UNIVERSIDADE FEDERAL DE SANTA CATARINA
CENTRO TECNOLÓGICO
PROGRAMA DE PÓS-GRADUAÇÃO EM ENGENHARIA QUÍMICA

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Study of the effects of household washing on polyester and cotton fabric properties.

Florianópolis
2023

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Dissertação submetida ao Programa de Pós-Graduação em Engenharia Química da Universidade Federal de Santa Catarina como requisito parcial para a obtenção do título de Mestra em Engenharia Química.

Orientador: Prof. Adriano da Silva, Dr.
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Florianópolis
2023

Sornas, Jéssica Jenifer
Study of the effects of household washing on polyester and cotton fabric properties. / Jéssica Jenifer Sornas ; orientador, Adriano da Silva, coorientadora, Ana Paula Serafini Immich, 2023.
100 p.

Dissertação (mestrado) - Universidade Federal de Santa Catarina, Centro Tecnológico, Programa de Pós-Graduação em Engenharia Química, Florianópolis, 2023.

Inclui referências.

1. Engenharia Química. 2. Lavagem doméstica de roupas. 3. Amaciante de roupas doméstico. 4. Detergente de roupas doméstico. 5. Resistência a tração de tecidos. I. Silva, Adriano da. II. Immich, Ana Paula Serafini. III. Universidade Federal de Santa Catarina. Programa de Pós-Graduação em Engenharia Química. IV. Título.

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O presente trabalho em nível de Mestrado foi avaliado e aprovado, em 04 de Setembro de 2023, pela banca examinadora composta pelos seguintes membros:

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CPF: ***.709.189-**
Verifique as assinaturas em https://v.ufsc.br

Prof. Adriano da Silva, Dr.
Orientador

Florianópolis, 2023.

AGRADECIMENTOS

À Universidade, seu corpo docente, direção e administração, e em especial ao Programa de Pós-Graduação em Engenharia Química, sou imensamente grata por possibilitarem a realização deste trabalho.

Aos meus estimados orientadores, Prof. Dr. Adriano da Silva e Prof. Dra. Ana Paula Serafini Immich Boemo, sou profundamente grata pelo suporte oferecido ao longo deste percurso, bem como pela calma e paciência com que responderam às minhas dúvidas e inquietações.

Ao suporte e incentivo da empresa que trabalho e em especial aos amigos, Débora Almeida, Felipe Scheer, Luisa Tobar, Luiz Campos, Luiza Gonzatto, Morgana Stopassole e Sara Morais, agradeço pelas contribuições e sugestões relacionadas ao trabalho.

À minha querida amiga Mileena Moreno, agradeço por tornar minhas disciplinas realizadas em Florianópolis mais agradáveis.

Agradeço imensamente ao meu namorado, Felipe Locks, por estar sempre presente quando precisei, proporcionando não apenas apoio emocional, mas também incentivo constante.

Por fim, dedico minha gratidão a todos os meus familiares e amigos que me apoiaram e incentivaram ao longo dessa jornada, tornando possível a realização deste trabalho. Seu apoio foi fundamental e inestimável. Muito obrigada a todos!

RESUMO

O aumento da durabilidade das roupas faz com que seja diminuído o impacto ambiental, visto que roupas que são danificadas durante o uso ou o cuidado acabam sendo descartadas em um menor intervalo de tempo. O cuidado das roupas consiste em várias etapas, sendo elas a lavagem, secagem, passadoria, armazenamento e bem como durante o uso. A lavagem é um processo que no âmbito doméstico é realizado usando água podendo ser manual ou com o auxílio de máquinas de lavar roupas. Apesar de ser um procedimento do cotidiano comum, os fenômenos envolvidos na conservação dos substratos têxteis são complexos, visto que as escolhas feitas para o cuidado das roupas podem danificá-las irreversivelmente. Dessa maneira, o presente trabalho tem como principal objetivo avaliar a durabilidade de tecidos de malha à lavagem, analisando fatores como: quantidade de ciclos de lavagem, uso de detergente, uso de amaciante e temperatura da água. A durabilidade tratada nesse estudo foi definida como sendo a resistência a tração, índice de brancura e encolhimento do substrato. A partir dos resultados observados neste trabalho, foi proposto um modelo estatístico capaz de sugerir a melhor combinação entre os fatores avaliados, para que os tecidos não percam suas características e mantenham suas propriedades mesmo após muitos ciclos de lavagem. Os resultados indicaram que os ciclos de lavagem alteram a resistência a tração, sendo os tecidos mais afetados os de 100% poliéster, poliéster com algodão e 100% algodão, nesta ordem. O uso de amaciante durante as lavagens diminuiu a resistência de praticamente todos os tecidos, pois ele forma um filme no tecido que aumenta a lubrificação entre os fios e fibras, diminuindo assim a sua resistência a tração. A temperatura da água de lavagem a 60ºC teve um efeito de -17N, diminuindo a resistência a tração do poliéster na direção das carreiras. O índice de branco (CIE/E313) foi aumentado com o aumento da temperatura da água de lavagem e o uso de detergente para os tecidos. A ação mecânica das lavadoras aumentou com a quantidade de ciclos de lavagem, assim, quanto mais ciclos de lavagem, mais ação mecânica as roupas sofrerão. O encolhimento dos tecidos não foi significativo, sendo muito baixo para a maioria deles (<4%), assim para os fatores estudados e tecidos não houve encolhimento durante a lavagem. Os resultados demonstram que para os tecidos contendo poliéster são recomendáveis ciclos de lavagem com água fria (20 ºC), contendo detergente e sem o uso de amaciante, dessa forma o tecido tende a ter menor perda de resistência e brancura. Já para o tecido 100% algodão é recomendado ciclos de lavagem a 60 ºC, com o uso de detergente, porém sem o uso de amaciantes.

Palavras-chave: detergente, amaciante, ciclos de lavagem.

RESUMO EXPANDIDO

Introdução

O *fast fashion* é a produção de roupas que são feitas para serem usadas pouquíssimas vezes e descartadas em seguida, ou porque estragam rápido durante o uso ou porque já saíram de moda. Um grande problema do *fast fashion* é que a cadeia produtiva utiliza matérias primas de baixa qualidade fazendo com que durante o uso ou cuidado dessas roupas elas se danifiquem com facilidade, aumentando de maneira significativa a produção de resíduos. O *slow fashion* é o contrário disso, onde se busca de maneira mais consciente o uso de matérias primas com maior durabilidade e um desenvolvimento sustentável em toda a cadeia, diminuindo consideravelmente a geração de resíduos. O cuidado das roupas consiste em várias etapas, sendo elas a lavagem, secagem, passadoria, armazenamento e durante o uso. A lavagem é um processo que no âmbito doméstico é realizado usando água podendo ser manual ou com o auxílio de máquinas de lavar roupas. Apesar de ser um processo realizado no cotidiano comum, é na verdade muito complexo sendo que as escolhas feitas para cuidar das roupas podem danificá-las irreversivelmente. Um exemplo de dano muito comum durante a lavagem de roupas, é por exemplo a lavagem de roupas de algodão coloridas com alvejante baseado em hipoclorito de sódio, esse tipo de alvejante não pode ser utilizado nesse tipo de tecido pois reduz o corante, causando manchas irreversíveis no tecido. Assim, quando se fala em lavagem somente, existem muitos parâmetros que podem ser escolhidos nesse processo que podem acarretar aumento de vida útil das roupas ou diminuição da mesma. Todas as roupas vendidas no Brasil devem seguir a legislação de etiquetagem, assim elas possuem alguns símbolos que são correspondentes aos cuidados das roupas. Algumas recomendações são por exemplo: não alvejar com cloro, lavar a mão ou não secar em secadora de tambor. Entretanto no cotidiano é possível utilizar vários insumos na lavagem como detergentes, sendo que esses podem ser líquidos ou em pó, amaciantes, sabão, desinfetantes, entre outros. As recomendações da etiqueta do produto não explicam por exemplo se para um tecido é melhor usar o detergente em pó ou o líquido, também não é explicado qual concentração é mais interessante. Sendo assim, fica remanescente para o consumidor muitas escolhas para serem feitas quando precisa lavar suas roupas. Os detergentes em pó existentes atualmente no mercado são usualmente aniônicos, contendo branqueador óptico na maioria das vezes e sendo um dos mais utilizados na América Latina. Esses detergentes são responsáveis por diminuir a tensão superficial da água e fazer que seja mais fácil penetrar nas roupas para a retirada da sujidade. O branqueador óptico presente deixa as roupas brancas com um tom azulado, pois absorve a luz no comprimento de onda ultravioleta e reflete a mesma na faixa do azul. Outro insumo também muito utilizado durante o enxágue das roupas é o amaciante, sendo que o doméstico é geralmente catiônico e composto por um sal quaternário de amônio. As funções principais dos amaciantes são deixar a roupa mais macia e adicionar cheiro as roupas.

Objetivo

Avaliar a resistência a tração, índice de brancura e encolhimento de tecidos de malha após a lavagem doméstica analisando os fatores de quantidade de ciclos de lavagem, uso de detergente, uso de amaciante e temperatura de água.

Como objetivos específicos:

- ✓ Avaliar e comparar a resistência à tração, índice de branco e encolhimento de malhas 100% poliéster, 100% algodão e 50% poliéster 50% algodão após repetidas lavagens domésticas com diferentes combinações de detergente, amaciante e variação de temperatura (20 ºC e 60 ºC).
- ✓ Avaliar o índice de ação mecânica dos ciclos de lavagem e tentar correlacioná-lo com a perda de resistência à tração em malhas de poliéster e algodão.
- ✓ Examinar as alterações na superfície do tecido após repetidos ciclos de lavagem usando microscopia digital e correlacionar esses achados com o índice de brancura e os resultados de resistência à tração.
- ✓ Avaliar se houve alteração dos tecidos após cada tratamento estudado com o uso de espectroscopia no infravermelho por transformada de Fourier.

Metodologia

Um experimento fatorial fracionado com dois níveis foi conduzido para investigar os efeitos de quatro fatores no processo de lavagem de três tipos de tecidos de malha *single Jersey*, incluindo algodão, poliéster e uma mistura de poliéster e algodão. Os fatores examinados no experimento incluíram o número de ciclos de lavagem, quantidade de detergente, quantidade de amaciante e temperatura da água. O objetivo foi entender o impacto desses fatores nas respostas do tecido, como resistência à tração, encolhimento, ação mecânica e índice de brancura. Os testes de resistência a tração foram feitos seguindo o método de tira conforme a norma ISO 13934-1:2016. O encolhimento durante a lavagem foi executado seguindo as normas ISO 3759:2011 e ISO 5077:2007. O índice de brancura CIE/E313 foi medido conforme a norma ISO ISO105-J02:1997 usando espectrofotômetro. Após a realização e análise do experimento fatorial fracionado, foi realizada microscopia dos tecidos com microscópico digital e espectroscopia infravermelho por transformada de Fourier.

Resultados e discussão

A resistência a tração foi afetada durante a lavagem, sendo que o tecido mais afetado foi o poliéster com até 25% de redução, seguido pelo tecido poliéster-algodão como 18% de redução e então o tecido de algodão com 14% de redução da resistência. O uso de amaciante durante as lavagens diminuiu a resistência de praticamente todos os tecidos, pois ele forma um filme no tecido que aumenta a lubrificação entre os fios e fibras, diminuindo assim a sua resistência a tração. A temperatura da água em 60ºC teve um efeito estatístico que diminuiu 17N a resistência à tração do poliéster na direção das carreiras. O índice de branco foi aumentado com o uso de detergente para os tecidos contendo algodão, pois continha branqueador óptico em sua composição. O índice de ação mecânica das lavadoras aumentou com a quantidade de ciclos, assim, quanto mais ciclos de lavagem, mais ação mecânica as roupas sofrerão. O encolhimento dos tecidos não foi significativo, sendo muito baixo para a maioria deles, assim para os fatores estudados e tecidos não afetou significativamente a durabilidade dos tecidos. Ao final o modelo estatístico sugeriu que para que os tecidos contendo poliéster é necessário lavar com água fria (20 ºC), com detergente e sem amaciante, assim o tecido irá ter menos perca de resistência e brancura. Já para o tecido 100% algodão é necessário lavar a 60 ºC, com detergente e sem amaciante.

ABSTRACT

The increase in clothing durability reduces environmental impact, as damaged clothes are discarded less frequently. Clothing care involves various steps like washing, drying, ironing, storage, and during use. Washing is a process that, in domestic settings, is carried out using water, either manually or with the assistance of washing machines. Despite being a common daily procedure, the phenomena involved in the conservation of textile substrates are complex, as choices made in clothing care can irreversibly damage them. Thus, this study aims to evaluate the durability of knit fabrics during washing, analyzing factors such as wash cycles, detergent use, fabric softener, and water temperature. Durability, in this study, is defined as tensile strength, whiteness index, and substrate shrinkage. Based on the observed results, a statistical model was proposed to suggest the best combination of evaluated factors so that fabrics retain their characteristics and properties even after numerous wash cycles. The results indicate that wash cycles impact tensile strength, with polyester-cotton, 100% cotton, and 100% polyester fabrics being the most affected, in that order. The use of fabric softener during washes decreased the strength of almost all fabrics, as it forms a film on the fabric that increases lubrication between fibers, reducing tensile strength. Washing at 60°C had a -17N effect, decreasing the tensile strength of polyester in the warp direction. The whiteness index (CIE/E313) increased with higher wash water temperatures and detergent use. The mechanical action of washing machines increased with the number of wash cycles, so more cycles result in greater mechanical action on clothes. Fabric shrinkage was not significant, remaining very low for most fabrics (<4%). Therefore, for fabrics containing polyester, it is advisable to use cold water wash cycles (20°C), with detergent and without fabric softener, to minimize loss of strength and whiteness. For 100% cotton fabric, washing cycles at 60°C with detergent are recommended, excluding fabric softeners.

Keywords: detergent; softener; washing.

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LIST OF ABBREVIATIONS AND ACRONYMS

CO	Cotton
DOE	Design of experiments
DTY	Draw textured yarn
PES	Polyester
PES+CO	Polyester + cotton
SD	Semi dull

SUMMARY

1 INTRODUCTION

Fast fashion represents a prevailing trend in which clothes are manufactured for short-term use and subsequently disposed of due to rapid wear or shifting styles. As a consequence of this practice, the fashion industry has become one of the most significant contributors to environmental pollution. (De Oliveira; Miranda,; De Paula Dias, 2022; Niinimäki, 2020; Zhang; Zhang; Zhou, 2021) This trend generates large amounts of textile waste, most of which is incinerated landfilled or exported to developing countries causing several environmental impacts. (Niinimäki, 2020)

One of the major drawbacks of fast fashion lies in the use of low-quality raw materials, leading to frequent damage during use and care, thus significantly increasing waste production.

In contrast, the slow fashion movement embraces a more conscious approach, emphasizing the use of durable raw materials and sustainable practices throughout the production chain, resulting in a substantial reduction in waste generation. (Štefko; Steffek, 2018)

The care of clothes involves various stages, including washing, drying, ironing, storage, and regular usage. Washing, a common household process, might seem straightforward, but it is, in fact, a complex one, as the choices made during this process can irreversibly damage the garments. (Fan; Hunter, 2009)

Thus, numerous parameters in the washing process can impact the longevity of clothes positively or negatively. To guide consumers, clothes sold in Brazil must follow labeling regulations with symbols indicating care instructions, like avoiding chlorine bleach, hand washing, or not using a tumble dryer.

However, in daily life, consumers have several choices of laundry inputs, such as liquid or powder detergents, fabric softeners, soaps, bleaches, and disinfectants, but the product label recommendations rarely explain which type or concentration is best suited for a specific fabric.

Currently, most detergents in the market are powder corresponding to 43.8% of global market in 2021, most of them containing anionic surfactant. (Transparency Market Research, 2021) This surfactant can decrease the water's surface tension, facilitating soil removal from the fabric. Fabric softeners, typically cationic surfactant and composed of quaternary ammonium salts, are widely used during the rinse cycle to add softness and fragrance to the clothes.

