysis of the experiments was carried out in accordance with the reference [35]. The average, standard deviation and coefficient of variation were determined using well-known statistical formulas.

During the experiment, the arithmetic average is used to calculate the average value of the properties of the performed experiments. The average value was obtained using Eq. 1.

$$\bar{x} = \frac{\sum_{n}^{i=1} x_i}{n}, \tag{1}$$

where: $\bar{x}$ is the average value; x_i is the value of each sample; *n* is a number of samples.

When analysing the results, it is critical to understand the dispersion of the results, which can be expressed in absolute or relative dispersion values. The standard deviation, which measures the departure of elementary test values from the arithmetic average, is the most extensively used absolute measure. The standard deviation was computed using Eq. 2.

$$s = \sqrt{\frac{\sum_{n}^{i=1} (x_i - \bar{x})^2}{n-1}}, \tag{2}$$

where: s is the standard deviation; x_i is the value of each sample; $\bar{x}$ is an average value; n is the number of samples.

The coefficient of variation, which calculates the dispersion with respect to the average test value and the number of elementary tests, is the most widely used relative measure of the dispersion of the results. The coefficient of variation was estimated using Eq. 3.

$$V = \frac{s}{\bar{x}}\, 100\%, \tag{3}$$

where: *V* is the coefficient of variation; s is the standard deviation; $\bar{x}$ is an average value.

ANOVA statistical analysis was performed using MatLab software.

2.4. Chapter Summary

This chapter examines the quality and durability of linen and hemp fabrics by analyzing their resistance to pilling and abrasion. These properties are crucial in assessing the performance of these fabrics in various applications. The investigation includes evaluating as well as treating the fabrics to determine their suitability for high-performance use.

The chapter begins by discussing the fabric structural parameters, which include unfinished and finished linen, hemp, and linen/hemp blends. The density of these fabrics is 28 tex. The chapter also covers the thread systems used, the raw materials used, and the changes in the warp and weft settings throughout the finishing process. The Itema 9500 rapier weaving loom was used for weaving the fabrics that were investigated. Following the fabric structure discussion, a thorough finishing procedure is explained. This procedure combines washing and dyeing using Novotron reactive dyestuffs to achieve long-lasting colours, as well as mechanical softening. Softening chemicals such as Everzol are also used to provide a softer texture. Enzymatic treatment with cellulase enzymes BEIZYM UL is also used to improve fabric durability, minimize pilling, and improve water absorption.

The methodology section describes the techniques used at Kaunas University of Technology's Laboratory of Materials Research under atmospheric conditions to ensure standardization. The Martindale method was used to test abrasion resistance, and the Martindale pilling and abrasion tester was used to evaluate pilling resistance. The results were statistically analyzed to measure critical factors such as the average, standard deviation, and coefficient of variation. In summary, this chapter provides a thorough description of the materials, manufacturing procedures, and testing methodology used to measure the pilling and abrasion resistance of linen and hemp fabrics. This foundation lays the groundwork for the study’s future investigation and findings.

3. Results and Discussion

The study thoroughly evaluated the abrasion resistance performance of linen, hemp, and blended linen/hemp fabrics in addition to their pilling resistance. Standard tests were performed on both finished and unfinished fabrics at different cycle intervals using Martindale's pilling and abrasion tester. The testing procedure was conducted in accordance with specific standards, i.e, LST EN ISO 12945-2:2000 “Textiles. Determination of fabric propensity to surface fuzzing and to pilling, Part 2: Modified Martindale Method” for evaluating the pilling resistance of the fabrics and LST EN ISO 12947-2 “Textiles. Determination of the abrasion resistance of fabrics by the Martindale method, Part 2: Determination of specimen breakdown” for the determining the abrasion resistance of the fabric, which guaranteed the durability of the fabric. This multidimensional approach made it possible to thoroughly examine the fabric's abrasion and pilling resistance, which gave important insights into their overall durability and suitability for a range of end-use applications.

3.1. Analysis of Pilling Resistance

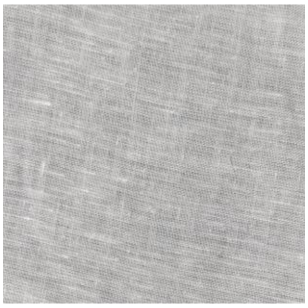
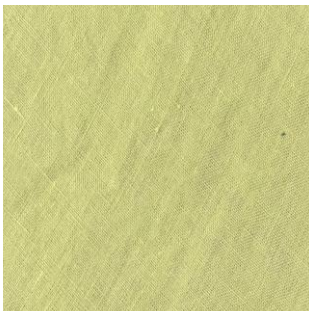
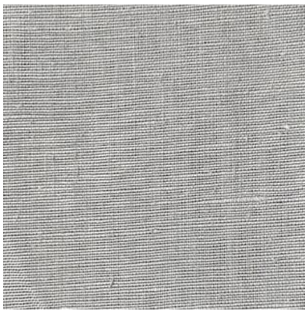
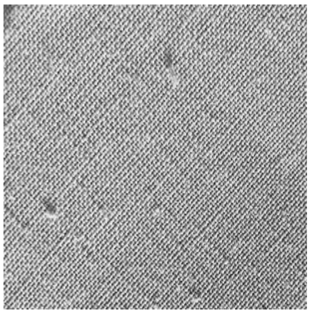
According to the situational analysis, pilling resistance has an important effect on the fabric's durability. The pilling resistance of unfinished and finished fabrics of linen, hemp, and linen/hemp blended fabrics was evaluated through a comprehensive analysis. The results included a comparison of pilling resistance among unfinished and finished fabrics, allowing for an investigation of the impact of the finishing procedure on this particular attribute. In addition, the overall pilling resistance of the woven fabric was improved by blending linen and hemp. Additionally, an enzymatic treatment was applied to all fabrics under investigation in an attempt to increase their resistance to pilling. Following treatment, the pilling resistance of all treated fabrics was evaluated, and comparisons were made to the results obtained for finished fabrics. The objective of this comparison was to determine which fabric showed the greatest improvement in pilling resistance after enzymatic treatment.

3.1.1. Pilling Resistance of Linen, Hemp and Linen/Hemp Blended Fabrics

The pilling resistance was assessed by performing a pilling test on unfinished and finished linen, hemp, and linen/hemp blended textiles in accordance with the standards mentioned in the methodology.

Table 3. Samples of unfinished and finished fabrics during the pilling resistance test after a specific number of cycles

Number of cycles	**0 cycles**	**500 cycles**	**2000 cycles**
Unfinished linen fabric			

Number of cycles	**0 cycles**	**500 cycles**	**2000 cycles**
Finished linen fabric			
Unfinished hemp fabric			
Finished hemp fabric			
Unfinished blended fabric			
Finished blended fabric			

The pilling characteristics of unfinished as well as finished samples of linen, hemp, and linen/ hemp fabric at various cycle intervals are presented in Table 3. It can be seen that at 500 cycles, the fabric's surface became fluffier, and some pills started to appear on the surface of the fabrics. Following 2000 cycles, it was observed that a distinct pill formation had occurred across the entire surface of all the fabrics.

The fabrics were then visually inspected and graded to determine their pilling resistance. The pilling grades of the investigated fabrics are displayed in Table 4.

Table 4. Grade of pilling for both unfinished and finished fabrics

Raw material	Number of samples	Number of cycles							
		125 cycles		500 cycles		1000 cycles		2000 cycles	
		Expert 1	Expert 2	Expert 1	Expert 2	Expert 1	Expert 2	Expert 1	Expert 2
Unfinished linen	1	3.5	3.5	2.5	2.5	2.0	2.0	1.0	1.0
	2	3.5	3.5	2.0	2.0	2.0	2.0	1.0	1.0
	3	3.0	3.0	2.0	2.0	2.0	2.0	1.0	1.0
Unfinished hemp	1	4.0	4.0	3.5	3.5	3.0	3.0	2.0	2.0
	2	4.0	4.0	3.5	3.5	3.0	3.0	2.0	2.0
	3	4.0	4.0	3.5	3.5	3.0	3.0	2.0	2.0
Unfinished linen/hemp	1	3.5	3.5	3.0	3.0	2.5	2.5	2.0	2.0
	2	3.5	3.5	3.0	3.0	2.5	2.5	2.0	2.0
	3	3.5	3.5	3.0	3.0	2.5	2.5	2.0	2.0
Finished linen	1	4.0	4.0	3.0	3.0	2.5	2.5	2.0	2.0
	2	4.0	4.0	3.0	3.0	2.5	2.5	2.0	2.0
	3	4.0	4.0	3.0	3.0	2.5	2.5	2.0	2.0
Finished hemp	1	4.5	4.5	4.0	4.0	4.0	4.0	3.0	3.0
	2	4.0	4.0	4.0	4.0	4.0	4.0	3.5	3.5
	3	5.0	5.0	4.0	4.0	4.0	4.0	3.5	3.5
Finished linen/hemp	1	4.0	4.0	3.5	3.5	3.0	3.0	2.5	2.5
	2	4.0	4.0	3.5	3.5	3.0	3.0	2.5	2.5
	3	4.0	4.0	3.5	3.5	3.0	3.0	2.5	2.5

Table 4 presents average pilling grades after 125, 500, 1000, and 2000 cycles for unfinished and finished fabrics made of linen, hemp, and linen/hemp blends. The unfinished hemp and linen fabrics, in particular, regularly demonstrated lower pilling grades than their finished equivalents across the prescribed cycle intervals. The linen/hemp blended fabric likewise complies with this pattern, exhibiting lower average pilling grades in its unfinished condition.

The column diagram/graph of pilling grades was drawn concerning the kind of fabric based on the average grades of three samples from Table 4 to examine the pilling resistance of all the researched textiles. The diagram is depicted in Figure 19. The evaluation of the pilling resistance of the fabrics that were tested does not include any statistical parameters that are calculated, as can be observed. This is because pilling resistance is evaluated based on grades rather than other values that are measured. Nevertheless, because of this, it is not possible to establish the statistical characteristics.