One way to assess fabric durability during washing can be with tests that measure tensile strength, changes in whiteness index, and shrinkage or extension of the fabric. Tensile strength is directly related to a fabric's durability, as reduced strength can result in easier tearing when stretched during use. The whiteness index helps to gauge whether factors can affect the fabric's color. High shrinkage indicates poor dimensional stability, leading to clothes no longer fitting properly and being discarded prematurely.

In this master's thesis, the effects arising from changes in washing parameters for polyester and cotton knit fabrics are examined. These parameters include the quantity of detergent and softener used, water temperature, and the number of washing cycles. Comprehending the impact of these factors on fabric properties, such as shrinkage, tensile strength, and whiteness index, is of utmost importance in optimizing laundry techniques and safeguarding the longevity of textiles. Through a comprehensive exploration of these relationships, it becomes feasible to propose improved combinations that enhance the durability of clothes and helps to mitigate the environmental consequences associated with discarding clothes damaged because of bad consumer choices during washing process.

1.1 STUDY MOTIVATION

The motivation of this thesis is driven by a notable research gap, as no previous study has comprehensively examined the collective impact of fabric softener, detergent, washing temperature, and the number of washing cycles on these particular types of fabrics. By filling this critical void in the literature, this research endeavors to shed light on the holistic effects of these factors on the durability and longevity of knitted fabrics.

With this comprehensive investigation, individuals will be equipped with crucial knowledge to make informed decisions while washing their clothes. These informed decisions are about understand what choices will improve the durability of single jersey knit fabrics (CO and PES composition) during washing process.

The insights gained from studying the combined influences of fabric softener, detergent, washing temperature, and the number of cycles will enable people to adopt effective washing practices that can prolong the fabric's lifespan, reduce waste accumulation, and contribute to sustainable textile care. Here, this more sustainable textile care is related to the fact that using the parameters proposed in this study, clothes will take longer to yellow, higher dimensional stability and will have their tensile strength less affected, thus maintaining their initial properties for longer and can also be used by more time.

Additionally, the study aims to address specific issues, such as preventing fabric yellowing caused by washing, ensuring dimensional stability to prevent shrinkage or size increase, and identifying the optimal conditions that maximize the lifespan of single jersey knit fabrics.

Through this innovative research approach, this thesis seeks to make a contribution to the fields of textile care, sustainability, and consumer decision-making, setting a foundation for future studies and encouraging more conscious fabric care practices.

1.2 OBJECTIVES

This section outlines the objectives of the study.

1.2.1 General Objectives

This research aims to investigate the effects of varying washing parameters on polyester, cotton and blend of cotton and polyester knit fabrics. The parameters under examination are the quantity of detergent and softener used, water temperature, and the number of washing cycles.

1.2.2 Specific Objectives

The specific objectives are:

- ✓ To evaluate the tensile strength, whiteness index, and shrinkage of 100% polyester, 100% cotton, and 50% polyester 50% cotton knit fabrics after repeated household washing cycles using different combinations of detergent, fabric softener, and two different temperatures (20 ºC and 60 °C).
- ✓ To assess the mechanical index of washing cycles and attempt to correlate it with the loss of tensile strength in 100% polyester, 100% cotton, and 50% polyester 50% cotton knit fabrics.
- ✓ To examine changes on the fabric surface after repeated washing cycles using digital microscopy and correlate these findings with whiteness index and tensile strength results.

1.3 ORGANIZATION OF CHAPTERS

This thesis has been organized into 6 chapters to improve its presentation and facilitate understanding. It starts with an introductory section, Chapter 1, which provides a general overview of the research and its proposed objectives.

Chapter 2 presents a literature review, offering a theoretical foundation for the study and a detailed discussion of the concepts and issues related to the proposed theme.

Chapter 3 describes the current state of art of this research, focusing on recent works related to the studied topic.

Chapter 4, presents the methodology section, outlining all the materials and methods used to conduct this study. The methods have been categorized into 3 sections for clarity and ease of understanding.

Chapter 5 presents the results with discussion. It begins with an analysis of the fractional factorial experiments' design, with the results separately presented for each response variable: whiteness index, tensile strength, shrinkage, and mechanical index. Within each response, the main effects and interactions of the factors are analyzed separately for better comprehension. Additionally, digital micrographs of the fabrics are provided at the end of the results section.

Finally, Chapter 6 synthesizes the concluding remarks, highlighting the most relevant results and conclusions drawn from this research.

CONCEPTUAL DIAGRAM

Why?

- ✓ Gaining insight into the impact of washing variables on the durability of knitted fabrics empowers people to make informed decisions while washing, prolonging the fabric's lifespan, and reducing waste accumulation.
- ✓ Preventing the yellowing of fabrics caused by washing helps to extend the lifespan of clothes, as it eliminates the need for their premature disposal.
- ✓ Understanding the effect of washing on the dimensional stability of fabrics is crucial in preventing shrinkage or size increase, which can render the clothing unfit for wear. This knowledge enables proactive measures to minimize damage and preserve the quality of clothes.
- ✓ To find the best condition for increasing the lifespan of single jersey knit fabrics.

Who did?

- ✓ Rathinamoorthy et al (2020) studied the effect of the rinsing cycle fabric softener cationic (15 repeated washing cycles) on the comfort and tensile properties of cotton woven using the Kawabata system to evaluate it.
- ✓ Yilmaz and Özgen (2023) and Khan et al. (2023) study the dimensional stability of knits during washing.
- ✓ Indeed, it is worth noting that there have been limited studies in recent years specifically focusing on the four factors investigated in this research and their impact on the tensile strength, whiteness index, and shrinkage of single jersey knits made from cotton, polyester, and polyester-cotton blend fabrics.

Hypotheses

- ✓ Can fabric softener during washing reduces the tensile strength of fabrics containing cotton and/or polyester?
- ✓ Can fabric softener during washing cause yellowing in fabrics containing cotton and/or polyester?
- ✓ Can repeated washing cycles or mechanical action decrease the tensile strength of fabrics containing cotton and/or polyester?
- ✓ Can water temperature cause shrinkage in fabrics containing cotton and/or polyester?
- ✓ Can detergent increase the whiteness index of fabrics containing cotton and/or polyester?

Methodologies

- ✓ A two-level factorial fractional experiment was conducted to investigate the effects of various factors on the washing process of three types of single jersey fabrics, including cotton, polyester, and a polyester-cotton blend. The factors examined in the experiment included the number of washing cycles, detergent quantity, softener quantity, and water temperature. The objective was to understand the impact of these factors on the fabric's responses, such as tensile strength, shrinkage, mechanical action, and whiteness index.
- ✓ Microscopic analysis was conducted on a few fabric samples to determine whether the surface undergoes any changes after washing.

Responses

- ✓ Fabric softener decreased the tensile strength of all fabrics, with a more pronounced decreased observed in polyester-containing fabrics.
- ✓ Detergent increased the whiteness index of fabrics containing cotton.
- ✓ The water temperature considerably reduced the tensile strength of polyester fabrics.
- ✓ The mechanical action of the washing machines increased with the number of cycles, indicating that clothes undergo more mechanical stress with higher washing cycles.
- ✓ The shrinkage of fabrics was not significant, thus suggesting that the hypothesis that temperature affects shrinkage was not supported for the factors levels studied.

2 LITERATURE REVIEW

This chapter provides a bibliographic review regarding textile fibers, specifically cotton and, polyester, which were used in this work, as well as knitted fabrics. It also includes a brief overview of laundry processes, focusing on the detergent and softener inputs used.

2.1 FIBERS

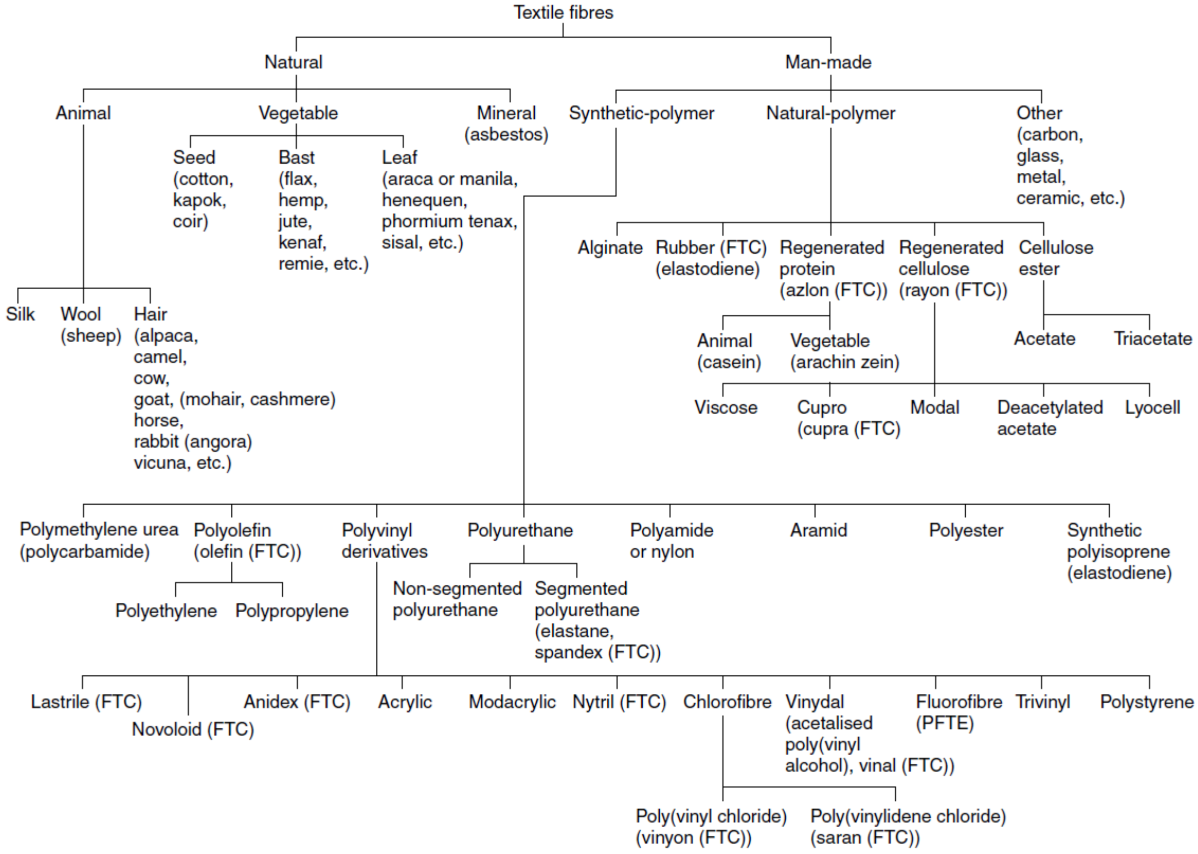
Textile fibers are thin and with a high ratio of length to thickness. These fibers must have essential characteristics such as flexibility, strength, and stability to fit as a textile material. (Eichhorn *et al*, 2009a). A textile material can be yarn, fabric, nonwoven, composite, or rope, and it will be discussed in the following pages.

It is important to emphasize that the fibers are responsible for the final characteristics of the textile material. An example is that a fabric with the same structure, and the same type of yarn, but made with different materials will have different characteristics concerning resistance, touch, color, thermal comfort, etc.

Fibers can be categorized based on their origin or natural source: natural and manufactured (man-made) fibers. Natural fibers are from plants, animals, or minerals, and manufactured fibers are fibers that are created through various industrial processes rather than being naturally occurring. These fibers are typically made from polymers or chemicals and are engineered to possess specific characteristics and properties. Examples of manufactured fibers include polyester, nylon, acrylic, and rayon. Figure 1 shows the complete classification of textile fibers.

Polyester is the dominant textile fiber worldwide, accounting for a significant 54% of total global production in 2021. Following is cotton, the second most important fiber, representing 22% of the total fiber market worldwide. (Statista, 2021) Both fibers find extensive application in clothing, home textiles, and technical fabrics.

Figure 1 – Classification of textile fibers according to nature origin.



Source: Clark (2011).

2.1.1 Cotton Fiber

Cotton is a fiber predominantly composed of cellulose and originates from the seed of plants of the genus Gossypium, with four species currently known: hirsutum, barbadense, arboreum, and herbaceum. Gossypium hirsutum is the most cultivated and sold, having a fiber length of around 13-33 mm and fineness of 10-20 μm. (Wakelyn, 2006)

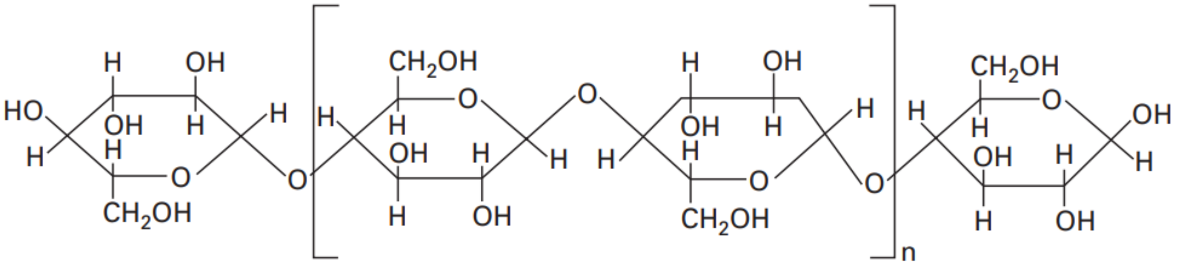
Cotton is a fiber that has excellent thermal comfort, as its moisture regain is 6.5-8 % in 20±4 ºC and 63±3 % relative humidity (Chu *et al*., 2020; Adamu; Gao, 2022), has a good tensile strength of 287-800 MPa (Chokshi *et al*., 2022), is biodegradable (Zambrano, et al., 2021), and has good wearability.

The chemical composition of the cotton fiber after mechanical cleaning (removal of husks and harvest impurities) is cellulose (88-95%). (Wakelyn, 2006, Wang; Siddiqui; Memon, 2020). Non-cellulosic materials can be proteins, pectin, lignin, ash, wax, sugar, organic acids, and very small amounts of pigment. Most non-cellulosic materials can be removed with scouring and bleaching, so the cellulose percentage after these treatments will be around 99%. (Wakelyn, 2006, Wang; Siddiqui; Memon, 2020)

Cellulose (Figure 2) is a natural linear polymer (polysaccharide) whose monomer is a pair of D-anhydroglucose ring units joined by β-1→4 glycosidic oxygen linkages, and the molecule can twist or bend. (Eichhorn, 2009b). The cellulose crystalline present in cotton is the I_β allomorphism, and this structure is more stable and rigid because of the hydrogen bonds happening between adjacent polymer chains. (Figure 3).

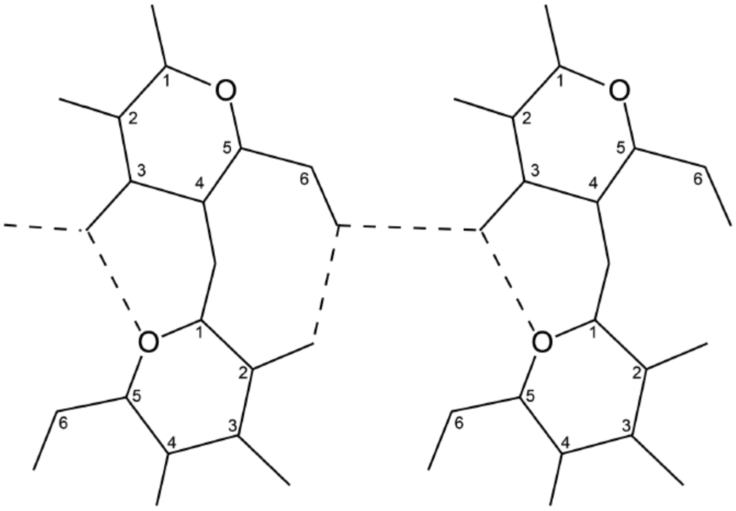
When cotton cellulose comes into contact with water during the washing process, it swells and creates internal stress within the fibers. (Liu *et al,* 2019) Subsequently, during the drying process, the reformation of hydrogen bonds (as depicted in Figure 3) occurs, leading to the formation of unwanted creases. (Wakelyn, 2006)

Figure 2 – Cellulose structure.



Source: Eichhorn *et al*, 2009b.

Figure 3 – Hydrogen bonding in Cellulose I.



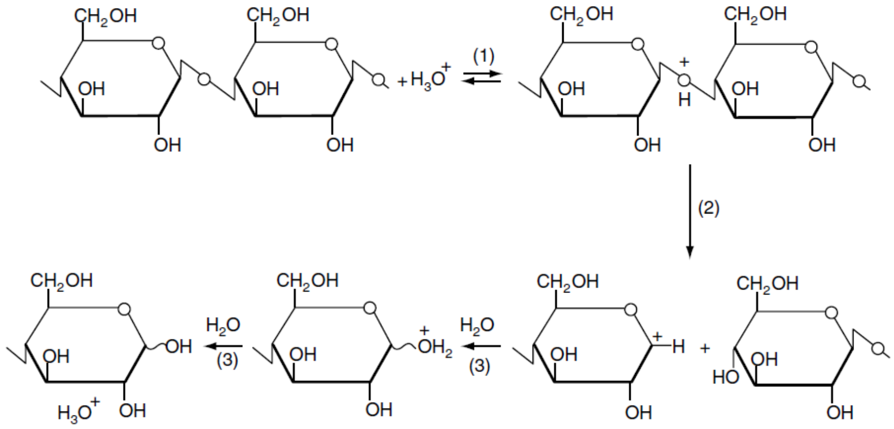
Source: Mather and Wardman, 2015.

Cellulose can be damaged in the degree of polymerization with some chemicals, and acids being the most damaging to cellulose. This degradation in the degree of polymerization considerably decreases fiber strength. (Mather; Wardman, 2015)

Acids can hydrolyze cellulose, that is, cleaving the glycosidic linkages, first attacking the regions that are easier to access, which are amorphous. Some acids that can be used for hydrolysis are sulfuric (Mari; Sornas; Bierhalz, 2023; Maciel *et al*., 2019), hydrochloric, and nitric (Costa *et al*., 2022).

This acid hydrolysis decreases the degree of polymerization and consequently, the tensile strength, which can be seen in Figure 44. Hydrolysis leads to the formation of hydro celluloses, which are materials with a lower degree of polymerization and possess one non-reducing and one reducing end group per macromolecule. (Mather; Wardman, 2015; Wakelyn, 2006)

Figure 4 – Acid hydrolysis of cellulose.



Source: Wakelyn, 2006.

In contrast to acids, cellulose does not undergo immediate hydrolysis under alkaline conditions. However, high-temperature conditions can still result in a decrease in the degree of polymerization. Cellulose can also lose its degree of polymerization with temperature; however, this loss only occurs at temperatures above 120°C and when exposed for long periods at this temperature. (Mather; Wardman, 2015; Lewin, 2006)

Cotton fibers are not so affected with common temperatures used in household laundry and usually high temperatures (>60 ºC) during washing or drying are interesting to eliminate microorganisms. (Tomšič; Ofentavšek; Fink, 2023.)

To determine if there has been a loss of glycosidic groups in cotton, one can compare the weight before and after the treatment. If there is no deposit from the treatment on the cotton, the difference in weight corresponds to the loss of glycosidic groups in the cotton (Mather; Wardman, 2015)

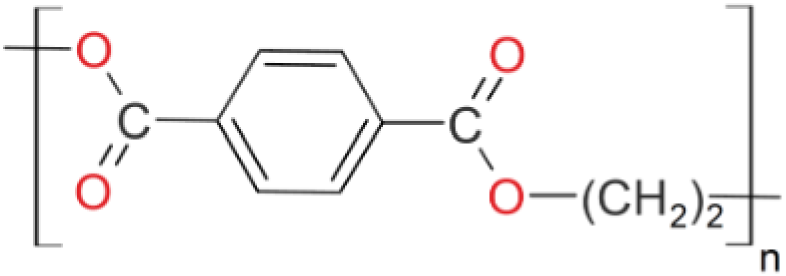
Another type of degradation that can occur in cellulose is oxidation, which usually occurs during bleaching and transforms the glycosidic rings into oxycellulose. The main goal of the bleaching agent is to destroy the pigments of soils (household) or the naturally occurring pigments of cotton (industrial). An example is bleaching with hydrogen peroxide, it must be done at 95 ºC for 2 h in an alkaline environment (ph 10-11) using sodium hydroxide and sodium silicate. Thus, there is also an irregular degradation here, as the amorphous regions are attacked first and if the temperature, pH, and time conditions are not controlled, overbleaching can occur and end up significantly reducing the tensile strength. (Mather; Wardman, 2015)

2.1.2 Polyester Fiber

In 1930 W. H. Carothers at Dupont was the pioneer in the synthesis of synthetic polymers, especially the synthesis of polyester, and he is considered responsible for creating the methods of polymerization by addition and condensation. (Mandal; Dey, 2019) The first textile polyesters to be sold were Terylene (ICI - Great Britain) and Dacron (Dupont - USA) around 1950 and since then they have been widely used worldwide.

There are several types of polyesters (PES), but the most used for textile fiber is polyethylene terephthalate (PET - Figure 5), which is also the most used synthetic fiber in the world, 52% of world fiber consumption in 2020. (Statista, 2022) The main reasons that polyester is widely used are low cost, convenient processability, and excellent and tailorable performance. (Lewin, 2006)

Figure 5 – Molecular structure of PET.



Source: Polymer database, 2023.

Polyester can be defined as a condensation polymer containing ester units in its chain as the main linkage of the polymers. (Mcintyre, 2004) PET can be produced by condensation polymerization of terephthalic acid and ethylene glycol (diol). (Lewin, 2006)

Polyester fibers exhibit remarkable strength and exceptional temperature resistance due to their glass transition temperature (Tg) of 60-84 ºC and a melting point of 255 ºC. (Nisticò, 2020) They are also highly resistant to chemicals, abrasion, mildew, creases and are not damaged by sunlight. (Deopura et al, 2008; Mather; Wardman, 2015)

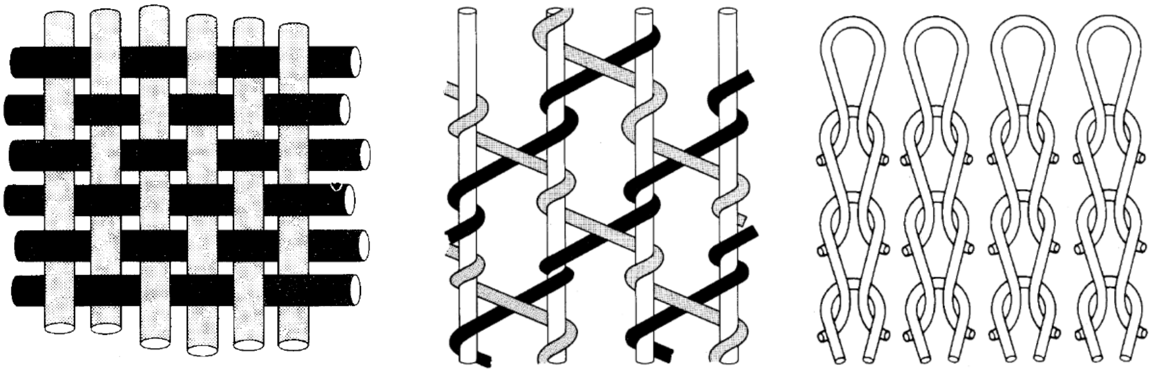
Being a thermoplastic polymer, this particular fiber undergoes molecular structural changes in response to temperature variations above the Tg. (Mcintyre, 2004, Deopura *et al,* 2008) Hence, it is advisable to dry the fabric at low temperatures and wash it using lower temperatures to prevent strength reduction and shrinkage.

Nevertheless, its moisture regain is exceedingly low, measuring at 0.4%, which renders fabrics made from this fiber physiologically uncomfortable in warm climates. (Deopura *et al,* 2008) However, the advantage of such low moisture regain lies in the fabric's rapid drying capability. As polyester is apolar, water alone finds it challenging to penetrate the fibers, necessitating the use of detergents to modify the surface tension of water and facilitate washing this type of fabric.

2.2 FABRICS

Fabrics can be produced by interlacing yarn in three main ways: interweaving, intertwining, and interlooping. (Figure 6)

Figure 6 - Ways to interlacing yarns.



(a) Interweaving

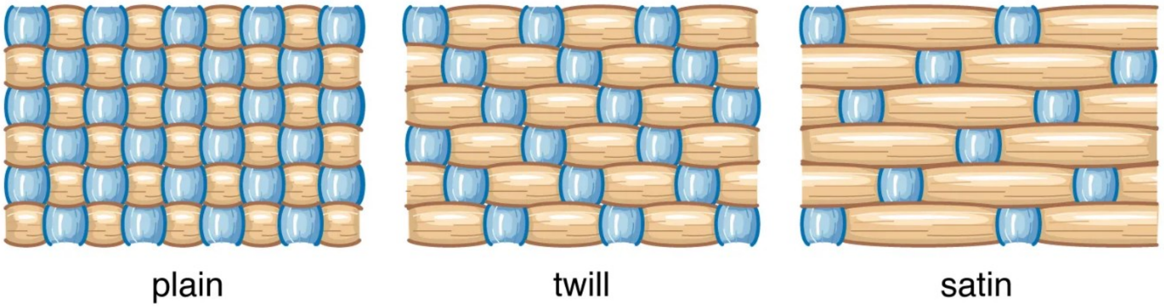
(b) Intertwining and twisting

(c) Interlooping

Source: Spencer, 2001.

The oldest method is interweaving, which consists of the threads vertically (warp) and horizontally (weft), thus producing various structures that can be seen in Figure **Error! Reference source not found.**7.

Figure 7 - Basic fabric structures plain woven.



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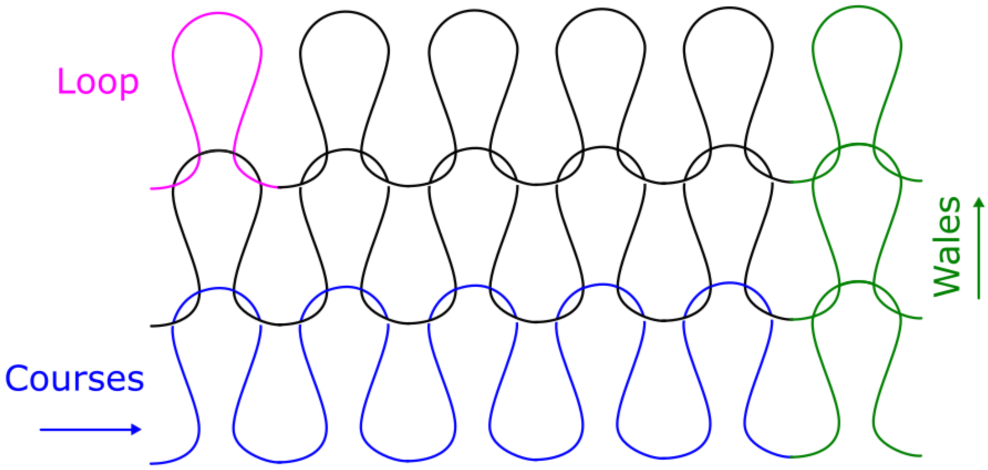
Source: Britannica (2023)

The process of interlooping creates knits, where the primary unitary element is the loop. (Figure 8) and it is a more recent method created by the Egyptians around the fourth century. (Au, 2011) In addition, they are divided into weft knit and warp knit. In weft knitting, the fabric is produced in the horizontal direction, that is, in the direction of the knitting courses (Figure 8), while in warp knitting it is the opposite, the loops occur in the vertical direction, that is, in the knitting wales (Figure 8).

Figure 8 – Schematic diagram of wale and course directions and a loop of a weft knitted fabric in single jersey structure.



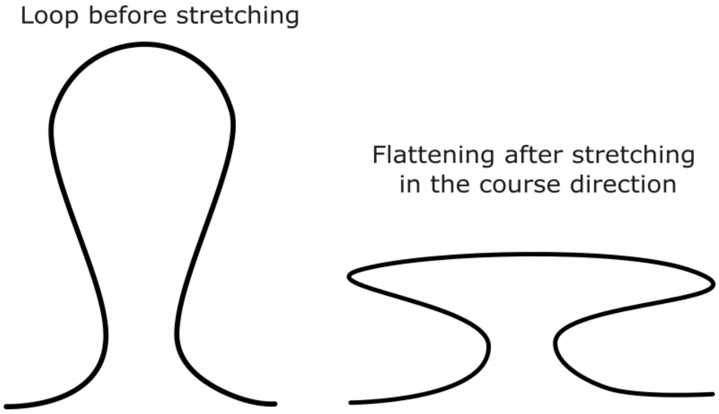
Source: by the author.

The basic stitches for weft knit are knit, float, and tuck, where from the combination of these stitches various types of structures can be formed with totally different characteristics between them.

The most basic knit is the single jersey (Figure 8) which is composed of the knit stitch and produced on a single-ply machine.

Weft knits exhibit excellent dimensional stability along the course direction. This occurs due to a transformation in the loop shapes when the fabric is stretched in this direction, resulting in the loops becoming flattened. This significant flattening is represented in Figure 9 and ensures a fabric elongation of approximately 15-20%. Remarkably, this elongation rapidly returns to its original state, a unique characteristic of knitwear even without the inclusion of elastomeric fibers. Beyond the point of elongation caused by loop deformation, the yarn itself begins to deform, allowing the knits to achieve elongation exceeding 100% in the course direction. However, once the deformation extends beyond the loop deformation and enters the realm of yarn elongation, the recovery of this elongation becomes impossible, unlike the scenario where only loop deformation was experienced. (Au, 2011)

Figure 9 – Loop flattening after stretching in the course direction.



Source: by the author.

The shrinkage of the knit fabrics can happen due to the relaxation of the tensions that were exerted during knitting. For synthetic fibers such as polyester, it is possible to perform thermosetting, where the fabric is tensioned at high temperatures (185~190 ºC) and fixing the structure in those dimensions. (Spencer, 2001)

For knits, it is common to use a technique called compacting, in which the fabric is pressed between two sets of rollers to stretch, fix and stabilize the fabric, avoiding shrinkage or bad dimensional stability for the end user. (Choudhury, 2017)

According to Spencer (2001, p. 280) “agitation of the knitted structure whilst it is freely immersed in water appears to provide the most suitable conditions for relaxation to take place as it tends to overcome the frictional restraints imposed by intermeshing of the structure.” It is interesting to note that this type of situation happens, for example, during the washing of clothes, so if the fabric was not relaxed in the industry, it will end up suffering deformations in its dimensions.