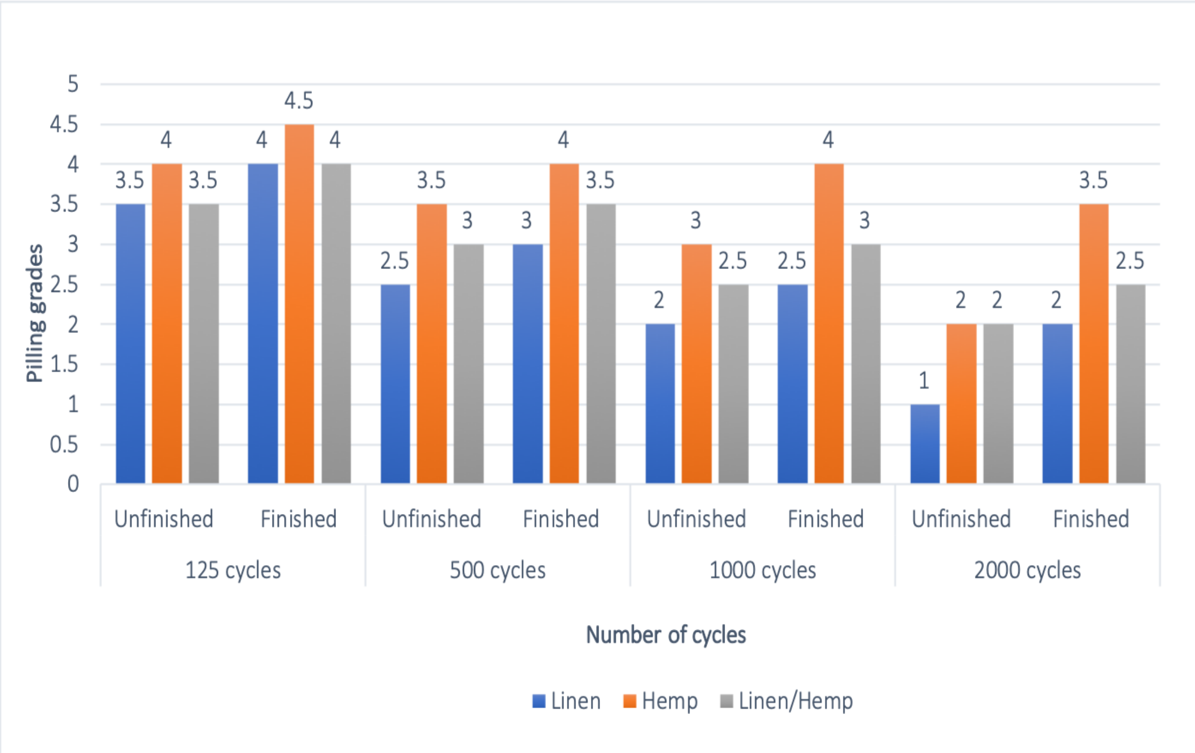


Fig. 19. Graph of pilling performance of investigated unfinished and finished fabrics

According to the graph (Fig. 19), unfinished hemp fabric has the highest pilling resistance in comparison to linen fabric at about 1.0 grade and to blended linen/hemp fabric at about 0.5 grade in all stages of the pilling test. The results of the finished fabrics are distributed similarly, i.e., the pilling grades are lower from 0.5 grade after 125 cycles to 1.5 grade after 2000 cycles for linen fabrics and from 0.5 grade after 125 cycles to 1.0 grade after 2000 cycles for blended linen/hemp fabric. Also, it can be seen that the finishing process improves the pilling performance of the fabrics of all raw materials, from 0.5 grades for linen and blended fabrics, 0.5–1.5 grades for hemp fabric. The reason for such results can be that hemp yarn is made from long fibres, and its surface becomes plainer than that of other fibre yarns during the pilling process. Thus, the results of the pilling test for hemp fabric are the highest, and for linen fabric, they are the lowest. Blended fabric's pilling resistance occupies an intermediate position between the other two fabrics, i.e., the blending of linen and hemp fibres in one fabric improves the pilling performance of linen fabric.

With the aim of improving the pilling resistance of linen fabrics individually, blending of linen with hemp fibres was employed and it was found that linen exhibited better pilling performance when blended with hemp both before and after finishing. This is because blended textiles provide pill resistance by integrating diverse fibre qualities. Blending natural fibres with another long-lasting natural fibre helps to maintain a smooth fabric surface over time. Blended fabrics reduce the possibility of pilling caused by repetitive rubbing by reducing friction between the threads. Moreover, the enhanced pilling resistance of these fabrics contributes to their durability, preventing the formation of fibers and pills on the surface of the fabrics. In order to avoid pilling, it is suggested to develop blended materials to minimize wear and friction in specific regions.

The obtained results are consistent with the findings from [15] on the pilling resistance of textiles made of the same raw material. It was also determined by the authors that hemp fabric has the highest value of all the properties of this fabric, and that all the textiles under investigation have greater pilling resistance upon finishing. It was also shown in [17] that cloth composed of longer hemp fibers resists pilling better than fabric composed of shorter cotton fibers. These findings are consistent with current results that showed similar tendencies for shorter linen and longer hemp fibers.

3.1.2. Improvement of Pilling Resistance of Linen, Hemp, Linen/Hemp Blended Fabrics

With the goal of improving the pilling strength of finished linen, hemp, and linen/hemp blended fabrics, the investigated finished fabrics were additionally treated enzymatically with an enzyme called “BEIZYM UL”. Later, the pilling performance was evaluated for the treated fabrics.

Table 5. Samples of chemically treated finished fabrics during pilling resistance test after a specific number of cycles

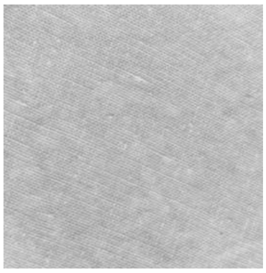
Number of cycles	**0 cycles**	**500 cycles**	**2000 cycles**
Finished linen fabric after treatment			
Finished hemp fabric after treatment			
Finished blended fabric after treatment			

Table 5 shows the pilling properties of treated linen, hemp, and linen/hemp fabric at different cycle intervals. It was discovered that when the number of cycles increased, specific changes occurred in the materials, but at the end of the test (after 2000 cycles), the number of pills as well as pilling grade was lower than that of fabrics without enzymatic treatment.

The enzymatically treated fabrics were then visually inspected and graded to determine their pilling resistance. The pilling grades of the finished fabrics before treatment and after treatment are displayed in Table 6.

Table 6. Grade of pilling for finished fabrics before and after enzymatic treatment

Raw material	**Number of samples**	**Number of cycles**							
		125 cycles		**500 cycles**		**1000 cycles**		**2000 cycles**	
		Expert 1	**Expert 2**	**Expert 1**	**Expert 2**	**Expert 1**	**Expert 2**	**Expert 1**	**Expert 2**
Finished linen fabric before treatment	1	4.0	4.0	3.0	3.0	2.5	2.5	2.0	2.0
	2	4.0	4.0	3.0	3.0	2.5	2.5	2.0	2.0
	3	4.0	4.0	3.0	3.0	2.5	2.5	2.0	2.0
Finished hemp fabric before treatment	1	4.5	4.5	4.0	4.0	4.0	4.0	3.0	3.0
	2	4.0	4.0	4.0	4.0	4.0	4.0	3.5	3.5
	3	5.0	5.0	4.0	4.0	4.0	4.0	3.5	3.5
Finished blended fabric before treatment	1	4.0	4.0	3.5	3.5	3.0	3.0	2.5	2.5
	2	4.0	4.0	3.5	3.5	3.0	3.0	2.5	2.5
	3	4.0	4.0	3.5	3.5	3.0	3.0	2.5	2.5
Finished linen fabric after treatment	1	4.0	4.0	3.5	3.5	3.5	3.5	3.0	3.0
	2	4.0	4.0	3.5	3.5	3.0	3.0	3.0	3.0
	3	4.0	4.0	3.5	3.5	3.0	3.0	3.0	3.0
Finished hemp fabric after treatment	1	4.5	4.5	4.5	4.5	4.0	4.0	4.0	4.0
	2	4.5	4.5	4.5	4.5	4.0	4.0	4.0	4.0
	3	4.5	4.5	4.5	4.5	4.0	4.0	4.0	4.0
Finished blended fabric after treatment	1	4.5	4.5	4.0	4.0	3.5	3.5	3.0	3.0
	2	4.5	4.5	4.0	4.0	3.5	3.5	3.0	3.0
	3	4.5	4.5	4.0	4.0	3.5	3.5	3.0	3.0

Table 6 presents average pilling grades after 125, 500, 1000, and 2000 cycles for finished fabrics made of linen, hemp, and linen/hemp blends before and after enzymatic treatment. The finished hemp and linen fabrics, in particular, regularly demonstrated lower pilling grades than the treated fabrics across the prescribed cycle intervals. The linen/hemp blended fabric likewise complies with this pattern, exhibiting lower average pilling grades before treatment. The column diagram was plotted using the obtained pilling grades from Table 6. The diagram is presented in Fig. 20.