2.3 HOUSEHOLD LAUNDRY

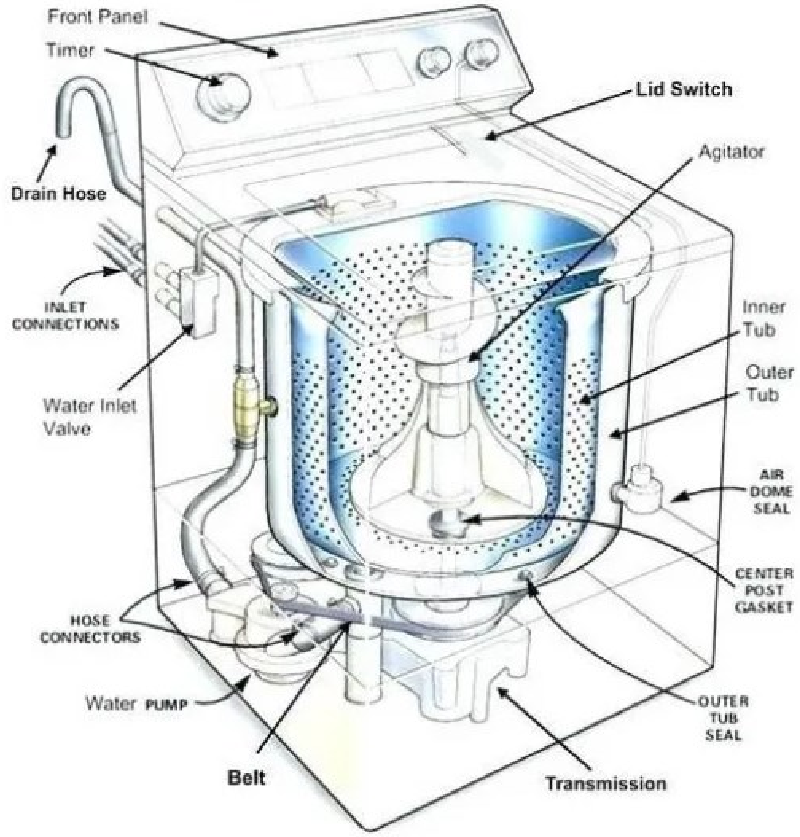
The first type of laundry that existed and was practiced by the ancient Egyptians was the act of washing clothes with their feet using water only. The oldest known surfactant is soap, being used by the Sumerians around 2500 BC. (Smulders *et al.,* 2002)

Nowadays, the laundry process has changed a lot, and many people today have access to washing machines, dryers, and various laundry supplies such as various types of detergents, softeners, bleaches, among other products.

A washing machine is a household appliance designed to clean and launder clothes and other textiles. It accomplishes this task by agitating the clothes in water with the help of detergent, which helps remove dirt, stains, and odors from the fabric. After the washing cycle, the machine typically goes through a rinsing process to remove any remaining detergent, and finally, it spins the clothes to remove excess water before they are ready for drying. Washing machines automate and simplify the process of cleaning clothes, making them more convenient for users.

There are two main types of washing machines available in the market: front load horizontal axis washing machines and top load vertical axis washing machines. The primary difference between them lies in the loading mechanism, where one is loaded from the top, and the other is loaded from the front. Front load washing machines utilize drum movement and clothes friction as the mechanical action for washing. On the other hand, top load washing machines are equipped with an agitator on the vertical axis, which provides mechanical action to the clothes during the washing process with your rotation. A scheme of this kind of washing machine can be seen the Figure 10. This kind of washing machine can be with an agitator (Figure 11) or an impeller (Figure 12), the difference is the mechanical action of each kind, being the high profile agitator Figure 11know as better mechanical action to remove difficult stains of clothes. For this study, a top load washing machine was used, as it is the most common type of washing machine in Brazil.

Figure 10 – Top load washing machine scheme.



Source: Textile learner, 2022.

Figure 11 – High profile agitator.

Source: Maytag, 2023.

Figure 12 – Impeller agitator.

Source: Maytag, 2023.

2.3.1 Household detergent for washing clothes

Detergents are components used in laundry where their main component is a surfactant, which is responsible for reducing the surface tension of water, making it possible to penetrate the fabric and remove dirt from it. (Grządka, *et al.,* 2021)

Water has a high surface tension of 72 mN/m and usually, to be possible to wash clothes it is needed to reduce the surface tension of water below 30 mN/m and anionic surfactants present in household powder detergents can do it. (Smulders et al, 2002)

The first detergent to be commercialized was Henkel's Bleichsoda in 1878, which had caustic soda and sodium silicate (water softener) in its composition. Shortly after, Persil (1907) was marketed, which had binders in its formula, in addition to soap, and was known to act alone to leave clothes clean and bleached, significantly reducing the effort of washing by hand. (Smulders *et al*, 2002)

In 2022, the global market size of laundry detergents reached US$ 96.94 billion, and it is projected to reach US$ 122.50 billion by 2028. The industry has experienced growth over the last four years, driven partly by the pandemic situation that heightened concerns about washing clothes (Statista, 2022). This indicates a continuous increase in detergent usage, making it significant to understand how it can impact clothes during laundry.

In 2021, the most common detergents in the market were powder, comprising 43.8% of the total share. Among detergent types, anionic detergents held the largest portion, accounting for 50.3% of the market. (Transparency Market Research, 2021) Regarding South American powder detergents, they usually contain the ingredients presented in Table 1. (Waldhoff, 2016)

Table 1 – Household powder detergents composition.

Ingredients	Examples	Composition (%)
Surfactants	Linear alkylbenzene sulfonate (LAS); Fatty alkyl sulfate (FAS); Fatty alcohol ethoxylate; (FAE)	18.25
Builders	Zeolite, sodium triphosphate, sodium citrate, sodium silicate, sodium carbonate/bicarbonate	40-55
Antiredeposition agents	Carboxymethyl cellulose, cellulose ethers	0.5-1.0
Enzymes	Protease, amylase, lipase, cellulase	0.3-0.8
Fluorescent whitening agents	Stilbene, Bisphenyldistyryl derivatives	0.1 - 0.3
Fillers/processing aids	Sodium sulfate	20-35
Minors	Fragrance	+
Water		5-15

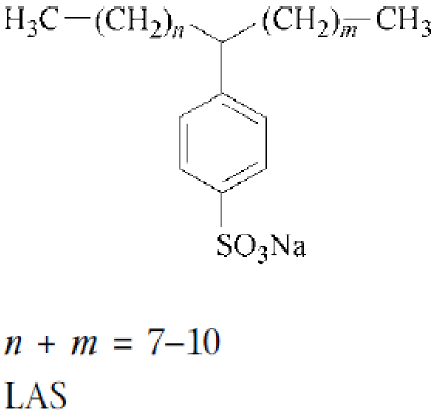
Source: adapted from Waldhoff (2016, p.3)

The surfactants, or surface-active agents, are the most important compounds present in detergents. (Yangxin; Jin; Bayly, 2008) They are composed of a hydrophilic and a hydrophobic part and can adsorb onto surfaces in an oriented manner. In addition to decreasing the surface tension of the water as mentioned, they are also responsible for removing dirt from the fabric with the help of mechanical action; emulsify, solubilize, and suspend these soils in the wash water. Sometimes detergents have more than one type of surfactant to be able to attack a greater variety of dirt on clothes. (Bajpai, 2007)

Usually, the powder detergents, such as Omo, used in this study are anionic, that is the hydrophilic part of the surfactant is negatively charged and the ionized moiety can be a phosphate, sulfate, sulfonate, or carboxylate. (Broze, 1999)

The compound most used as a surfactant in powdered detergents in Latin America is linear alkyl benzene sulfonates (LAS) and its structure can be seen in Figure 133. This surfactant is cost-effective, provides excellent detergency, and is also a foaming agent. A problem with this surfactant is that it is sensitive to hard water, so as water hardness increases, its detergency performance decreases. (Smulders, 2002)

Figure 13 – Molecular structure of linear alkylbenzene sulfonate (LAS).



Source: Smulders, 2002.

The second most important component in a detergent is the builders, which are responsible for improving the cleaning efficiency of the surfactant. Some of the functions of these components are to decrease water hardness; prevent the formation of ions that increase water hardness; increase alkalinity; disperse and suspend dirt. (Bajpai, 2007). In Brazil’s southern region, the water usually is soft, so it is not a concern. (Sória *et al.*, 2020)

Another type of component present in detergents is a combination of enzymes (protease, amylase, lipase and cellulase). The enzymes are ingredients that usually act in different kinds of stains so protease can remove protein stains (from blood, for example), amylase is for carbohydrate stains, lipase (Nerurkar *et al.,* 2013) for oil stains (from salad oil, for example) and cellulase acts by biopolishing the cellulose fibers, so the fibrils in the surface are removed by cellulase and the fabric surface stay smoother and brighter.

And a last component in the detergent is the fluorescent whitening agent, which is responsible to add a blue whiteness to fabrics because this compound absorbs light in the ultraviolet region (340-380 nm) and reflects in the blue region (400-500 nm), so fabric appears whiter with these agents.

2.3.2 Household fabric softener

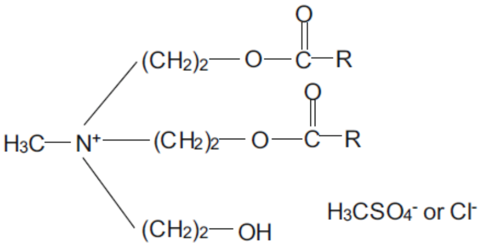
With the introduction of detergents around 1950 in the USA, it was necessary to create a product that made the fabrics softer, since the detergent now left the clothes with an unpleasant touch compared to the well-known soap that left magnesium and calcium salts deposited on fibers and the hand was softer. (Egan, 1978) This is how softeners were created, which are used both in the textile industry and in the laundry.

The market size of fabric softeners in 2022 was US$ 19.99 billion and is expected to achieve US$ 27.20 billion by 2029. The most used fabric softeners are liquid softeners followed by dryer sheets. North America corresponds to more than 50% of the market, followed by Europe with 27% of the market (Maximize, 2023).

Currently, fabric softeners are used in domestic laundries to improve the softness of clothes, facilitate ironing, and add a pleasant smell to clothes. (Cimilli Duru; Şahin, 2020)

The most common household liquid fabric softeners are the cationic ones that have a quaternary ammonium salt as their main active component and usually with ester being mono or triester, but usually are diester in the chain. The structure of ester quat based softener can be seen in Figure 144, usually the R there are 16 or 18 carbons, which means long alkyl chains. (Murphy, 2015; Igarashi; Nakamura 2021)

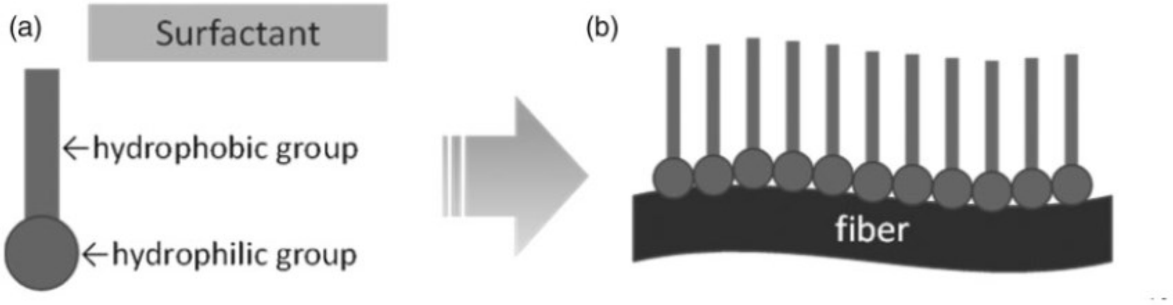
Figure 14 – Molecule structure for ester quat based cationic fabric softeners.



Source: Murphy, 2015

Cotton are highly known to have a surface partially negatively charged (zeta potential) (Ling *et al.,* 2019) so because of it the cationic softeners have a greater propensity to deposit on these fibers and form a film of hydrocarbons as can be seen in Figure 155. (Schindler; Hauser, 2004)

Figure 15 – Fabric softener deposition on fiber: (a) surfactant softener cationic structure (b) cationic softener deposited on the fiber.



Source: Kim *et al,* 2021.

The cationic softeners are hydrophobic and because of it are commercialized as emulsions. Some properties of this type of softener compared to other existing ones are that they provide great softness to the fibers, do not form foam, and do not have yellowing stability, that is, they make the fabrics more yellowish when used. (Schindler; Hauser, 2004; Sk *et al*., 2021.)

There are a few theories about how fabric softeners work on fibers. Initially, it was believed that the hydrocarbon chain in the softener acted as a lubricant, enhancing interactions between the fibers and yarns, resulting in a soft touch.

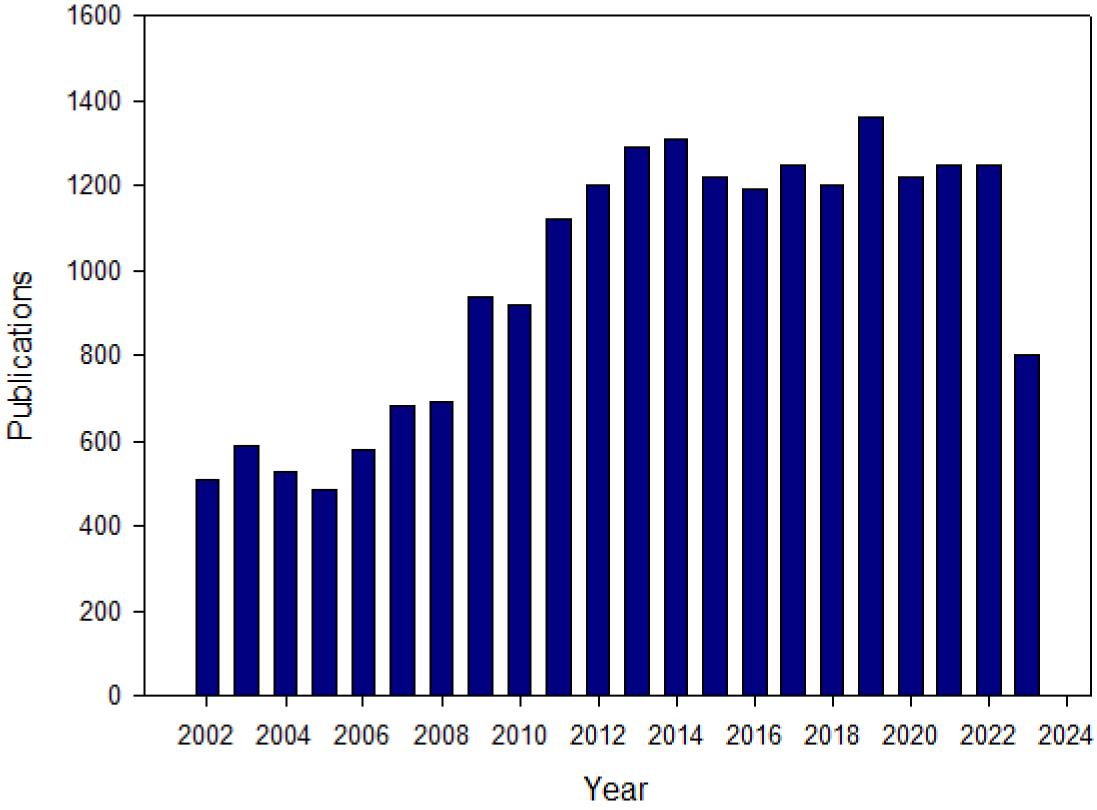
Other studies have also elucidated that, for cotton, the fiber softening mechanism occurs by avoiding the hydrogen bonds between the cellulose molecules. Additionally, it has been observed that softeners provide a more superficial coverage on cotton fabric with uneven adsorption patterns (Igarashi *et al*., 2016a, 2016b).

3 STATE-OF-ART

The present study aims to investigate the effects of different washing parameters on polyester and cotton knitted fabrics, but it is worth noting that there are limited studies directly comparable to this research. A keyword search for "washing" and "knit" and "fabric" yielded 15300 publications on this subject in the last 20 years, as illustrated in Figure 16. Furthermore, it is evident that this research area has been experiencing growth in recent years.

Currently, numerous publications focus on microplastic release during washing (Volgare *et al*., 2021; Le *et al.,* 2022; Yang *et al.,* 2019), the development of more sustainable chemicals for household washing (Liu *et al*., 2020; Oikonomou; Berret, 2021; Shao *et al*., 2021), and the treatment of laundry effluents (Li; Dagnew; Ray, 2022; Hyeon *et al.,* 2023; Kim; Park, 2022).

Figure 16 – Publications history with keywords “washing”, “knit”, and “fabrics”.



Source: Google Scholar. (2023)

Rathinamoorthy (2018) examined the effects of commercial household fabric softeners on 100% polyester and 100% cotton plain woven fabrics after 5, 10, and 15 wash cycles. For the cotton fabric, repeated washings resulted in decreased air permeability and absorbency. Conversely, for the polyester fabric, there were no significant changes observed in these parameters with increasing wash cycles.