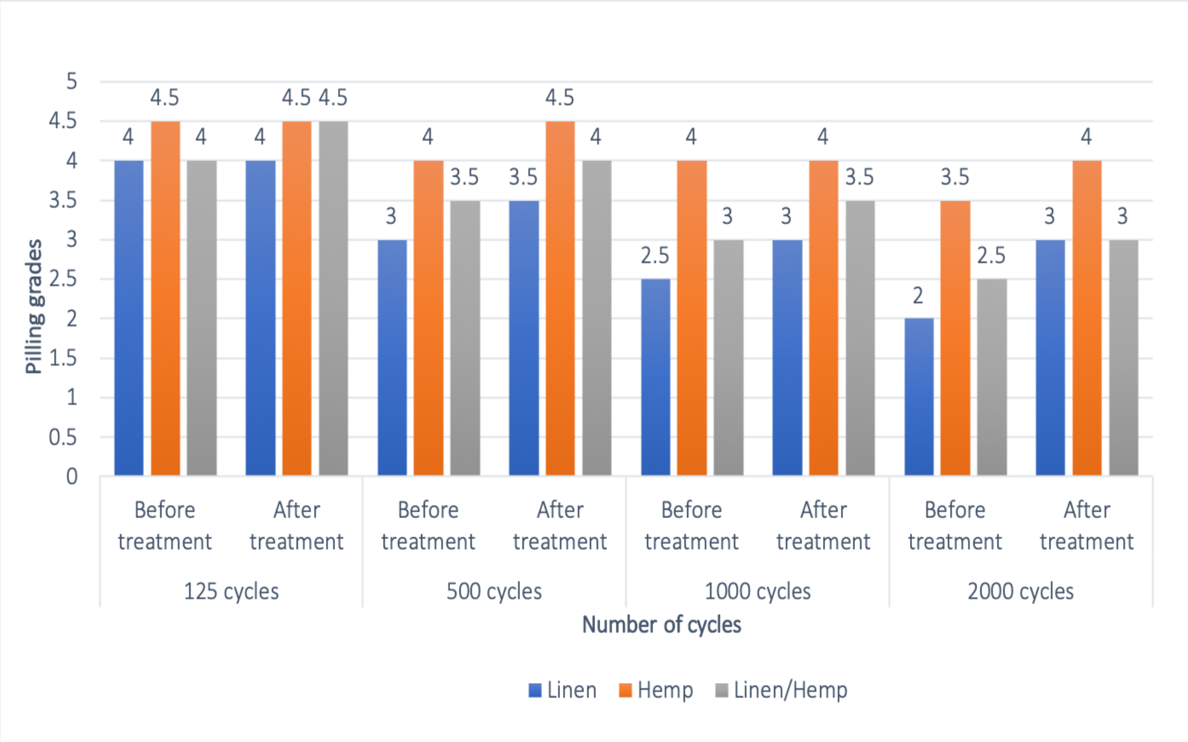


Fig. 20. Graph of pilling performance of investigated finished fabrics before and after treatment

The graph indicates that the pilling performance was further enhanced by treating the finished fabrics with the enzyme. After 125 cycles, this improvement is not visible, but it becomes high with the increase in the number of cycles. For example, at the end of the pilling test, the pilling resistance rises to 1.0 grade for linen fabric and 0.5 grade for hemp and blended linen/hemp fabrics. Thus, finishing has the highest influence on linen fabric pilling resistance and the lowest one on hemp fabric pilling resistance because the usual finishing improves the pilling performance of hemp fabric more than the additional enzymatic treatment.

The results obtained are consistent with those published in [16], demonstrating that finishing techniques affect the end-use characteristics of fabrics made of cotton, hemp, and linen. Enzyme treatment also improves the resistance of bleached hemp fabric to pilling, as confirmed in reference [18]. While chitosan was the chemical utilized in another experiment [19], the use of chitosan improves hemp fabric's ability to pill. The results that were obtained line up with the findings of other researchers in [16, 18, 19].

3.1.3. Influence of Raw Material and Finishing Type on Pilling Resistance

In order to find out whether the raw material and the type of finishing (independent variables) affect the pilling resistance of the fabric (dependent variable), a two-way analysis of variance was applied using MatLab software.

At first, the null hypothesis and alternate hypothesis are formulated in Table 7.

Table 7. Raised hypothesis for pilling resistance

Null hypothesis (H_0)	**Alternate hypothesis (H_a)**
There is no difference in average yield for any raw materials.	There is a difference in average yield by raw materials.
There is no difference in average yield depending on the type of finishing.	There is a difference in average yield by type of finishing.
The effect of one independent variable on average yield does not depend on the effect of the other independent variable.	There is an interaction effect between the group of materials and the type of finishing on average yield.

The ANOVA analysis table for the influence of pilling resistance on raw material ("columns" in the table) and type of finishing ("rows" in the table) is presented in Fig. 21.

ANOVA Table

Source	SS	df	MS	F	Prob>F
Columns	5.6045	2	2.80224	6.12	0.0064
Rows	7.9964	2	3.99822	8.74	0.0012
Interaction	0.1993	4	0.04983	0.11	0.9784
Error	12.3557	27	0.45762		
Total	26.156	35			

Fig. 21. ANOVA table for the influence of pilling resistance on raw material and type of finishing

The obtained results show that the hypothesis "There is no difference in average yield for any raw materials" is rejected (p_{value} =0.0064<0.05) and the alternate hypothesis, "There is a difference in average yield by raw materials" is accepted. That means that raw materials influence pilling performance.

The second null hypothesis, "There is no difference in average yield depending on the type of finishing" is also rejected (p_{value} =0.0012<0.05), and the alternate hypothesis, "There is a difference in average yield by type of finishing" is accepted. That result shows that the type of finishing influences pilling resistance.

However, the third null hypothesis, "The effect of one independent variable on average yield does not depend on the effect of the other independent variable" is accepted because p_{value} =0.9784>0.05. That means that the raw material and the type of finishing independently affect pilling resistance.

The multiple comparison test was performed to see how different raw materials affect the pilling performance (p_{value}=0.0064<0.05). The confidence intervals of linen, hemp, and blended linen/hemp fabrics are presented in Fig. 22. The average of the second group (hemp fabric) is statistically different from the rest of the groups (linen and blended fabrics). This means that the raw material affects pilling performance.

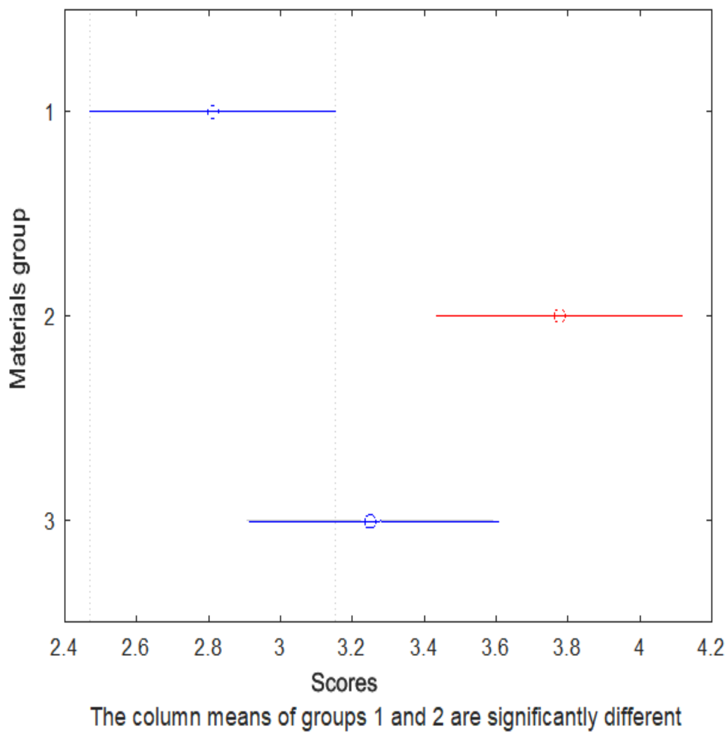


Fig. 22. Confidence intervals for different raw materials in pilling resistance: (1) linen; (2) hemp; (3) blended linen/hemp

Also, a multiple comparison test was performed to see how the type of finishing affects the pilling performance (p_{value}=0.0012<0.05). The confidence intervals of pilling resistance for fabrics under different types of finishing are shown in Fig. 23.

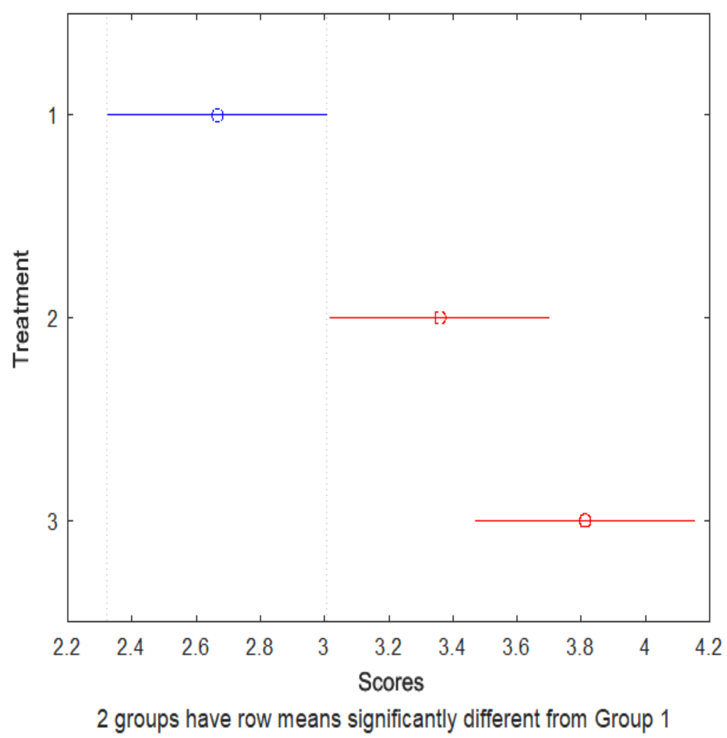


Fig. 23. Confidence intervals for different types of finishing in pilling resistance: (1) unfinished fabric; (2) finished fabric; (3) fabric after enzymatic treatment

The average of the first group (unfinished fabric) differs statistically from those of the other groups (finished fabric and finished fabric after enzymatic treatment). This means that the type of finishing influences pilling performance.