In their 2019 study, Liu et al. delved into the factors contributing to wrinkles in cotton clothing during front load washing machine cycles. The research highlighted two key parameters significantly influencing creasing: the quantity of clothes being washed and the spinning speed. The study revealed that a higher clothing load resulted in increased mechanical stress on the garments, leading to more pronounced wrinkling. Additionally, the distance of clothes from the machine's center played a role in creasing, with clothes farther from the center experiencing more significant wrinkling. Consequently, higher spin speeds contributed to enhanced creasing in clothes positioned away from the center of the washing drum.

Sülar and Oner (2019) studied the impact of repeated washings on 12 different types of knitted fabrics made from viscose, polyamide, and spandex yarns. They used a universal tensile test machine with computer control to assess the fabrics' cyclic deformation. After subjecting the samples to two deformation cycles, they found that the critical recovery time for all fabrics was 30 minutes, indicating full recovery within this period. Moreover, after 25 washing cycles, most knit fabrics showed an increase in g/m², suggesting a change in fabric weight during washing.

In a separate study, Rathinamoorthy et al. (2020) conducted a comprehensive investigation on the impact of repeated washing cycles with cationic fabric softener on the comfort and tensile properties of cotton woven fabrics. Using the Kawabata system for evaluation, the researchers found that the fabric softener led to enhanced comfort, but it also resulted in a considerable decrease (41.29%) in the tensile properties of the cotton fabric. Similarly, other studies by Othman Adli et al. (2019), Cimilli Duru; Şahin (2020) Al Belihy, (2021) also analyzed the comfort properties of fabric softeners, confirming their positive effect on enhancing the softness and hand feel of clothes.

Elrys et al. (2023) studied single jersey knit structures using ring-spun, dual-core, and tri-core spun yarns after one wash at 40 ºC using Wascator. Cotton ring-spun yarns showed the least shrinkage, with about 10% in courses and 3.5% in wales. Cotton plain knitted had higher force at 30% extension in the wales (18 N) than courses (5 N). Ring-spun yarns had the highest air permeability, while tri-core yarns had the lowest. Blended cotton/tencel (50/50%) ring-spun yarns are recommended for highly permeable fabrics, while blended cotton/tencel (50/50%) tri-core spun yarns are suitable for sports garments with better mechanical comfort (recovery extension and dimensional stability).

Yilmaz and Özgen's (2023) study focused on three types of knitted fabric structures (single jersey, rib, and interlock) made from a combination of recycled and virgin polyester and cotton fibers. The fabrics were subjected to multiple wash cycles at different temperatures and drying methods. After 20 washes, all fabrics experienced increased weight loss. Fabrics made from fully recycled cotton-polyester yarns showed more dimensional changes than those made from semi-recycled and virgin yarns. Line drying minimized dimensional changes. Tumble drying should be avoided to reduce fabric loss. Fabrics made from fully recycled cotton-polyester yarns performed better in weight loss compared to semi-recycled and virgin yarns. The study concluded that using recycled cotton fibers in knitted fabric production did not negatively affect performance properties.

Khan et al. (2023) studied the shrinkage of a 216 g/m² polyester single jersey fabric after one washing cycle. Shrinkage was greater in the wales direction (1.98%) compared to the courses direction (-0.07%). This was attributed to higher courses per inch, making the fabric more compacted in the direction of the courses. The fabric didn't undergo finishing after knitting.

Lashgari, Ramazani, and Aghahosseini (2023) examined the effect of silicone softener emulsion on polyester knit fabric with varying particle sizes. They discovered that using nanoemulsion resulted in a 13 N reduction in tensile strength specifically in the wales direction, compared to the use of macroemulsion.

There are several studies about the washing performance of fabrics (mechanical, comfort, appearance, and/or finishing durability) for different kinds of fibers such as silk (Luo *et al*., 2022; Kumar *et al.,* 2022; Çakmakçi; Candan; Arslan, 2022), wool (Wiedemann, 2021; El-Apasery *et al.,* 2021; Cheng *et al.,* 2022), recycled polyester (Khan *et al*., 2023; Yilmaz; Özgens, 2023), polyester/Tencel blends (Kumar *et al*., 2022), cotton/Tencel (Elrys *et al*., 2023), cotton/modal (Elrys *et al.,* 2023), cotton/flax (Bukhonka, 2023), cotton/polyester/spandex (Hoque *et al.,* 2022), Viscose (Sülar; Oner, 2019), Polyamide (Sülar; Oner, 2019; Rahman *et al.,* 2023), and e-textiles (Rotzler; Schneider-Ramelow, 2021; Veske, *et al.,* 2020)

Indeed, it is worth noting that there have been limited studies in recent years specifically focusing on the four factors investigated in this research and their impact on the tensile strength, whiteness index, and shrinkage of single jersey knits made from cotton, polyester, and polyester-cotton blend fabrics.

This thesis fills an important gap in the existing literature, as no previous study has comprehensively examined the collective impact of fabric softener, detergent, washing temperature, and the number of cycles on these particular types of fabrics. By conducting a detailed analysis of the relationships between washing cycles, water temperature, softener quantity, and detergent quantity, and their influence on fabric properties, valuable insights have been gained to optimize laundry practices.

4 MATERIALS AND METHODS

This chapter aims to present all the chemical reagents, analytical methods, and experimental procedures used in this thesis, as well as the experimental setups employed to obtain the data relevant to the understanding of the process.

4.1 MATERIALS

Three types of knit fabrics scoured were used with different compositions but with the same structure, supplied by a textile industry (Indaial, SC, Brazil). The characteristics of the fabrics used are shown in

Table 22. The polyester fabrics were produced with multifilament yarns, specifically draw textured yarns (DTY) with TiO_2 added during extrusion to achieve semi dull (SD).

Table 2 – Fabrics characteristics.

Fabric composition	Structure	Weight (g/m²)	Thickness (mm)	Yarn type
100% Cotton (CO)	Single Jersey	159	0.51	Ring spun
100% Polyester (PES)	Single Jersey	174	0.42	DTY SD
50/50% Polyester and Cotton (PES+CO)	Single Jersey	180	0.38	DTY SD and Ring spun

Source: by the author.

To bleach fabrics containing cotton as part of their composition, 50% hydrogen peroxide (Quimidrol), sodium hydroxide lentil (Biotec), and ECE-2 (WFK Testgewebe) reference detergent without optical brightener (ISO105-C06:2010 “Textiles - Tests for color fastness - Part C06: Colour fastness to domestic and commercial laundering”) were used.

The load used for the experiments was 3 kg of standard white clothes following AS/NSZ 2040.1:2005 “"Performance of household electrical appliances - Clothes washing machines - Part 1: Methods for measuring performance, energy, and water consumption" and the components of the load were: t-shirts interlock knit (100% CO), shirt plain woven (50%CO and 50% PES), men’s underwear (100% CO), bath towels (100% CO), and pillowcases (100% CO).

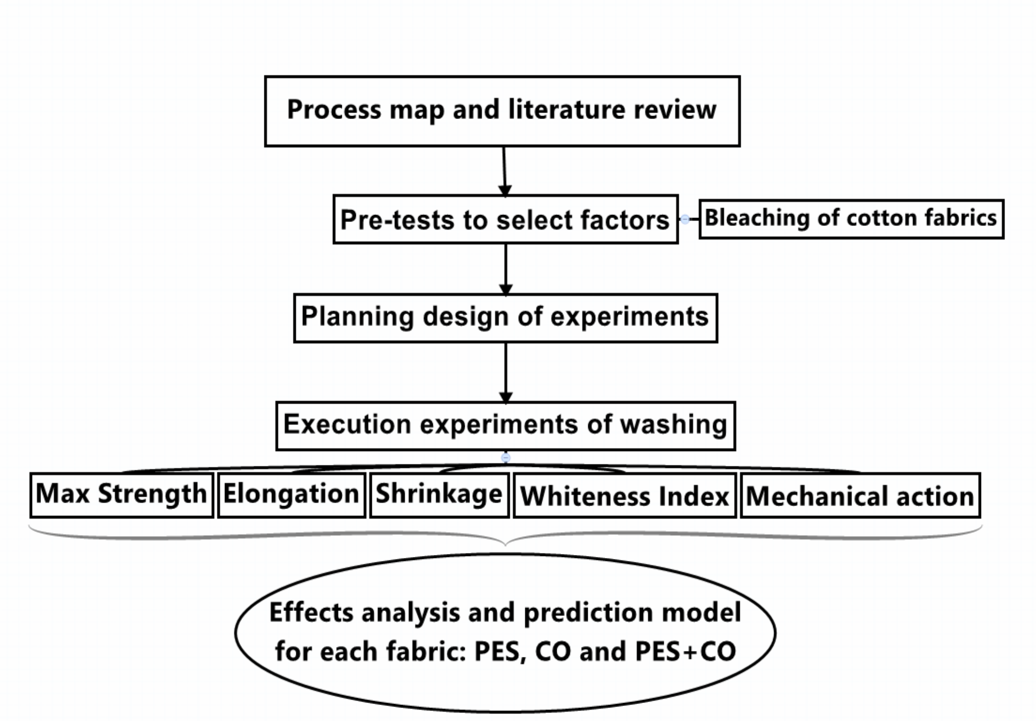
For the washing cycles, powdered detergent Omo Lavagem Perfeita and Downy fabric softener concentrate were used.

Washing was carried out in an Electrolux washer top load vertical axis, model LPE16. The drying of the load and samples used the Electrolux drum dryer model SFP12.

4.2 METHODS

This section presents the methodology used during this study. A flowchart of the methodology is presented in Figure 177 and summarizes the steps of this work.

Figure 17 – Flowchart of methodology.



Source: By the author.

4.2.1 Design of experiments (DOE)

To gain a more profound comprehension of the washing process, a comprehensive list was compiled, encompassing all the variables that could impact the fabric's durability in terms of strength loss, shrinkage, and color changes. This initiative led to the identification of significant factors, and several pre-tests were conducted to ascertain their relevance and impact.

After selecting the factors, a fractional factorial experimental design was planned and carried out with 2 levels, 4 factors, resolution IV, and 8 treatments and the responses of the planning were shrinkage, max strength, whiteness index, and mechanical index.

The different treatments tested can be seen in Table 3. The cold-water temperature of 20 ºC was choose because standard IEC 60456:2010 - Clothes washing machines for household use – Methods for measuring the performance suggest it and standard ISO 6330:2021 Textiles — Domestic washing and drying procedures for textile testing suggests lower than 25 ºC. The temperature of 60 ºC was choose because this temperature can eliminate microorganisms. (Tomšič; Ofentavšek; Fink, 2023.)

Many parameters were fixed during the experiments, the most important of which are mentioned here:

- Water hardness: 50 ppm CaCO3
- Room temperature during washing and drying: 23ºC +/- 3ºC
- Room relative humidity during washing and drying: 65% +/- 15%
- Washing program selected: Normal, 90min
- Washing water level: Medium (80 L by step, total 160 L)
- Drying time: 120 min
- Drying temperature: Maximum (40-70 ºC)

The washings were conducted using 3 samples measuring 50x50 cm of fabrics (Table 2). These fabric samples were analyzed for durability, including tensile strength, whiteness index, and shrinkage. To simulate a domestic laundry, a standardized load of clothes was used in conjunction with the fabric samples, following the AS/NSZ 2040.1:2005 "Performance of household electrical appliances - Clothes washing machines - Part 1: Methods for measuring performance, energy, and water consumption" standard.

Table 3 – Test plan DOE factorial fractioned.

Treatment	**Pattern levels**	**Cycles number**	**Water temperature**	**Detergent quantity**	**Softener quantity**
0	No-wash	0	-	-	-
1	----	1	20±2 ºC	0 g	0 mL
2	--++	1	20±2 ºC	90 g	70 mL
3	-+-+	1	60±2 ºC	0 g	70 mL
4	-++-	1	60±2 ºC	90 g	0 mL
5	+--+	20	20±2 ºC	0 g	70 mL
6	+-+-	20	20±2 ºC	90 g	0 mL
7	++--	20	60±2 ºC	0 g	0 mL
8	++++	20	60±2 ºC	90 g	70 mL

Source: by the author.

The loading of the fabric samples and clothes in the washing machine was also standardized, adhering to the AS/NSZ 2040.1:2005 standard. This initial loading standardization is essential to ensure that the fabric samples start each treatment of the DOE from the same position, avoiding any potential variation in mechanical action. Including such variation could introduce unnecessary noise to the experiments, which can be easily avoided through this standardized loading approach.

After each treatment of the design, both the clothes load and fabric samples were dried using a domestic tumble dryer (Electrolux SFP12 model) before proceeding to the subsequent tests. To minimize the impact of the dryer on the experimental factors, the samples were dried only after the completion of each treatment. Thus, the treatments with 20 cycles underwent drying only after all washes were finished.

Before beginning the next treatment of the DOE, the clothes load underwent two washes in a professional washing machine (Electrolux Wascator FOM71 CLS) at 40 ºC. One wash was performed using 30g of ECE-2 standard detergent of ISO105-C06:2010 "Textiles - Tests for color fastness - Part C06: Color fastness to domestic and commercial laundering," and the other wash was conducted without detergent. Subsequently, the clothes load was dried using a household tumble dryer SFP12. This procedure was put in place to prevent any potential contamination between treatments, as each fabric sample with a different composition was used for all experimental treatments.

Following each treatment of the design, both the load and fabric samples were dried using a domestic tumble dryer (Electrolux SFP12 model) before proceeding to the subsequent tests. To ensure that the dryer's impact on the factors was minimal, the samples were dried only after the conclusion of each treatment. Therefore, the treatments consisting of 20 cycles were dried only after all washes were completed.

The statistical analysis of this design of experiments was performed using JMP 16.1.0 software, utilizing the least squares method to create a prediction model.

4.2.1.1 Whiteness index

The CIE/E313 whiteness index was measured following the ISO105-J02:1997 "Textiles — Tests for colour fastness — Part J02: Instrumental assessment of relative whiteness" using the Datacolor model 800V spectrophotometer. The measurements were taken with a 0% UV and 100% UV filter, utilizing a D65/10º lamp.

Fabric samples measuring 20x20 cm were obtained from the larger fabric samples (50x50 cm) that had undergone washing. Four replicates were used for each measurement to ensure accuracy and consistency in assessing the whiteness index of the fabrics.

4.2.1.2 Tensile strength

The maximum tensile strength tests were conducted according to the ISO 13934-1:2016 "Textiles — Tensile properties of fabrics — Part 1: Determination of maximum force and elongation at maximum force using the strip method" standard. The testing equipment utilized was the Instron model 34TM-30-SA with smooth surface grippers. The fabric samples for this test had dimensions of 25x300 mm and were obtained from the previously washed samples (50x50 cm) and stored for 24 hours in a controlled environment with a temperature of 23±2 ºC and humidity of 65±10%. The testing speed was set at 100 mm/min, and a 1 kN load cell was used. A pre-force of 2 N was applied to all samples as specified in the standard. For each sample, five replicates were tested both in the direction of the courses and wales. The equation 1 demonstrate percentage of loss strength or gain when compared with fabrics unwashed. So m_i was the maximum strength of fabric unwashed and m_f was the maximum strength of fabric after each treatment of DOE.

$$\%Loss\ or\ gain\ strength = \frac{m_i - m_f}{m_i} \times 100 \tag{1}$$

4.2.1.3 Shrinkage

The shrinkage tests were conducted following the ISO 3759:2011 "Textiles — Preparation, marking, and measuring of fabric specimens and garments in tests for determination of dimensional change" and ISO 5077:2007 "Textiles — Determination of dimensional change in washing and drying" standards.