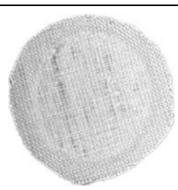
3.2. Analysis of Abrasion Resistance

The situational analysis additionally revealed that the durability and endurance of the fabric are greatly influenced by abrasion resistance. Abrasion resistance is an important property of textiles that significantly impacts the functionality and durability of various products, including clothing, furniture upholstery, and industrial applications. The abrasion resistance of a fabric is mostly determined by the composition of its fibers. The present study conducted a thorough investigation to evaluate the abrasion resistance of unfinished and finished linen, hemp, and linen/hemp blended fabrics. The objective of this chapter is to identify the fabric with the highest resistance to abrasion. An analysis was conducted to compare the abrasion resistance of unfinished and finished fabrics, with the aim of examining the influence of the finishing process on the fabric's performance in practical applications. In addition, linen and hemp yarns were blended to enhance the specific abrasion resistance of linen fabric. Furthermore, all fabrics under consideration underwent an enzymatic treatment to strengthen their abrasion resistance. The abrasion resistance of all treated fabrics was compared with the finished fabrics before treatment. The purpose of this study was to ascertain which fabric exhibited the highest increase in abrasion resistance following enzymatic treatment.

3.2.1. Abrasion Resistance of Linen, Hemp, Linen/Hemp Blended Fabric

The abrasion resistance of linen, hemp, and line/hemp blended fabrics was evaluated according to the specified requirements described in Chapter 2. These standards were applied to both unfinished and completed variations of the materials. The statistical values pertaining to the abrasion resistances were determined utilizing the formula for statistical characteristics, as specified in the methodology. Furthermore, the Matlab software was utilized in order to conduct an analysis of variance (ANOVA) of the data.

Table 8. Samples of unfinished and finished fabrics after a specific number of abrasion cycles

No. of cycles	**4000 cycles**	**12000 cycles**	**16000 cycles**	**18000 cycles**	**22000 cycles**	**24000 cycles**
Unfinished linen fabric			-----	---	---	---
Finished linen fabric				---	---	---

No. of cycles	4000 cycles	12000 cycles	16000 cycles	18000 cycles	22000 cycles	24000 cycles
Unfinished hemp fabric					---	---
Finished hemp fabric						
Unfinished blended fabric				---	---	---
Finished blended fabric						---

Table 8 depicts the effect of various abrasion cycles on both unfinished and finished linen, hemp, and linen/hemp blended fabrics. The unfinished linen fabric sustained 12000 abrasion cycles, the unfinished hemp fabric sustained 18000 abrasion cycles, and the blend of linen and hemp fabric sustained 16000 abrasion cycles, whereas the finished linen fabric sustained 16000 abrasion cycles, the finished hemp sustained 24000 abrasion cycles, and the finished blended fabric sustained 22000 abrasion cycles. It can be seen from the pictures that, at first, the surface of the fabrics is flat and smooth. After a specific number of abrasion cycles, pills and hairiness started to form on the fabric surface, and the threads of the fabric became thinner. At the final stage of the abrasion test, two threads break and two holes appear in the fabric samples.

At every 2000-cycle interval, the average mass loss for each fabric was calculated. In addition, statistical parameters such as standard deviation, and coefficient of variation were determined to explain the dispersion of mass loss across the fabric, as shown in Table 9. All the statistical values were determined using the statistical analysis formula.

Table 9. Statistical values and average mass loss of unfinished and finished linen, hemp, and linen/hemp blended fabric sample

Samples	Statistical characteristics	Number of cycles											
		2000	**4000**	**6000**	**8000**	**10000**	**12000**	**14000**	**16000**	**18000**	**20000**	**22000**	**24000**
Unfinished linen fabric	Average mass loss, mg	2.9	6.3	9.7	12.1	16.7	20.7	--	--	--	--	--	--
	Standard deviation, mg	0.4	1.1	0.4	1.8	3.2	4.6	--	--	--	--	--	--
	Co-efficient of variation, %	12.4	17.5	4.2	14.6	18.9	22.4	--	--	--	--	--	--
Finihsed linen fabric	Average mass loss, mg	8.3	12	14	17	19	21.7	26.3	28.7	--	--	--	--
	Standard deviation, mg	1.5	1	1.7	1.7	1	1.5	4.9	5.5	--	--	--	--
	Co-efficient of variation, %	18.3	8.3	12.4	10.2	5.3	7.1	18.7	19.2	--	--	--	--
Unfinished hemp fabric	Average mass loss, mg	2.3	5	7	9	10	11.3	13.3	16	19	--	--	--
	Standard deviation, mg	0.6	1	1	1	1	0.6	2.1	3.5	4.4	--	--	--
	Co-efficient of variation, %	24.7	20	14.2	11.1	10	5.1	15.6	21.7	22.9	--	--	--
Finished hemp fabric	Average mass loss, mg	4.7	9	12.7	14.7	17	19.7	20.7	21.7	25	27	28.3	30.3
	Standard deviation, mg	0.6	1	0.6	1.5	3	2.5	1.2	1.5	1	1	1.5	1.5
	Co-efficient of variation, %	12.4	11.1	4.6	10.4	17.7	12.8	5.6	7.1	4	3.7	5.4	5
Unfinished blended fabric	Average mass loss, mg	3.3	6	9	12.7	17.3	23.3	30	35	--	--	--	--
	Standard deviation, mg	0.6	1	1.7	1.5	1.5	5	7	6.6	--	--	--	--
	Co-efficient of variation, %	17.3	16.7	19.2	12.1	8.8	21.6	23.3	18.7	--	--	--	--
Finished blended fabric	Average mass loss, mg	2.3	5.3	8.3	11.7	17.3	23	26.7	30	34	38.3	41.3	--
	Standard deviation, mg	0.6	1.5	1.5	2.1	4	1	2.3	5.2	5.3	5.5	6.6	--
	Co-efficient of variation, %	24.7	28.6	18.3	17.8	23.3	4.3	8.7	17.3	15.7	14.4	16.1	--

The average mass loss and statistical values for all the investigated fabrics at various cycle counts are displayed in Table 9. The fabric samples showed very little average mass loss at 2000 cycles. The mass loss increases in tandem with the number of cycles. Unfinished linen fabric had a maximum coefficient of variation of 22.4%, hemp fabric of 24.7%, and blended fabric of 23.3% whereas finished linen had 19.2%, hemp had 17.7% and the blended fabric had 28.6%. The unfinished linen fabric sample experienced progressive damage after 12000 cycles, indicating its inferior abrasion performance when compared to other fabrics as indicated by the data in Table 6. The highest number of cycles was reached for finished hemp fabric, i.e., 24000 cycles.

The dependence of mass loss and abrasion cycles in both unfinished and finished fabrics are depicted in Fig. 24 and Fig. 25, respectively, on the calculated average mass loss of all textiles. The graph indicates a linear relationship between the mass loss of both finished and unfinished fabrics and the number of abrasion cycles, respectively.

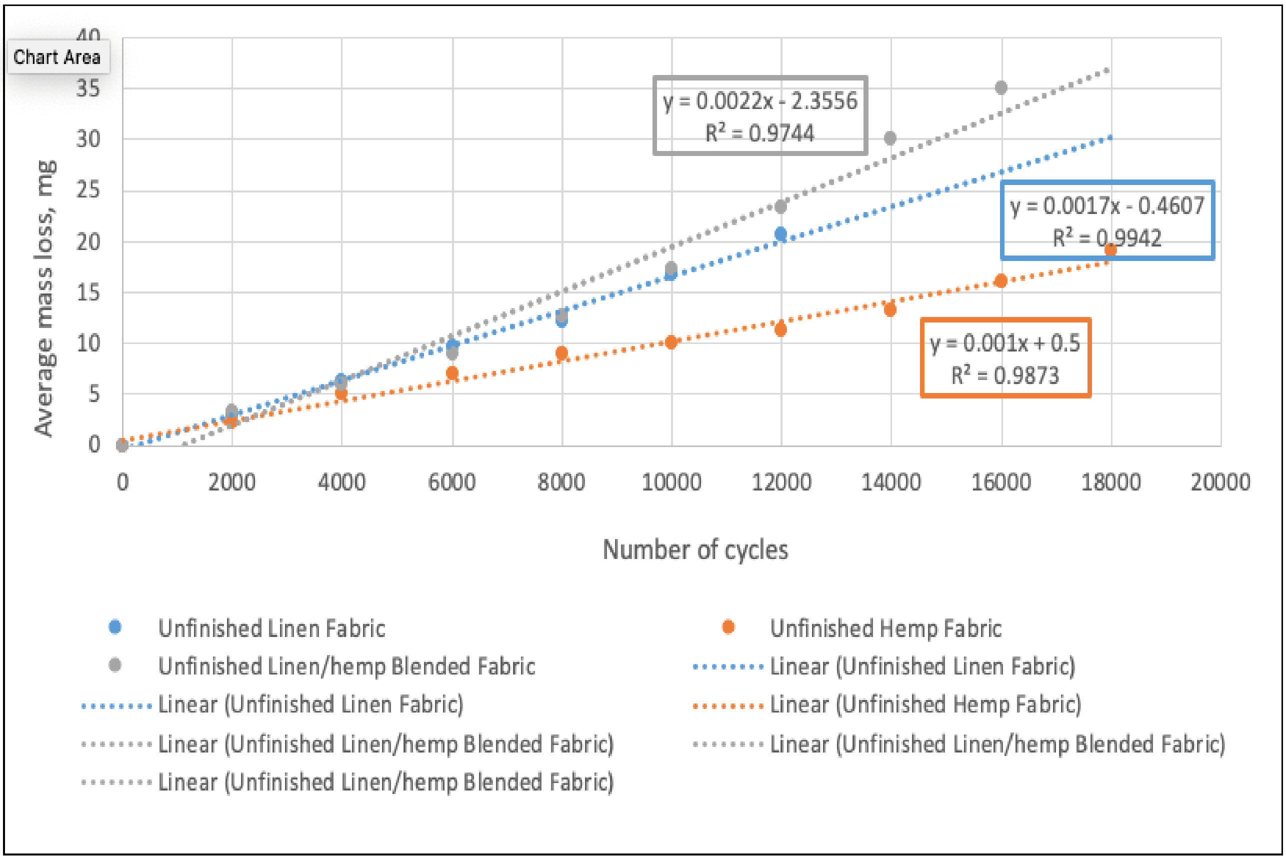


Fig. 24. Graph of mass loss versus abrasion cycles in unfinished fabrics

According to the findings, unfinished linen fabric showed the least abrasion resistance (12000 cycles) when compared to other fabrics. In comparison to other fabrics, the unfinished hemp fabric sustained 18000 abrasion cycles. The blended fabric showed medium abrasion resistance because it sustained 16000 abrasion cycles. The blended fabric showed medium abrasion resistance because it sustained 16000 abrasion cycles. Blending natural hemp materials with linen cloth improved its abrasion resistance. The unfinished linen/hemp fabric was able to withstand up to 16,000 cycles. The reason for this is the fabric blending process, which aims to improve abrasion resistance by blending natural fibers. This approach yields a fabric with superior end-use properties such as durability and friendliness; the resulting fabric is more durable and resistant to wear. Additionally, blended fabrics are economical and durable due to their reduced cost. Blending enables manufacturers to produce customized fabrics for specific functions, including activewear and work uniforms, thus fostering an environment that promotes innovation. In summary, fabric blending is a beneficial process that enhances many aspects of performance, comfort, affordability, and durability. It can be seen from Fig. 24 that the dependencies of mass loss on the number of abrasion cycles can be described by linear equations with very high coefficients of determination (from 0.9744 to 0.9942). Therefore, the value of every unfinished fabric under investigation was equal to 1, suggesting that the mass loss in the unfinished fabric is highly correlated with its number of abrasion cycles.

Furthermore, the finishing process for the fabrics further improved the abrasion resistance of all the investigated fabrics. Finishing was performed on each of the fabrics, utilizing Novotron reactive dyestuff and Eversol softener. This finishing method affects the abrasion resistance of all fabrics. The finished linen fabric sustained up to 16000 abrasion cycles, the finished hemp fabric sustained up to 24000 abrasion cycles, and the blended fabric withstood up to 22000 abrasion cycles. The results showed that the finished fabrics were more resistant to abrasion than the unfinished fabrics. However, finished hemp was more resistant to abrasion. In addition, the abrasion resistance of the blended fabric increased after the finishing process, as illustrated in Fig. 25. The coefficients of determination of linear dependencies also had very high values (from 0.9658 to 0.9934) that were close to one which means that the mass loss in the finished fabric is strongly related to the number of abrasion cycles.

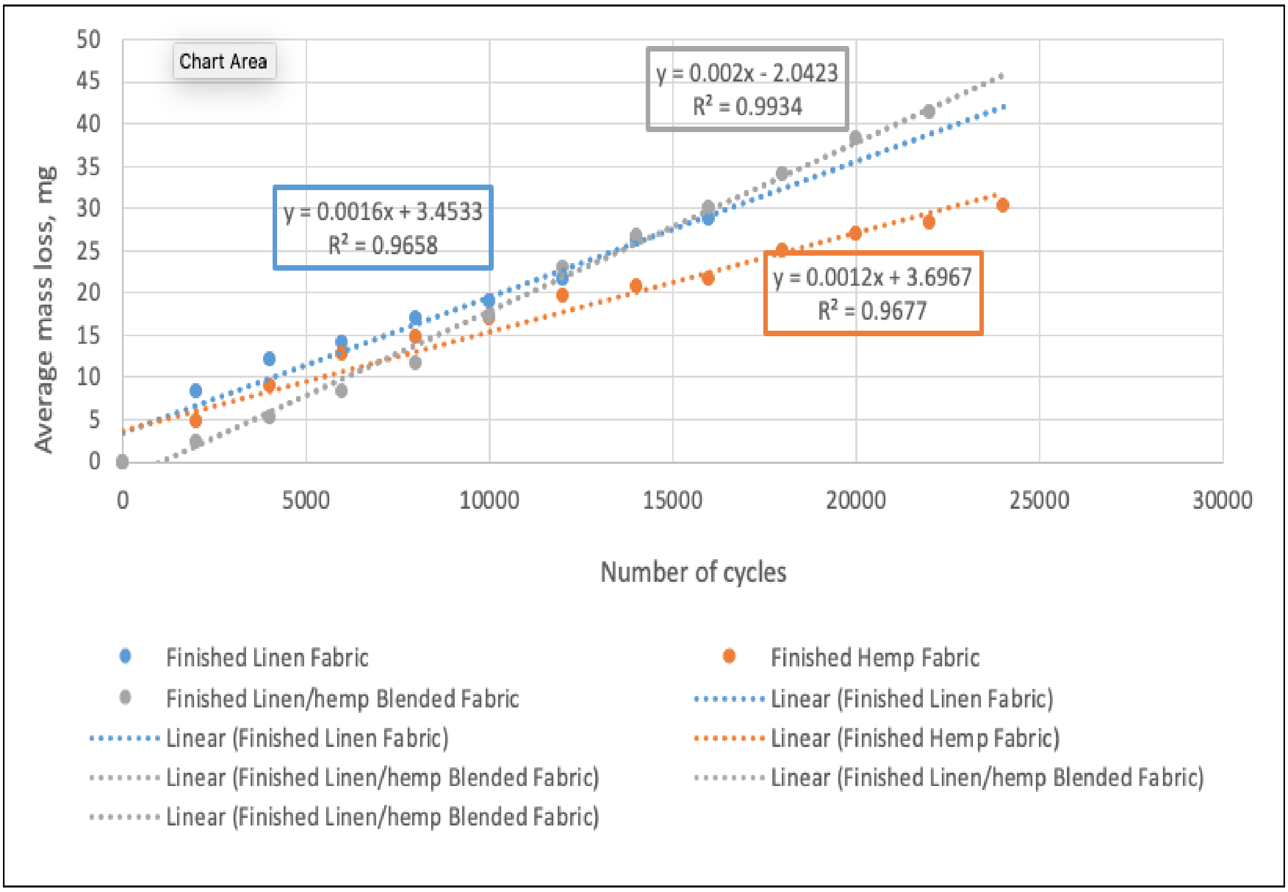


Fig. 25. Graph of mass loss versus abrasion cycles in finished fabrics

The improvement is due to the fact that finishing procedures have a substantial impact on fabric abrasion resistance by changing the surface properties and structural integrity of the fabric [17]. For example, by applying durable finishing or coatings to a fabric, its resistance to wear and friction can be improved, thereby enhancing its abrasion resistance [18]. These results do not contradict the results of the final project. In contrast, poor finishing may damage the fabric's durability, making it more prone to abrasion and lowering overall wear resistance.

3.2.2. Improvement of Abrasion Resistance of Linen, Hemp, Linen/Hemp Blended Fabrics

An enzyme "BEIZYM UL" was used to improve the abrasion resistance of finished linen, hemp, and linen/hemp blended fabrics. BEIZYM UL, with its cellulase base, produces smooth and lint-free cellulose fiber surfaces. As a liquid, this enzyme is ideally suited for use in anti-pilling and biopolishing treatments.

Table 10. Samples of chemically treated finished fabrics after a specific number of abrasion cycles

No. of cycles	**0 cycles**	**4000 cycles**	**16000 cycles**	**20000 cycles**	**26000 cycles**
Finished linen fabric after treatment					---
Finished hemp fabric after treatment					
Finished blended fabric after treatment					

Table 10 shows the effect of various abrasion cycles on enzymatically treated finished linen, hemp, and linen/hemp blended fabrics. Following chemical treatment, linen, hemp and a blend of linen and hemp fabrics endured 20000, 26000 and 26000 abrasion cycles, respectively. The average mass loss for each fabric was calculated per 2000 cycles. The pictures show that the evaluation of the appearance changes in the samples after enzymatic treatment is similar to those in the samples without the special treatment, i.e., at first the pilling appears, after that, the threads become thinner, and finally, the holes appear in the fabric's samples. Statistics were also used to explain mass loss dispersion over the cloth. Additionally, statistical analysis was conducted to determine the influence of finishing and enzymatic treatment on the abrasion resistance by adopting ANOVA analysis, which was performed using the software, Matlab.

Table 11. Statistical values and average mass loss of finished linen, hemp, and linen/hemp blended fabric samples after enzymatic treatment

Samples	Statistical characteristics	Number of cycles												
		2000	4000	6000	8000	10000	12000	14000	16000	18000	20000	22000	24000	26000
Finished linen fabric after treatment	Average mass loss, mg	4	9.5	13	14	17	23	28.5	33.5	37.5	43	--	--	--
	Standard deviation, mg	1.4	2.1	2.8	1.4	2.8	1.4	0.7	0.7	0.7	1.4	--	--	--
	Co-efficient of variation, %	35.4	22.3	21.8	10.1	16.6	6.2	2.5	2.1	1.9	3.3	--	--	--
Finihsed hemp fabric after treatment	Average mass loss, mg	6.5	11.5	14.5	15.5	20.5	23.5	29	34	39.5	46.5	52.5	60	63.5
	Standard deviation, mg	0.7	0.7	3.5	2.1	3.5	3.5	4.2	1.4	0.7	0.7	0.7	1.4	0.7
	Co-efficient of variation, %	10.9	6.1	24.4	13.7	17.2	15	14.6	4.2	1.8	1.5	1.3	2.4	1.1
Fininshed blended fabric after treatment	Average mass loss, mg	7.5	11.5	16	19.5	24	28.5	31	36	39	44	48.5	53.5	58.5
	Standard deviation, mg	0.7	0.7	1.4	2.1	7	4.9	2.8	1.4	1.4	1.4	2.1	2.1	4.9
	Co-efficient of variation, %	9.4	6.1	8.8	10.9	29.4	17.4	9.1	3.9	3.6	3.2	4.4	3.9	8.5

The changes in average mass loss of each investigated treated fabric at different abrasion cycle intervals are shown in Table 11. According to the study, enzymatically treated finished linen fabric resisted 20000 abrasion cycles, enzymatically treated hemp fabric resisted 26000 abrasion cycles, and enzymatically treated blended fabrics resisted 26000 abrasion cycles. Enzymatically treated fabrics have the highest abrasion resistance when compared to unfinished and finished fabrics. The highest coefficient of variation for treated linen fabric is 35.4%, for treated hemp fabric 24.4%, and for treated blended fabric 29.4%.