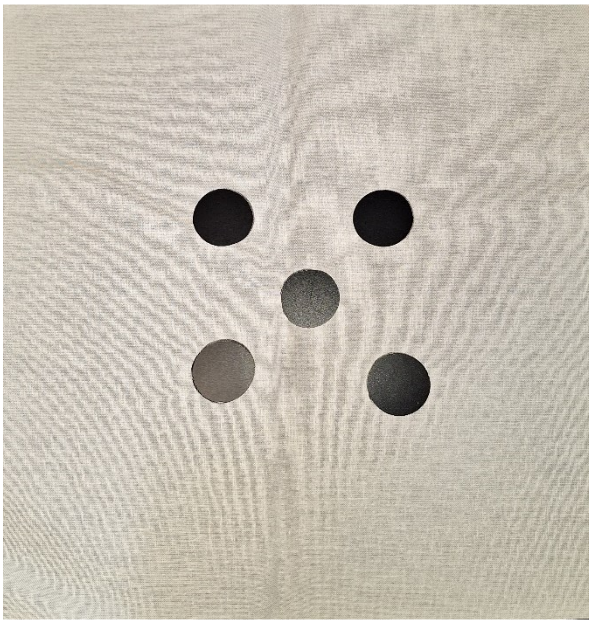
For each sample, 50x50 cm fabric pieces were cut and marked with a fabric pen for textiles before washing. The markings were made at a distance of 35 cm in both the vertical and horizontal directions.

The samples were conditioned in a room with a controlled environment (23±2 ºC and 65±10 % relative humidity) for at least 4 hours before taking the measurements. The distances between the markings on the fabric were measured using a ruler, and duplicate measurements were taken for each configuration of the experimental design. This rigorous procedure was followed to obtain reliable and consistent results in assessing the fabric shrinkage after washing.

4.2.1.4 Mechanical index of washing machine

The mechanical index is a test conducted following the AHAM-HLW-1-2013 "Performance Evaluation Procedures for Household Clothes Washers" standard. For this test, 4 samples of 100% cotton plain woven fabric with 5 holes (Figure 188) each are utilized to assess the level of mechanical action during the washing cycle. After washing, the fabric's holes are examined to determine the number of broken threads, which is used to calculate the mechanical index. A higher number of broken threads indicates a more aggressive washing cycle.

Figure 18 – 5-hole fabric to evaluate mechanical index.



Source: by the author.

4.2.2 Bleaching of cotton fabrics

Before conducting the Design of Experiments (DOE), fabrics containing cotton were subjected to a bleaching process using a professional Electrolux Wascator FOM71 CLS laboratory washing machine. The bleaching process followed the recommendation by Clark (2011) and involved the use of the following chemicals: 4% v/v hydrogen peroxide 50%, 4% v/v sodium hydroxide, and ECE-2 detergent as per

ISO105-C06:2010 "Textiles - Tests for colour fastness - Part C06: Colour fastness to domestic and commercial laundering."

During the bleaching process, the liquor bath ratio was set at 1 kg to 8 L. The heating ramp was maintained at 1.5 ºC/min until the temperature reached 90 ºC, at which point the washing machine was agitated for 1.5 hours at this temperature to facilitate the bleaching process.

After the bleaching step, the fabrics underwent 5 rinse steps, with each rinse lasting for 5 minutes and involving agitation to neutralize the pH. The extraction step was performed at 500 rpm, and the drying process took place in a domestic tumble dryer (Electrolux) at a low temperature for 90 minutes.

4.2.3 Digital microscopic

To evaluate the fabric sample structure before and after washing, a digital microscope (Dino-lite) model AM4113ZT with 50x and 230x magnification was utilized.

4.2.4 Fourier-Transform infrared spectroscopy of fabrics

Fourier transform infrared spectroscopy with attenuated total reflection (FTIR–ATR) was performed for the fabrics after treatments and unwashed fabrics using a spectrometer (Shimadzu, IFAffinity-1 model, MIRacle10 ZnSe) with 16 scans at a resolution of 4 cm^{-1}.

5 RESULTS

This section presents the results of this study. Firstly, the design of experiments analysis and effects of the studied factors on each response (whiteness index, tensile strength, shrinkage, and mechanical index) are presented. Within the section of each response, the effects of each factor (cycles number, softener quantity, detergent quantity, and water temperature) are presented separately, followed by the 2nd order interactions and the best conditions according to the model to increase the durability of clothes. Finally, a microscopic analysis of the fabrics before and after undergoing 20 washes is presented.

5.1 DESIGN OF EXPERIMENTS ANALYSIS

The intention was to verify the effects of washing factors on the following responses: mechanical action index, max strength, shrinkage, and whiteness index of fabric.

This factorial fractionated design of experiments, with a resolution IV, exhibits certain aliases of effects, as evident in Table 4. One example of this is that the effect attributed to the interaction between Cycles number and Water temperature may actually be caused by the levels of Detergent quantity and Softener quantity, and similarly for other second-order interactions presented in Table 4.

Table 4 – Aliases of effects.

Effects	Aliases
Cycles number*Water temperature	Detergent quantity*Softener quantity
Cycles number*Detergent quantity	Water temperature*Softener quantity
Cycles number*Softener quantity	Water temperature*Detergent quantity

Source: by the author.

5.1.1 Factors effects on the whiteness index of fabrics

Tables 5, 6, and 7 present the statistical summary of the prediction models developed in this study for the whiteness index response. Table 5 corresponds to cotton fabric, Table 6 to polyester fabric, and Table 7 to polyester-cotton blend fabric. As the fabrics have different compositions, their washing behaviors differ, requiring the creation of separate prediction models for each case.

The coefficient of determination (R^2) for the prediction models were 99% for cotton fabric (Table 5), 91% for polyester fabric (Table 6), and 96% for polyester-cotton blend fabric (Table 7). These high R² values indicate that the prediction models are highly accurate and well-fitted to the experimental data.

Table 5 – Statistics summary of the model for CO whiteness index.

R²	Mean of response	Factor	Effect	Standard error	p-value
0.99	114.10	Cycles number	1.56	0.37	0.0469
		Detergent quantity	45.82	0.37	<.0001
		Water temperature	31.94	0.37	<.0001
		Softener quantity	-8.80	0.37	<.0001
		Cycles number*Detergent quantity	34.74	0.37	<.0001
		Cycles number*Softener quantity	23.15	0.37	<.0001

Source: by the author.

Table 6 - Statistics summary of the model for PES whiteness index.

R²	Mean of response	Factor	Effect	Standard error	p-value
0.91	72.09	Cycles number	-11.36	0.68	0.0469
		Detergent quantity	12.74	0.68	<.0001
		Water temperature	-6.30	0.68	<.0001
		Softener quantity	2.52	0.68	0.0759
		Cycles number*Detergent quantity	11.94	0.68	<.0001
		Cycles number*Softener quantity	4.08	068	<.0001

Source: by the author.

Table 7 - Statistics summary of the model for PES+CO whiteness index.

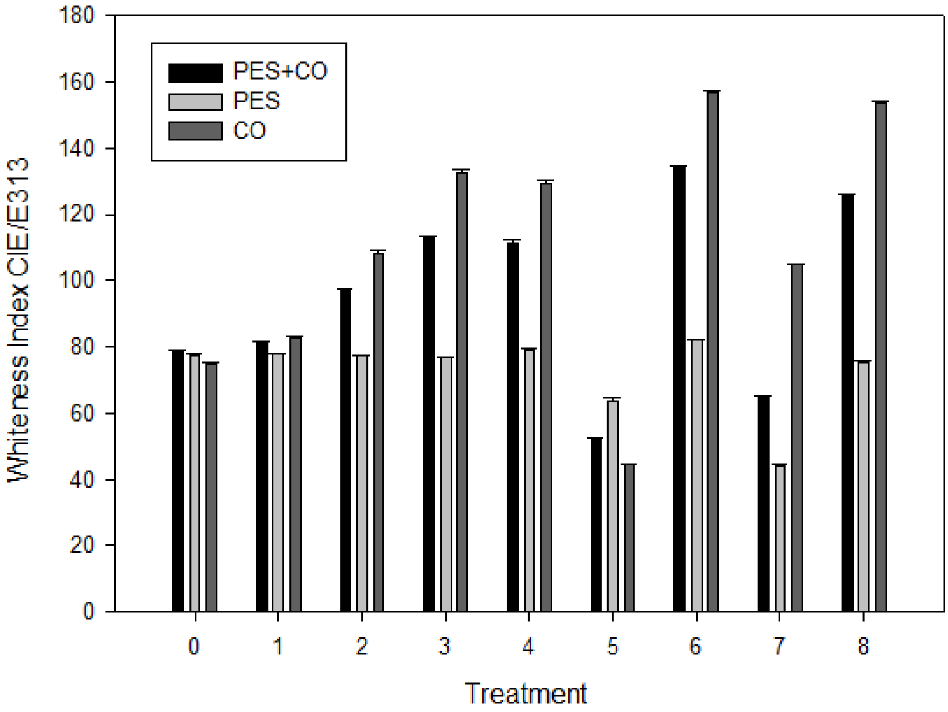
R²	Mean of response	Factor	Effect	Standard error	p-value
0.96	97.47	Cycles number	-6.72	1.03	0.0034
		Detergent quantity	39.10	1.03	<.0001
		Water temperature	12.52	1.03	<.0001
		Softener quantity	0.98	1.03	0.6381
		Cycles number*Detergent quantity	32.34	1.03	<.0001
		Cycles number*Softener quantity	-9.88	1.03	<.0001

Source: by the author.

The mean whiteness index responses were highest for cotton at 114.10 (Table 5), followed by polyester-cotton blend at 97.47 (Table 6), and polyester at 72.09 (Table 7).

In Figure 1**Error! Reference source not found.**9, the average whiteness index for each treatment of the DOE is presented. It is evident that for the 100% cotton fabrics, the whiteness index mostly increased (treatments 1, 2, 3, 4, 6, 7, and 8), indicating the significant influence of the optical brightener in the detergent. The use of detergent with an optical brightener enhances the whiteness of cellulosic fabrics by increasing spectral radiance, resulting in a perception of superior cleanliness. (Kert; Krkoč; Gorjanc, 2019)

Figure 19 – Average whiteness index of all fabrics and treatments.



Source: by the author.

On the other hand, the polyester fabric either maintained its whiteness or experienced a reduction in certain combinations, such as treatments 5 and 7. Treatment 5 involved 20 washes at 20°C with fabric softener, while treatment 7 consisted of 20 washes at 60°C. These results confirm the model's suggestion that fabric softener and temperature were the main factors influencing the decrease in the whiteness index of polyester.

In the upcoming sections, a more in-depth discussion will be presented on the effects and interactions of each factor studied on the whiteness index. The results obtained from the factorial fractionated design of experiments will be analyzed and interpreted to gain a comprehensive understanding of how each variable contributes to the whiteness of the fabrics. Additionally, the significance of the statistical data and the implications for practical applications will be explored. This thorough analysis aims to provide valuable insights into the behavior of the fabrics during the washing process and the impact of various factors on their whiteness.

5.1.1.1 Effect of detergent quantity on the whiteness index

In this study, the detergent quantity factor was evaluated at two concentration levels: 0g, indicating no detergent, and 90g, following the label recommendation of detergent. The statistical analysis showed that detergent quantity had a highly significant impact on the whiteness index of all fabrics, as indicated by the low P-value (< 0.0001) shown in Tables 5, 6, and 7.

Across all fabric samples, the primary factor contributing to increased whiteness was the detergent quantity used. Fabrics containing cotton (Table 5 and Table 7) exhibited a significant rise in the whiteness index as the detergent quantity increased. The effect of changing the detergent quantity factor was particularly pronounced for cotton fabrics, with an increase of approximately 40 in the whiteness index (Table 5 and Table 7). In comparison, the 100% polyester fabric showed a milder effect of 12.74 (Table 6).

Therefore, across all fabrics examined in this study, the use of detergent led to a significant increase in the whiteness index. The results highlight the importance of detergent quantity, especially in cotton-containing fabrics, where optical brighteners have a more substantial effect in improving whiteness.

5.1.1.2 Effect of water temperature on the whiteness index

The water temperature factor during washing was studied in this work at two levels, 20 ºC, and 60 ºC. The statistical analysis showed that water temperature had a highly significant impact on the whiteness index of all fabrics, as indicated by the low P-value (< 0.0001) shown in Tables 5, 6, and 7.

The interaction between water temperature and other variables, such as detergent quantity and softener quantity, had a higher effect on the whiteness index compared to the individual effects of the cycle number factor. This suggests that water temperature interacts with detergent and softener, influencing the overall whiteness index of the fabrics.

Specifically, for the 100% cotton fabric (Table 5), increasing the water temperature to 60 ºC resulted in a notable increase in the whiteness index, reaching up to 31.94. This effect can be attributed to the enhanced bleaching power of detergents at higher temperatures.

The polyester-cotton blend fabric displayed a similar response to water temperature, with a whiteness index increase of 12.52, although not as significant as the 100% cotton fabric.

In conclusion, the water temperature during washing had a significant effect on the whiteness index of all fabrics studied. Higher temperatures enhanced the bleaching power for cotton fabrics and polyester-cotton blends, resulting in increased whiteness. However, for polyester fabrics, the higher temperature led to a decrease in whiteness due to changes in the polymer's structure and the impact of softeners on the fabric's reflectance.

5.1.1.3 Effect of softener quantity on the whiteness index

In this study, the softener quantity factor was investigated at two levels: 0 mL and 70 mL (following the supplier's recommendation). The statistical analysis revealed that the softener quantity had a significant effect on the whiteness index of fabrics containing cotton, as indicated by the highly significant P-value of < 0.0001, as shown in Table 5. However, for fabrics made of polyester and polyester-cotton blends, this factor did not exhibit statistical significance.

For fabrics containing cotton, increasing the softener quantity resulted in a decrease in their whiteness index. Notably, the effect was more pronounced for 100% cotton fabric, with an estimated decrease of -8.8, as presented in Table 5. This decrease in whiteness can be attributed to fabric softeners' propensity to form a film on the fabric's surface after repeated washing cycles, which alters the fabric's reflectance and leads to a reduction in the whiteness index. This phenomenon has been previously reported by authors such as Mao *et al.* (2019) and Sk *et al*. (2021), highlighting the well-known capacity of cationic softeners to diminish this parameter (Schindler; Hauser, 2004).

Nevertheless, it's essential to acknowledge that the contribution of the softener quantity factor to the overall variation in the whiteness index was relatively small when compared to the effects of other factors, such as detergent quantity and water temperature. These latter factors appeared to have more substantial impacts on the whiteness index of the fabrics studied.

5.1.1.4 Effect of cycles number on the whiteness index

In this study, the cycles number factor was investigated at two levels: 1 and 20 washing cycles. The statistical analysis revealed that the cycles number had a significant effect on the whiteness index of all fabrics, as indicated by the highly significant P-value of < 0.0050, as shown in Tables 5, 6, and 7.

For polyester fabrics, the cycles number factor resulted in a decrease in the whiteness index, with a more significant effect of -11.36 (Table 6). Conversely, for cotton fabrics, the effect was smaller, leading to an increase of 1.56 (Table 5) in the whiteness index when the quantity of washing cycles increased. For polyester and cotton blend fabric, the effect was a decrease in the whiteness index of -6.72 (Table 7).

The difference in the fabric surfaces can explain these results. Polyester fabrics studied here were produced with multifilament yarn, which results in a smoother surface compared to fabrics made of 100% cotton, which are manufactured with ring-spun yarn and have a more textured surface due to the presence of fibrils. As the number of cycles increases, the mechanical action on the fabric's surface intensifies, both from the washing machine and from interaction with other fabrics. Since polyester was not as affected by the optical brightener, its reflectance remains relatively unchanged. On the other hand, cotton fabric, being more exposed to the optical brightener with increased cycles, undergoes a higher degree of whitening.