The graph of mass loss in relation to abrasion resistance was plotted using average mass loss values. The graph is depicted in Figure 26. According to the graph, the abrasion resistance of treated linen fabric was improved in comparison to unfinished and finished linen fabric, withstanding the maximum abrasion cycles of 20000. The treated hemp fabric resisted 26000 abrasion cycles, and the treated blended fabric also resisted 26000 cycles. In comparison to unfinished and finished fabric, the value of all investigated treated fabrics was from 0.9818 for hemp fabric to 0.9967 for blended fabric, i.e., it is almost equal to 1, demonstrating that mass loss is largely reliant on the number of abrasion cycles. This also means that the treated fabric is more abrasion-resistant.

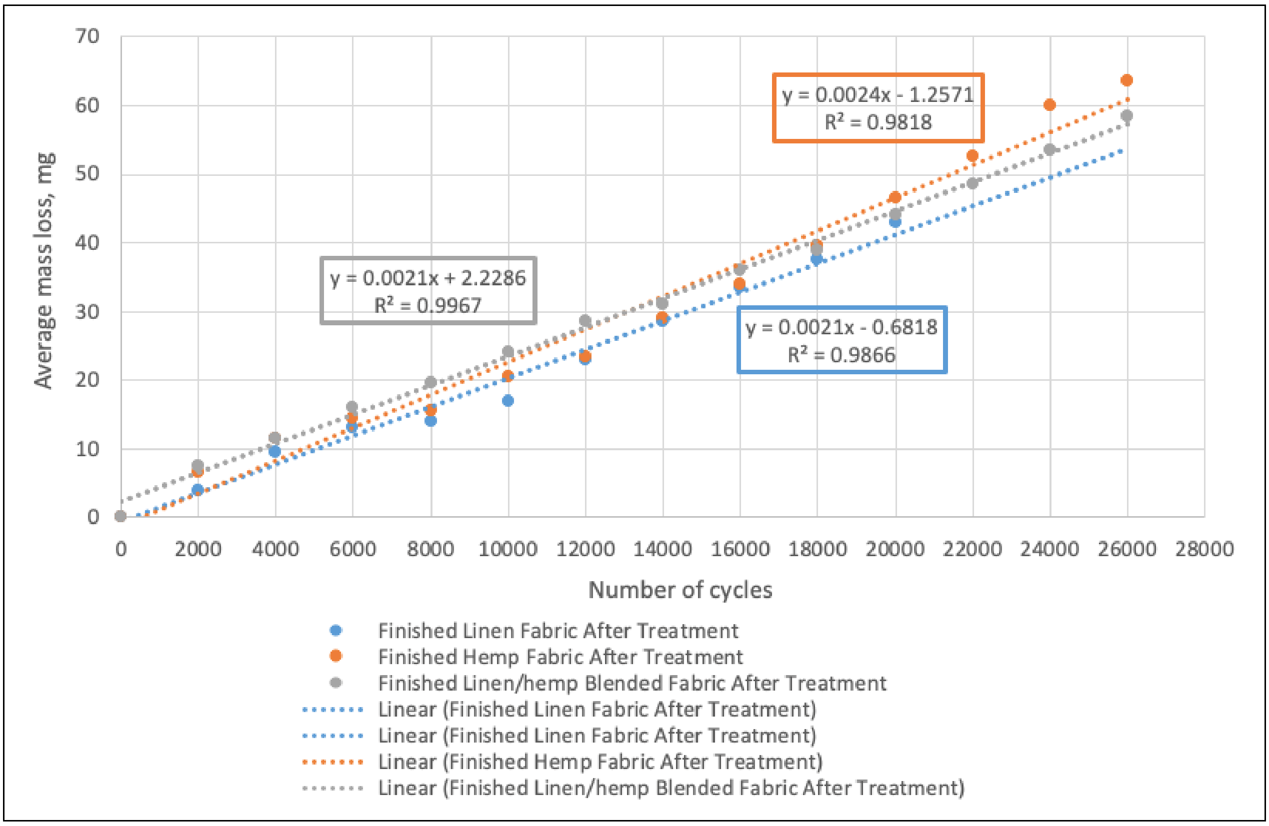


Fig. 26. Graph of mass loss versus abrasion cycles after treatment

The treated fabric exhibited higher abrasion resistance in comparison to the unfinished fabric due to the improvement of the fabric surface, which became smoother and flatter, and the unnecessary hair and fibers were removed from the surface of the fabric. This suggests that the treated fabric was more resistant to the friction created by the abrasion tests. As a result, the treated fabric had a larger mass loss than the unfinished fabric, indicating that the treated fabric was more durable. Furthermore, the abrasion resistance of blended linen and hemp fabric was gradually increased to withstand the same 26000 abrasion cycles as treated hemp fabric.

According to the findings, enzymatic treatment enhanced the overall abrasion resistance of all linen, hemp, and blended linen/hemp fabrics tested. After enzymatic treatment, the treated fabrics sustained maximum abrasion resistance, enabling them to endure the friction created by the abrasion tests. As a result, the treated fabric had a larger mass loss than the unfinished fabric. Along with the optimized dyeing, softening, and washing processes, the enzymatic treatment with BEIZYM UL in an acidic environment likely removed microfibers and impurities, resulting in a refined fabric structure. This describes the fabric's ability to endure greater abrasion cycles despite having a greater mass loss.

The results of [26] prove that different finishings and treatments improve the abrasion resistance of fabrics from different natural fiber's fabrics, like those from cotton, silk, and different synthetic fibers. Although the other fibers were used in the research [26], they correspond to the results obtained in the final project. Also, [27] reviews that various finishing processes improve the abrasion resistance of socks of different natural and synthetic yarns. Despite the fact that the garments are different from those in the final project, it can be stated that they correspond to the obtained results.

Furthermore, compared to linen fabric, hemp fabric and linen/hemp blended fabric experienced a higher mass loss; yet, both materials were still able to endure numerous abrasion cycles without experiencing any thread breaks before linen. This is because the fibers in hemp yarn are longer than those in other yarns. As a result, the shorter fibers broke, increasing the fabric's mass loss, but no holes appeared on the fabric because the longer fibers did not break. In comparison to all other investigated fabrics, hemp fabric showed more substantial end-use performance both before and after finishing. The pilling and abrasion resistance of hemp fabric gradually improved with further enzyme treatment. These results are similar to those in other investigations, which state that fabrics made from longer, compact spun yarns are more resistant to pilling and abrasion than those made from shorter ring-spun yarns.

3.2.3. Influence of Raw Material and Finishing Type on Abrasion Resistance

In order to find out whether the raw material and the type of finishing (independent variables) affect the abrasion resistance of the fabric (dependent variable), a two-way analysis of variance was applied using MatLab software.

At first, the null hypothesis and alternate hypothesis are formulated in Table 12.

Table 12. Raised hypothesis for abrasion resistance

Null hypothesis (H_0)	**Alternate hypothesis (H_a)**
There is no difference in average yield for any raw materials.	There is a difference in average yield by raw materials.
There is no difference in average yield depending on the type of finishing.	There is a difference in average yield by type of finishing.
The effect of one independent variable on average yield does not depend on the effect of the other independent variable.	There is an interaction effect between the group of materials and the type of finishing on average yield.

The ANOVA analysis table for the influence of abrasion resistance on raw material ("columns" in the table) and type of finishing ("rows" in the table) is presented in Fig. 27.

ANOVA Table

Source	SS	df	MS	F	Prob>F
Columns	32.99	2	16.497	0.41	0.6667
Rows	250.97	2	125.485	3.11	0.0543
Interaction	146.71	4	36.676	0.91	0.4667
Error	1814.97	45	40.333		
Total	2245.64	53			

Fig. 27. ANOVA table for the influence of abrasion resistance on raw material and type of finishing

The obtained results show that the hypothesis "There is no difference in average yield for any raw materials" is accepted because (p_{value} =0.6667>0.05), which means that raw materials do not influence mass loss during the abrasion test.

The second null hypothesis, "There is no difference in average yield at the type of finishing" is also accepted because (p_{value} =0.0543>0.05). That result shows that the type of finishing also does not influence mass loss. However, since the obtained p_{value} is slightly higher than 0.05, it is possible that with more test results, this hypothesis will be rejected, and then the alternative hypothesis will have to be accepted. Therefore, a deeper analysis of the data will be performed.

In addition, the hypothesis "The effect of one independent variable on average yield does not depend on the effect of the other independent variable" is accepted because (p_{value} =0.4667>0.05). In conclusion, mass loss does not depend on the interaction between raw materials and the type of finishing.

The multiple comparison tests were performed to see how different raw materials affect the mass loss during the abrasion tests(p_{value}=0.6667<0.05). The confidence intervals of linen, hemp, and blended linen/hemp fabrics are presented in Fig. 28.

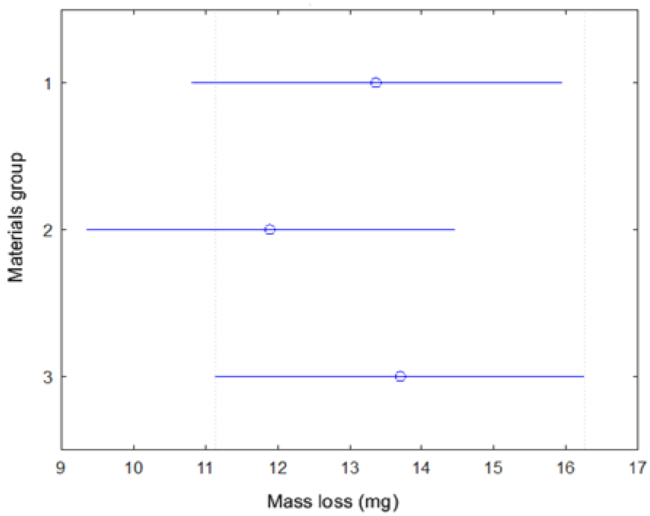


Fig. 28. Confidence intervals for different raw materials in abrasion resistance: (1) linen; (2) hemp; (3) blended linen/hemp

The averages of these groups do not differ statistically, and this means that the raw material does not affect the mass loss. These results can also be seen from the graph in Fig. 28.

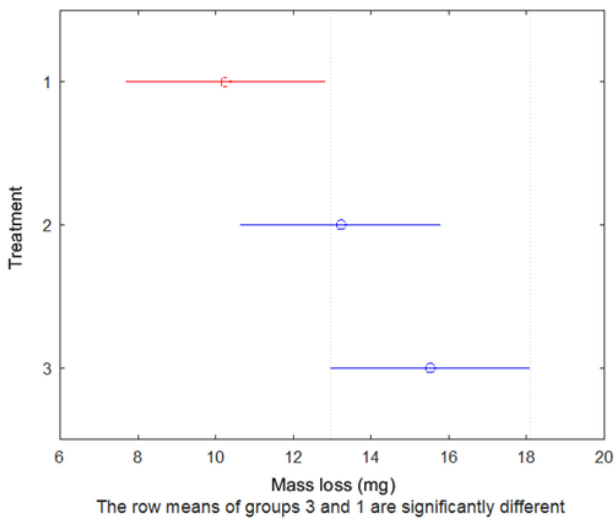


Fig. 29. Confidence intervals for different types of finishing in abrasion resistance: (1) unfinished fabric; (2) finished fabric; (3) fabric after enzymatic treatment

Also, a multiple comparison test was performed to see how the type of finishing affects the mass loss during the abrasion test (p_{value}=0.0543>0.05). The confidence intervals of mass loss for fabrics under different types of finishing are shown in Fig. 29.

The p_{value} value is slightly higher than 0.05, and the confidence intervals of the averages show that the average mass loss of the unfinished fabrics is statistically different from the remaining two groups. Hence, the second null hypothesis is rejected, and the alternate hypothesis is accepted. This means that the type of finishing affects the mass loss during the abrasion test.

3.3. Economic Factors Influencing Pilling and Abrasion Resistance

The study proved that hemp fabric is known for its outstanding pilling and abrasion resistance due to its inherent fibre strength and long staple length. This strength enables the fabric to withstand wear and friction, which in turn ensures that it will have a longer lifespan. Because of its natural density and long staple length, it produces a tightly woven fabric that reduces pilling. Hemp's eco-friendly cultivation practices also contribute to healthier fibers, improving fabric durability and quality. Additionally, the ability to blend hemp fabric with other natural fabrics enables improved strength, resilience to abrasion and pilling, and durability. The investigation results showed that hemp has more pilling and abrasion resistance compared to linen. However, the linen's pilling and abrasion resistance can be improved. Firstly, economic improvements can begin at the fibre selection stage. High-quality flax fibres with longer staple lengths tend to result in stronger and more resistant linen yarn. Blending linen with other fibres, such as hemp, cotton, or synthetic fibres like polyester, can create a fabric with enhanced abrasion resistance. This was one of the methods used in the research to improve the pilling and abrasion resistance of linen, which is considered an ecological technique. While this may add a nominal cost, the overall improvement in performance can justify the investment.

Employing cost-effective finishing techniques can significantly enhance linen's resistance to wear. Chemical finishes, such as anti-pilling treatments and abrasion-resistant coatings, can be applied to the fabric surface. Manufacturers can explore eco-friendly and economical finishing options that not only improve performance but also align with sustainability goals. As per the study, enzymatic treatment was used to improve the end-use characteristics of linen, hemp and linen/hemp fabrics which resulted in the improvement of the pilling and abrasion resistance of investigated fabrics. Furthermore, this enzymatic treatment is environmentally beneficial and ecological because it requires less water, does not involve any other conventional chemicals, and degrades naturally due to its cellulose nature.

Furthermore, investing in modern spinning technologies that ensure a more uniform and tightly twisted yarn can enhance the overall durability of the fabrics. Although the initial capital investment might be involved, the long-term benefits in terms of product quality can outweigh the costs. Processing and manufacturing techniques are critical in determining the structural integrity of fabrics, which has a direct impact on their resistance to pilling and abrasion. Linen and hemp, with their distinct fibre characteristics, respond differently to different processing methods, and the economic implications of these techniques ripple throughout the entire production cycle.

The processing of fibres into fabric involves intricate steps such as retting, spinning, and weaving. These processes necessitate careful handling and can contribute to overall manufacturing costs. The delicate nature of fibres also necessitates precision in processing, which, if not done efficiently, may compromise the fabric's pilling and abrasion resistance.

3.4. Chapter Summary

The chapter explores the pilling and abrasion resistance properties of linen, hemp, and linen/hemp blends. Standardized tests, specifically using Martindale's abrasion tester, were performed at varied cycle intervals to measure the end-use performance of both unfinished and finished fabrics. The pilling resistance of these linen, hemp, and linen/hemp blends was investigated, and it was found that unfinished linen fabric had lower resistance compared to hemp and linen/hemp blends. Enzymatic treatment has gradually enhanced the pilling grades of all fabrics. The blending of hemp with linen in a fabric significantly improved the pilling resistance of the linen fabric. Using "BEIZYM UL" for enzymatic treatment also made the finished fabrics even less likely to pill.

Abrasion performance was assessed for unfinished and finished linen, hemp, and linen/hemp blended fabrics at different cycle intervals. The average mass loss, standard deviation, and coefficient of variation were among the statistical measures used. By blending linen with hemp fabric, the durability of linen fabric was increased. The utilization of Novotron reactive dyestuff and Eversol softener in the finishing process greatly enhanced the abrasion resistance of all fabrics. The enzymatic treatment further increased the finished fabric's abrasion resistance, demonstrating increased durability. The chapter also emphasizes that hemp fabric surpasses other fabrics in terms of pilling resistance, and abrasion resistance. The hemp fibre contributes to its durability and ability to tolerate wear and friction. The use of hemp fabric with other natural materials improves their strength, resilience, and durability.

In order to determine the effect of finishing types and raw materials on fabric pilling and abrasion resistance, a two-way analysis of variance was conducted in MatLab. In terms of resistance to pilling, it was observed that fabric performance was independently impacted by both finishing types and raw materials. Significant variations in this regard were detected through the utilization of multiple comparison experiments and found that pilling resistance was influenced by the type of finishing. Nevertheless, no interaction effect between raw materials and finishing types was found to be statistically significant. The study determined that raw materials did not have a significant impact on mass loss in terms of abrasion resistance. However, the influence of finishing types was inconclusive and indicated the necessity for additional investigation. According to the results of multiple comparison tests, the mass loss observed during abrasion testing was significantly influenced by the type of finishing.

The study also covered the economic aspects that impact the resistance of materials to pilling and abrasion. Hemp fabrics demonstrated greater resilience compared to linen fabrics, which led to discussions on enhancing linen fabric's durability. The use of different fibres, blending, and economical finishing methods were among the strategies. The study promotes the use of environmentally friendly alternatives, such as enzymatic treatment, to improve the properties of fabrics. Investment in new spinning technologies and meticulous processing processes were highlighted as critical for fabric longevity. In general, the economic ramifications of these approaches contribute to the development of durable and sustainable textile solutions.

4. Economic and Ecological Friendliness of Hemp

Linen, made from flax fibers, is known for its smooth texture and natural luster. The economic benefits of linen include using limited resources, enduring a long time, and being able to adapt to various climates. It benefits local communities and creates environmentally sustainable demand. But it wrinkles easily and needs intricate processing, which could raise the cost of production. Also, the processing of flax into linen involves intricate steps such as retting, spinning, and weaving. These processes necessitate careful handling and can contribute to overall manufacturing costs. The delicate nature of linen fibers also necessitates precision in processing, which, if not done efficiently, may compromise the fabric's pilling and abrasion resistance.

For decades, hemp faced stringent restrictions and outright bans due to its association with cannabis, a psychoactive substance. This prohibition cast a pall over hemp's adaptability and sustainability, relegating it to the fringes of the textile industry. However, there has been a discernible shift in perception and policy regarding hemp in recent times. Recognizing hemp's potential as a valuable resource, governments and industries have begun to revisit and revise regulations that previously stifled its use. This reassessment has allowed hemp to reclaim its place in the textile manufacturing industry with advanced processing techniques like retting procedures, which influence the composition of chemical fibers, ultimately resulting in specific fiber qualities.

Hemp cultivation is a lucrative avenue for job creation, particularly in areas where it is growing. Because of the hardiness of the hemp plant, it can be grown in a variety of climates, potentially revitalizing local economies by providing farmers with a resilient and profitable cash crop. This economic ripple effect extends beyond the farm gate, creating opportunities in the processing, manufacturing, and retail sectors, all of which contribute to a more robust and diverse economic ecosystem. At the same time, hemp's environmental friendliness emerges as a hallmark of its significance in contemporary textile production. Hemp cultivation requires fewer pesticides and herbicides than traditional crops like cotton, helping to reduce the textile industry's environmental footprint.