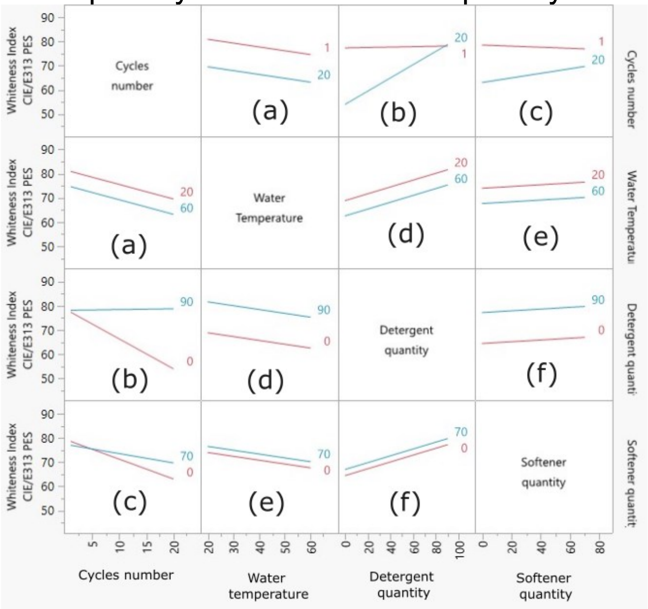
In summary, the cycles number factor had a significant impact on the whiteness index of all fabrics tested. Polyester fabrics showed a decrease in whiteness with more washing cycles, while cotton fabrics exhibited a slight increase in whiteness, and polyester-cotton blend fabrics experienced a decrease in whiteness. These differences can be attributed to the distinct surface properties of the fabrics and the varying effects of the optical brightener on their reflectance during the washing process.

5.1.1.5 2nd order interactions among factors

The interaction profiles presented in this study are illustrated in Figure **Error! Reference source not found.**20 for polyester fabrics, Figure 21 for cotton fabrics, and Figure 22 for polyester-cotton blend fabrics.

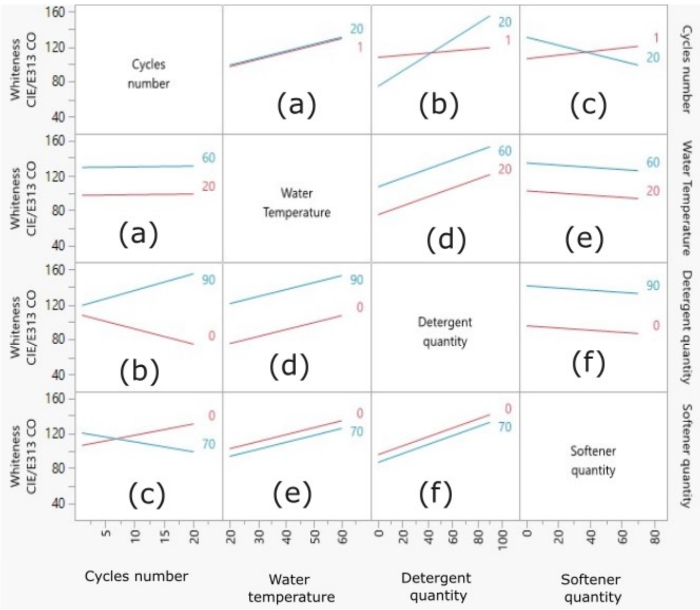
Regarding polyester fabrics, the cycles number factor exhibited weak interactions with the detergent quantity Figure 20 (b)) and softener quantity (Figure 20 (c)) factors. This implies that regardless of the number of cycles used, the effect of using detergent remains consistent, leading to an increase in the whiteness index. Similarly, the use of softener in 20 wash cycles significantly reduced the whiteness index, while its impact was minimal when used in just one cycle. These observations align with the presence of optical brighteners in the detergent, which shows enhanced whitening effects with prolonged exposure to fabrics. Understanding these interactions is essential for optimizing washing conditions to achieve increased whiteness in polyester fabrics.

Figure 20 – Interaction profiles for the whiteness index response in polyester fabric. Interaction between (a) water temperature x cycles number, (b) cycles number x detergent quantity, (c) cycles number x fabric softener quantity, (d) water temperature x detergent quantity, (e) water temperature x fabric softener quantity, (f) detergent quantity x fabrics softener quantity.



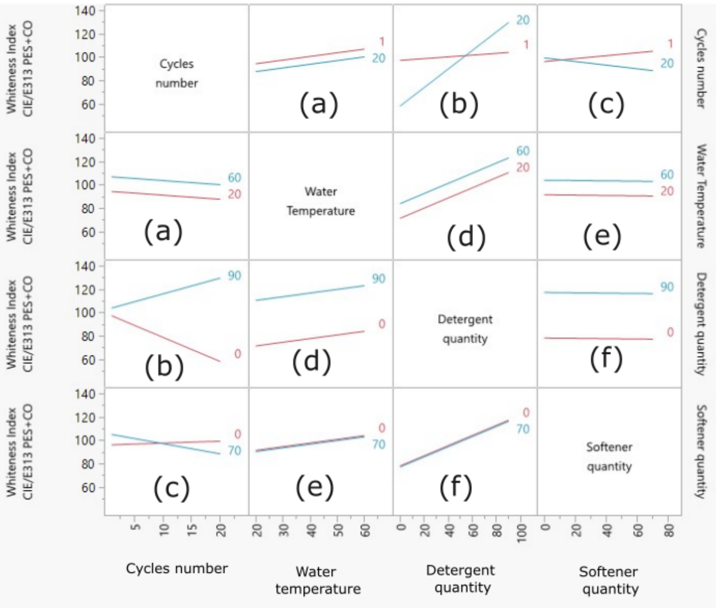
Source: by the author.

Figure 21 - Interaction profiles for the whiteness index response in cotton fabric. Interaction between (a) water temperature x cycles number, (b) cycles number x detergent quantity, (c) cycles number x fabric softener quantity, (d) water temperature x detergent quantity, (e) water temperature x fabric softener quantity, (f) detergent quantity x fabrics softener quantity.



Source: by the author.

Figure 22 – Interaction profiles for the whiteness index response in polyester-cotton blend fabric. Interaction between (a) water temperature x cycles number, (b) cycles number x detergent quantity, (c) cycles number x fabric softener quantity, (d) water temperature x detergent quantity, (e) water temperature x fabric softener quantity, (f) detergent quantity x fabrics softener quantity.



Source: by the author.

For cotton fabrics, a strong interaction was observed between the number of cycles and the amount of detergent used (Figure 21 (b)). When detergent is used in 20 washing cycles, a substantial increase in the whiteness index occurs, while using it in a single cycle result in minimal change. Similarly, the effect of the softener (Figure 21 (b)) on the response is more pronounced in 20 cycles, leading to a significant reduction in whiteness. The softener forms a thicker film on the fabric, altering its reflectance and causing it to appear more yellow.

Polyester-cotton blend fabrics also exhibited strong interactions, particularly between cycles number and detergent quantity (Figure 22 (b)), as well as cycles number and softener quantity (Figure 22 (c)), similar to cotton fabrics.

For all other variables, no significant interactions were found within the scope of this study. It is important to note that as these experiments have a resolution IV, the 2nd-order interactions may be confounded with 2nd-order interactions, as indicated in Table 4**Error! Reference source not found.**. This highlights the need for careful analysis and interpretation of the experimental data.

In conclusion, understanding the interactions between the factors influencing the whiteness index is crucial for optimizing washing conditions and achieving desired levels of whiteness in different fabric types. The presence of optical brighteners in detergents and the use of fabric softeners play significant roles in impacting the whiteness index, especially when considering the number of washing cycles. Careful consideration of these factors can lead to improved fabric whiteness and overall fabric performance.

5.1.1.6 Best condition according to the model

The model predicts that to increase the whiteness index of both 100% cotton and polyester-cotton blend fabrics after 20 washing cycles, it is necessary to wash them at 60°C with detergent and without fabric softener. These conditions are found to be most effective in maintaining or enhancing the whiteness of these fabrics over multiple cycles.

Conversely, for 100% polyester fabric, the model suggests washing at a cold temperature of 20°C with detergent and fabric softener. However, in this case, the fabric softener's impact on increasing the whiteness index is minimal. Therefore, its use may not significantly affect preserving the whiteness of the polyester fabric.

In summary, the appropriate washing conditions to enhance the whiteness index differ based on the fabric type. For cotton and polyester-cotton blend fabrics, washing at 60°C with detergent and without fabric softener is recommended, while for 100% polyester fabric, washing at a cold temperature with detergent and fabric softener may not have a substantial effect on preserving its whiteness

5.1.2 Factors effect on tensile strength of fabrics

The higher tensile strength of polyester fiber resulted in the polyester knit exhibiting the highest maximum strength in both fabric directions. The model for polyester in the courses direction showed a coefficient of determination (R^2) of 91% (Table 8), and for wales, it was 82% (Table 9), indicating a good percentage of adjustment to the experimental data.

Table 8 – Statistics summary of the model for PES fabric max strength in the courses direction.

R^2	Mean of response (N)	Term	Effect (N)	Standard error (N)	p-value
0.91	206.84	Cycles number	-24.88	1.55	<.0001
		Detergent quantity	16.88	1.55	<.0001
		Water temperature	-17.00	1.55	<.0001
		Softener quantity	-29.10	1.55	<.0001

Source: by the author.

Table 9 - Statistics summary of the model for PES fabric max strength in the wales direction.

R^2	Mean of response (N)	Term	Effect (N)	Standard error (N)	p-value
0.82	445.04	Cycles number	-21.34	2.09	<.0001
		Detergent quantity	1.58	2.09	0.7066
		Water temperature	-4.34	2.09	0.0468
		Softener quantity	-26.68	2.09	<.0001

Source: by the author.

For cotton, the R^2 was 76% in the courses direction (Table 10) and 65% for wales (Table 11), representing a good percentage of adjustment but smaller than polyester. This difference can be attributed to the natural properties of cotton, such as variation in fiber diameter, yarn count, and molecular structure, which are higher compared to synthetic fibers like polyester. This natural variability makes it harder to replicate the same behavior in replicates.

Table 10 - Statistics summary of the model for CO fabric max strength in the courses direction.

R²	Mean of response (N)	Term	Effect (N)	Standard error (N)	p-value
0.76	64.29	Cycles number	-0.58	0.31	0.3505
		Detergent quantity	2.64	0.31	<.0002
		Water temperature	0.48	0.31	0.4380
		Softener quantity	-0.58	0.31	0.3491
		Cycles number*Water temperature	2.38	0.31	0.0007
		Cycles number*Detergent quantity	4.32	0.31	<.0001

Source: by the author.

Table 11 - Statistics summary of the model for CO fabric max strength in the wales direction.

R²	Mean ofresponse (N)	Term	Effect (N)	Standard error (N)	p-value
0.65	105.85	Cycles number	-5.28	0.88	0.0060
		Detergent quantity	5.16	0.88	0.0071
		Water temperature	5.34	0.88	0.0055
		Softener quantity	-2.62	0.88	0.1494
		Cycles Number*Water temperature	-6.24	0.88	0.0015
		Cycles Number*Softener quantity	-4.66	0.88	0.0138

Source: by the author.

Polyester and cotton blended fabrics exhibited similar coefficient of determination to cotton fabrics, with values of 75%(Table 12) for courses and 79%

(Table 13) for wales direction, indicating a good fit to the experimental data, but not as high as those observed for pure polyester.

Table 12 – Statistics summary of the model for PES+CO fabric max strength in the courses direction.

R²	Mean of response (N)	Term	Effect (N)	Standard error (N)	p-value
0.75	56.58	Cycles number	0.05	0.27	0.9253
		Detergent quantity	-0.64	0.27	0.2475
		Water temperature	-3.04	0.27	<.0001
		Softener quantity	0.38	0.27	0.4928
		Cycles Number*Water temperature	-3.92		<.0001
		Cycles Number*Detergent quantity	1.30		0.0256

Source: by the author.

The average maximum strength for the pure PES fabric in the courses direction was 206.84 N (Table 10), while for pure CO, it was 64.29 N (Table 11) Notably, the PES + CO presented an average of 56.58 N (Table 14), very similar to that of the cotton fabric. The similarity in maximum strength between the PES + CO fabric and the pure cotton fabric is attributed to the way the fabric was produced.

The PES + CO fabric was created by interspersing polyester and cotton yarns on the loom. During testing, the cotton yarn broke first, leading to the knit interlooping with polyester yarns to also break, leaving only the polyester yarn as the primary support in the fabric. Consequently, the test could not continue after the cotton yarns were broken, resulting in a comparable maximum strength observed in the PES+CO fabric and the pure cotton fabric presented.

Table 13 – Statistics summary of the model for PES+CO fabric for max strength in the wales direction.

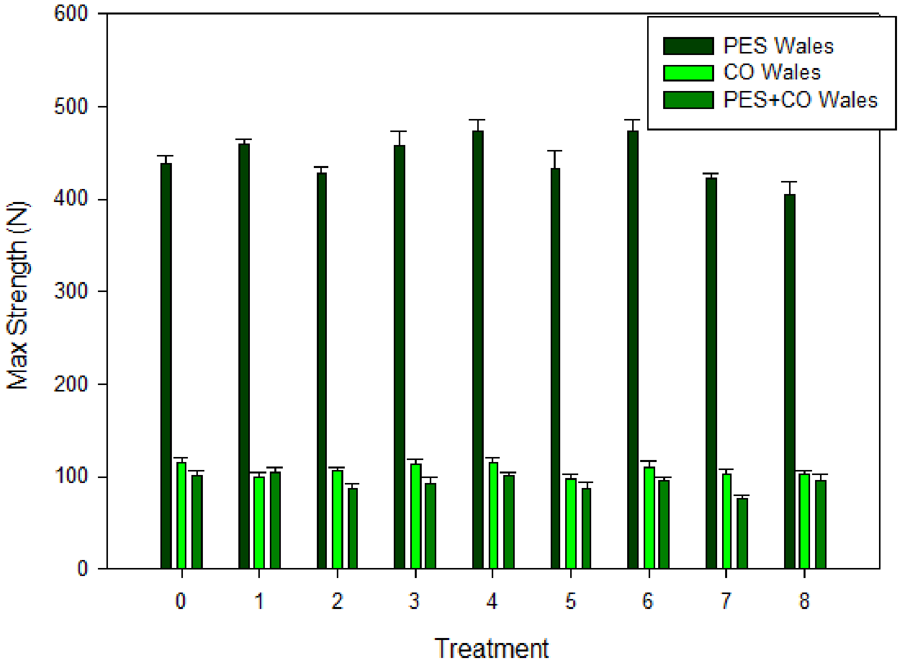
R²	Mean of response (N)	Term	Effect (N)	Standard error (N)	p-value
0.79	92.90	Cycles number	-7.60	0.80	<.0001
		Detergent quantity	4.68	0.80	0.0067
		Water temperature	-2.48	0.80	0.1317
		Softener quantity	3.70	0.80	0.0282
		Cycles Number*Detergent quantity	9.54	0.80	<.0001
		Cycles Number*Softener quantity	9.50	0.80	<.0001

Source: by the author.

The average max strength for all treatments and all fabrics can be seen in Figure 23 for wales direction and in Figure 24 for courses direction. In the wales direction the max strength for polyester was around 400 N and for cotton and polyester cotton blend was around 100 N. For the courses direction polyester presented maximum strength around 200N and cotton and polyester and cotton blend around 70 N.