Hemp's economic and environmental benefits extend to its end-use applications in textile manufacturing. Hemp fiber-woven fabrics have exceptional durability, breathability, and moisture-wicking properties, making them not only economically viable but also environmentally responsible alternatives. As consumer preferences shift towards more environmentally friendly products, hemp's marketability grows, reinforcing its role in fostering an environmentally conscious textile industry. Conversely, hemp, known for its toughness and versatility, offers opportunities for cost-effective processing techniques. Hemp fibers are strong and can withstand a variety of processing methods without losing their inherent strength. The hardiness of hemp not only contributes to its eco-friendliness but also allows for streamlined manufacturing processes, potentially lowering overall production costs. Hemp fabrics amplify the environmental benefits compared to other traditional textiles like cotton, linen, etc. With their inherent strength and resistance to pilling and abrasion, hemp fabrics contribute to garment longevity, potentially reducing the frequency of replacements and minimizing textile waste.

4.1. Market Price Comparison of Hemp Fabric and Linen Fabric

The cost of each raw material becomes a key factor when comparing fabrics made of hemp and linen. Aspects such as flax production, harvesting, and processing determine the particular cost structure of linen. On the other hand, hemp offers a distinct economic profile due to its quick growth cycle and adaptability. Due to its resilience, reduced need for pesticides, and efficient use of resources, the cost of cultivating and processing hemp is frequently cheaper than that of linen.

Linen, a classic fabric noted for its breathability and durability, has long been a standard in the textile industry. Siulas, a prestigious linen manufacturing company in Lithuania since 1928, offers customers a collection of linen goods with exclusive names, codes, and technical details. Siulas positions its linen fabric as a premium choice in the market, priced at around $30. The detailed technical details and unique identification code provide value to the product, appealing to buyers seeking transparency and quality in their textile purchases. Linen fabrics have a distinct cost structure influenced by factors such as flax cultivation, harvesting, and processing.

Conversely, hemp, with its rapid growth cycle and versatility, presents a different economic profile. The cost of cultivating and processing hemp is often lower than that of linen due to its hardiness, reduced need for pesticides, and efficient use of resources. Therefore, hemp cloth is starting to make a name for itself in the market as an environmentally friendly textile. Hemp has acquired growing popularity as a long-lasting and adaptable material because of its environmentally benign growth procedure, which requires less water and chemicals. Hemp textiles are currently a competitive alternative to linen, costing $23.27 per unit in the Lithuanian textile market. This competitive pricing outlines hemp fabrics effectively, especially for consumers who value sustainability and affordability, which results in hemp being more affordable than linen fabrics in some economic contexts.

4.2. Possibilities of Ecologically Sustainable Manufacturing

The development and use of environmentally friendly materials are one path to achieving manufacturing sustainability. Substituting sustainable alternatives for traditional raw materials, such as organic cotton, bamboo, and, most notably, hemp, can significantly reduce the environmental footprint of textile production. Hemp, in particular, stands out for its rapid growth, low water and pesticide requirements, and potential for regenerative agriculture practices, making it a frontrunner in the pursuit of sustainability.

Another critical factor is the adoption of cleaner and more efficient manufacturing processes. Water and energy management innovations, waste reduction, and recycling technologies all contribute to a more sustainable manufacturing ecosystem. The cultivation of hemp and linen typically requires less water than the cultivation of other textile crops. It is also possible to grow both plants in a variety of climates, which lessens the requirement for intensive irrigation. By implementing closed-loop systems and water recycling initiatives in hemp and linen manufacturing processes, it is possible to reduce water waste, a major concern in the textile processing industry. The use of energy-efficient machinery powered by renewable sources can also minimize the environmental impact of manufacturing.

In the current scenario, it is necessary to transition to an ecological treatment process. Every fabric needs to be treated to enhance its durability and endurance; such treatments should be eco-friendly and sustainable. According to this research, the treatment that was carried out was an enzymatic treatment using a natural enzyme called “BEIZYM UL”. This enzyme is non-iconic, with an ideal pH range of 4.5–5.5. Due to the fact that “BEIZYM UL” is one of the natural enzymes, it was selected for the fabric treatment in this investigation. Furthermore, this treatment is environmentally beneficial and ecological because it requires less water, does not involve any other conventional chemicals, and degrades naturally due to its cellulose nature. The treatment using “BEIZYM UL” can be used in the textile industry to treat different kinds of natural fabrics like hemp, linen, and blended fabrics as it results in sustainable manufacturing.

Hemp products can adhere to certifications and standards to give consumers transparency, just like other textiles can. Furthermore, certifications and standards such as the Global Organic Textile Standard (GOTS) and OEKO-TEX can be applied to hemp fabrics and textiles, which provides consumers with transparency about the environmental and social aspects of the products they buy. These certifications incentivize manufacturers to meet stringent environmental and social standards, fostering a responsible culture within the industry.

4.3. Chapter Summary

This chapter investigated how the textile industry is undergoing a revolutionary shift due to economic causes and the possibility of creating linen and hemp materials in an environmentally friendly way. Previously hindered by cannabis-related restrictions, hemp’s resurgence now represents both technological advancement and sustainability. According to the analysis, hemp is more suitable for end use and can change fabric quality standards. Additionally, hemp is more cost-effective and efficient than other fabrics in terms of pricing, quality, and other aspects. In addition to the economic implications pertaining to the expenses associated with raw materials and manufacturing processes, hemp’s numerous benefits encompass job generation, environmental sustainability, and socioeconomic influence.

The substitution of conventional textile raw materials with ecologically sound alternatives such as organic cotton and bamboo can substantially diminish the environmental impact of textile manufacturing using hemp, a sustainable textile crop. Hemp is an excellent option for sustainability due to its rapid growth, low water and pesticide needs, and potential for regenerative agriculture. A more sustainable manufacturing ecosystem can be the result of implementing cleaner and more efficient manufacturing processes, including innovations in water and energy management, waste reduction, and recycling technologies. Additionally, environmental impact can be reduced through the use of energy-efficient apparatus powered by renewable sources. The utilization of an enzymatic treatment incorporating the naturally occurring enzyme “BEIZYM UL” has the potential to augment the longevity and resilience of fabrics within the textile sector. Hemp products can also surpass certifications and standards, ensuring environmental and social transparency. With widespread consideration of these factors and the adoption of sustainable manufacturing practices, the textile industry can look forward to a prosperous and environmentally conscious future.

Conclusions

1. Linen and hemp fabrics have similar characteristics. However, they differ in origin and physical properties. Linen is derived from the fibres of the flax plant and comprises components such as pectin, lignin, and wax. In contrast, hemp fabric is derived from the bast fibres. The main cell walls of both fibres are made of cellulose and hemicelluloses, but linen also contains a higher percentage of cellulose and pectin. The linear density of the investigated unfinished and finished linen and hemp fabrics is the same, which is 28 tex. The investigated fabrics have the same weave type, however, the warp and weft settings differ in the finished fabrics but not significantly. Linen has a smooth surface texture, whereas hemp has a stiff and rigid surface. In general, there are notable similarities between linen and hemp concerning their chemical composition, morphological structure and physical properties.

2. The end-use qualities of fabrics are crucial in terms of durability. It is vitally important to evaluate the fabric's end-use properties. Pilling and abrasion resistance were two of them. The most affordable and effective testing apparatus, Martindale's abrasion tester, was used in this study to assess the pilling and abrasion resistance of linen, hemp, and linen/hemp fabrics following standards. According to the research, hemp fabric is the most resistant to pilling. The pilling grades are lower from 0.5 grade after 125 cycles to 1.5 grade after 2000 cycles for linen fabrics and from 0.5 grade after 125 cycles to 1.0 grade after 2000 cycles for blended linen and hemp fabric. Hemp has 33% higher abrasion resistance than linen, while mixing linen with hemp fabric boosted its abrasion resistance by 25%. Therefore, a linen-hemp blend can significantly enhance linen fabric pilling and abrasion resistance.

3. The finishing process improves the pilling performance of the fabrics of all raw materials, from 0.5 grades for linen and blended fabrics to 0.5–1.5 grades for hemp fabric. Additional enzymatic treatment using the enzyme BEIZYM-UL improved the material pilling resistance to 1.0 grade for linen fabric and 0.5 grade for hemp and blended linen/hemp fabrics. Finishing has the highest influence on linen fabric pilling resistance and the lowest one on hemp fabric pilling resistance because the usual finishing improves the pilling performance of hemp fabric more than the additional enzymatic treatment. Furthermore, the finishing treatment also influenced the abrasion resistance by 25% for both linen and hemp fabric and 27% for blended linen and hemp fabric in comparison with unfinished fabric. Nevertheless, the enzymatically treated hemp fabrics outlasted the other treated linen and linen/blended materials in terms of abrasion resistance.

4. In conclusion, hemp and linen have positive environmental and economic effects on the textile industry. Linen's silky feel and weather resistance come with processing complexity, which may raise expenses. Hemp, which was previously stigmatized, has evolved into a sustainable and multipurpose material source that is breathable, moisture-wicking, and long-lasting. Hemp's market prices are less expensive ($23.27 per unit) than those of linen ($30) due to its durability and economical processing. The implementation of environmentally sustainable manufacturing practices can be achieved by incorporating sustainable materials such as hemp, adopting cleaner processes, and using eco-friendly treatments like enzymatic treatments, which also result in increased durability of the fabric. Standards and certifications can influence industry-wide responsibility and provide consumers with greater transparency. In conclusion, the benefits of hemp contribute to the development of an environmentally sustainable textile industry by providing economical substitutes that possess a competitive edge in the market.

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