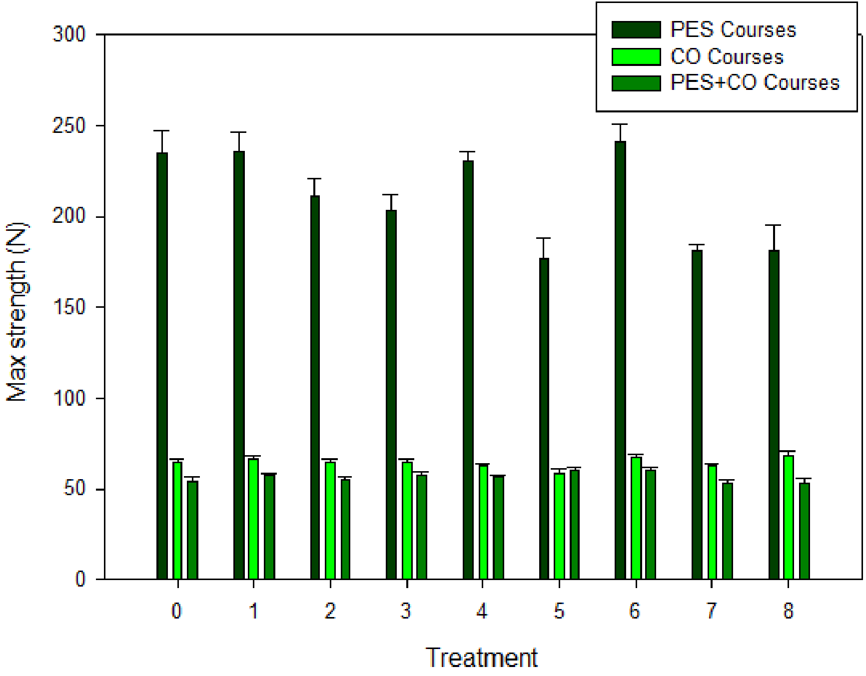
In the fabrics subjected to testing, the maximum strength consistently demonstrated higher values in the wales direction and same behavior was reported by Choi, Kim and Kwon (2022). This phenomenon can be attributed to the distinctive characteristics of the knit structure in that specific direction. When the fabric is stretched in the wales direction, there is no horizontal flattening of the interlooping. Instead, each loop appears to transform into two vertical yarns, leading to intensified stretching force and greater resistance in this direction.

Figure 23 – Average max strength in the wales direction for all treatments.



Source: by the author.

Figure 24 – Average max strength in the courses direction for all treatments.



Source: by the author.

On the other hand, in the courses direction, each knitted loop transforms into only one thread when stretched, as the loops flatten almost entirely into a horizontal yarn. As a result, the maximum force exerted in this direction is comparatively lower.

Additionally, in the wales direction, the fabric is pulled opposite to the direction in which it was produced, making it more challenging to break the forces between the knit stitches compared to the horizontal direction.

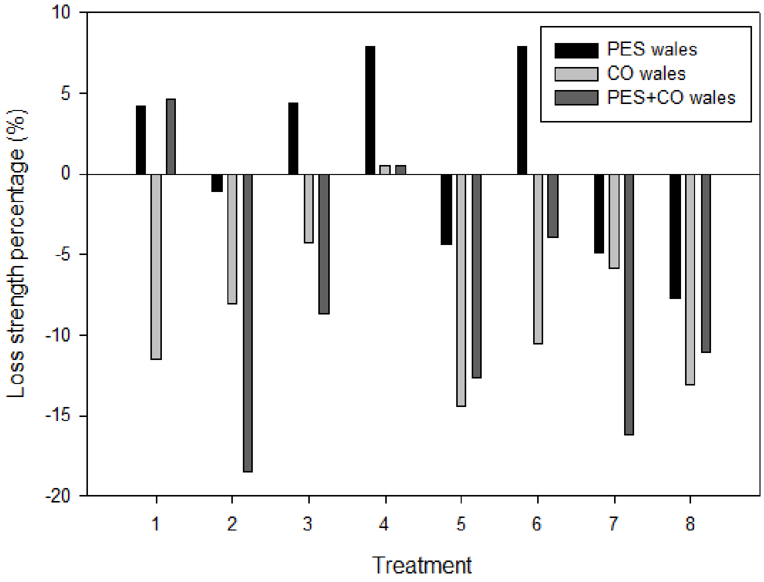
This difference in max strength is also connected to the observed shrinkage in the fabrics. The highest percentage of shrinkage was found in the wales direction, suggesting that a significant portion of this shrinkage is due to the decrease in loop length. The shorter loop length reduces the initial stretch when the fabric is pulled in the wales direction, subjecting the yarns to stress earlier during the shrinkage process.

These findings emphasize the importance of considering the knit structure when evaluating the strength and shrinkage behavior of fabrics. The distinct behavior observed in the wales direction can be attributed to the lack of interlooping flattening, resulting in increased stretching force and higher resistance.

Moreover, knowing that the resistance of single jersey fabrics is greater in the wales direction, it can be beneficial to sew clothes in that direction to ensure that points that are more likely to be stretched will have greater resistance than when sewn in the courses direction. This understanding of fabric behavior can be applied in garment construction to optimize strength and durability.

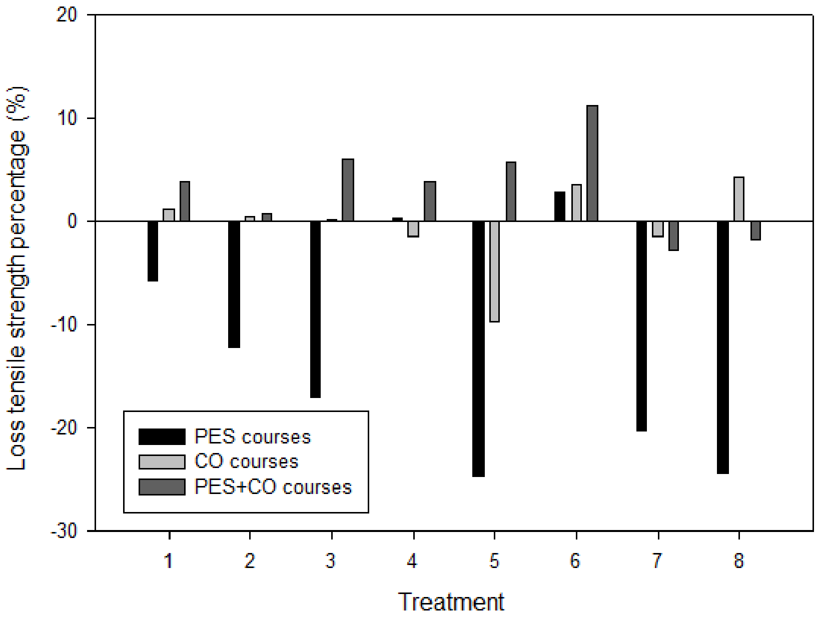
The percentage change in maximum fabric strength is illustrated in Figure 25 for the wales direction and Figure 26 for the courses direction across all treatments, as compared to the fabric's strength prior to washing.

Figure 25 - Percent change in maximum strength after treatments compared with unwashed fabrics for wales direction.



Source: by the author.

Figure 26 - Percent change in maximum strength after treatments compared with unwashed fabrics for courses direction.



Source: by the author.

In the courses direction, polyester exhibited a loss of strength in almost all treatments, ranging from -6% to -25% strength reduction. Treatments 5, 7, and 8 displayed the most substantial strength losses, with a common factor being 20 wash cycles. Treatments 5 and 8 included fabric softener.

On the other hand, cotton experienced a strength reduction of only -10% in the courses direction, specifically in treatment 5 involving 20 wash cycles at 20°C with fabric softener. Notably, treatment 6 in the courses direction led to an increase in maximum strength for all fabrics, with the most significant rise of 11% observed in PES+CO. This treatment involved 20 wash cycles at 20°C with detergent, highlighting the detergent's ability to enhance strength and the fabric softener's capacity to reduce strength in the courses direction.

For the PES+CO fabric in the courses direction, strength increased for nearly all treatments, except for treatments 7 and 8 involving 20 wash cycles at 60°C, which resulted in minor strength reductions of -3% and -2%, respectively.

In the wales direction, virtually all treatments led to decreased strength for both CO and PES+CO fabrics. The strength reduction for CO ranged from -4% to -14%, while PES+CO experienced reductions of -4% to -18% depending on the treatment. However, in the case of PES fabrics in the wales direction, about half of the treatments exhibited strength increases of up to 8%. The impact of each factor will be elaborated further in the subsequent subsections of this section. It's essential to note that due to fractionalization, the model predicted maximum strength for an additional 8 treatments. Therefore, there are other similar behavior combinations of factors not depicted in these graphs.

5.1.2.1 Effect of detergent quantity on the tensile strength

In the courses direction for cotton fabrics, the most important factor was the detergent quantity, which showed statistical significance and increased the maximum strength of the fabric by 2.64 N (Table 13). Similarly, in the wales direction, the detergent quantity increased the maximum strength by 5.16 N (Table 14), although without statistical significance.

One explanation for this increase in the maximum strength of cotton-containing fabrics is that the detergent used in the study contained enzymes, such as cellulase, which helps remove impurities from cotton and smoothens its surface. As a result, this cellulase could also remove part of the film formed by the softener when used in subsequent washes, reducing the lubrication of the fibers and consequently increasing the maximum tensile strength.

For polyester-cotton blend fabrics (PES+CO), the detergent quantity showed a slight increase of 4.68 N in the wales direction, but without statistical significance. In the courses direction, the effect was minimal, with a decrease of 0.64 N, and also lacking statistical significance.

Regarding pure polyester (PES) fabrics, the detergent quantity factor was highly statistically significant in the courses direction, resulting in a substantial increase of 16.88 N in maximum strength. However, in the wales direction, the detergent quantity did not show any significant impact on the fabric's strength.

A plausible explanation for the significant increase in maximum strength when using a detergent for polyester fabrics is that the detergent can remove the fabris softener film formed on the surface of polyester, thereby enhancing the fabric's maximum tensile strength. Additionally, during the rinse step, the detergent may form a complex with the fabric softener. As the detergent used in this study is anionic (Omo), and the fabric softener is cationic (Downy), a complex may first form between the two before the softener can act on the fabric.

In summary, the detergent quantity appears to be an essential factor in influencing the maximum strength of cotton and polyester-containing fabrics. The presence of enzymes in the detergent could contribute to the increased strength of cotton fabrics, while the removal of the softener film and possible complex formation with the detergent might explain the significant increase in maximum strength observed for polyester fabrics.

5.1.2.2 Effect of water temperature on tensile strength

The water temperature factor had a statistically significant effect on polyester fabrics in both the courses and wales directions, as well as on fabrics containing a blend of polyester and cotton (PES+CO) in the courses direction and cotton (CO) in the wales direction. Increasing the washing temperature to 60 ºC resulted in a decrease in the maximum strength of these fabrics. For polyester, the strength reduction was approximately -17 N in the courses direction and -4.34 N in the wales direction.

Another important aspect to highlight is that all fabrics were dried for the same duration of 2 hours at the maximum temperature (~70ºC), which may not have been suitable for polyester fabrics. Synthetic fibers, including polyester, tend to dry much more quickly than cotton. Therefore, it is recommended to dry synthetic fibers at low temperatures and for a shorter duration to prevent damage. In this study, the same drying parameters were used for all fabrics to maintain consistency, but it's essential to consider the specific drying requirements of different fabric types in practical settings.

In conclusion, the water temperature during washing can significantly impact fabric strength, particularly for polyester fabrics and blends containing polyester. Careful consideration of washing and drying parameters is crucial to preserve the strength and durability of fabrics, especially when dealing with different fabric types.

5.1.2.3 Effect of softener quantity on tensile strength

The softener quantity significantly influenced the strength of the polyester (PES) fabric in both the courses (Table 10) and wales (Table 11) directions, causing a notable loss of strength (-29.10 N and -26.68 N, respectively). Moreover, for all other fabrics in both directions, the softener also decreased the maximum strength, but its impact was statistically significant only for the PES fabric (Tables 10 and 11) and the PES+CO fabric in the wales direction (Tables 14 and 15). For the cotton (CO) fabric, the softener quantity reduced the strength, but the effect was relatively minor (-0.58 N for courses - Table 12, and -2.62 N for wales - Table 13), and the statistical significance was low.

The softening mechanism involves increasing the flexibility between fibers and yarns in the fabric, which affects the maximum strength by making it easier to flatten the looped yarns, resulting in faster yarn traction (Chiweshe; Crews, 2000). Previous studies on plain woven fabrics have also reported a decrease in tensile strength due to household cationic softeners during the rinse cycle (Brenneman, 1978; Chiweshe; Crews, 2000; Reddy; Salam; Yang, 2008).

In summary, fabric softeners have a significant impact on fabric strength, particularly polyester fabrics. Understanding the interactions between softeners and different fabric types is essential to maintain fabric strength and durability during washing and care.

5.1.2.4 Effect of cycles number on tensile strength

The study revealed that the quantity of washing cycles has a detrimental effect on the maximum strength of almost all fabrics studied. This impact was statistically significant for polyester (PES) fabrics in both directions and for cotton (CO) and polyester-cotton blend (PES+CO) fabrics in the wales direction. With each washing cycle, the clothes undergo mechanical action due to agitation caused by water, the agitator, the drum's surface, and friction with other clothes present in the washing machine.

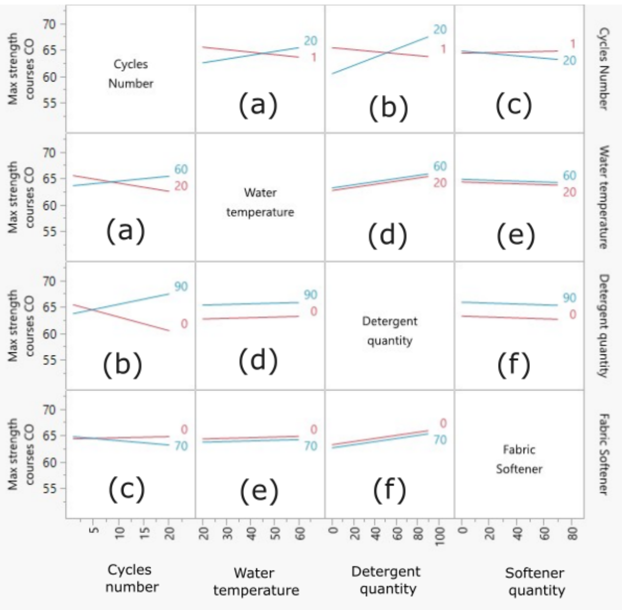
This mechanical action is well-known to cause damage to the fabric (Nayak; Ratnapandian, 2018) because the abrasion between the fabric and the agitator leads to the breaking of fibrils and subsequent damage. These fibril breakages create weaker points in the fabric, reducing its tensile strength and overall lifespan.

It's important to highlight that as the number of cycles increases, there is also an increase in the contact between fabrics and the chemicals used during washing, making these factors closely related. This combination of mechanical and chemical actions contributes to the deterioration of fabric properties over multiple washing cycles. Therefore, to prolong the life and strength of fabrics, minimizing the number of washing cycles is advisable.

5.1.2.5 2nd order interactions among parameters

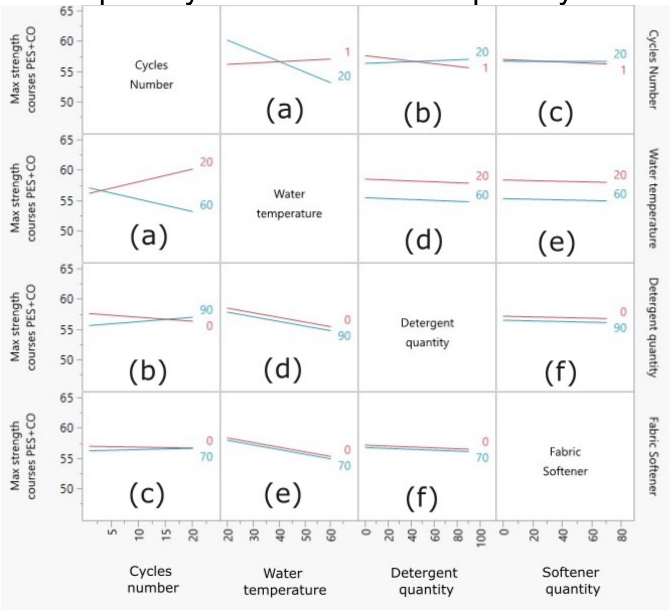
In the courses direction, for both cotton and polyester-cotton blend fabrics, the factor "cycles number" exhibited a stronger interaction with "detergent quantity" (Figure 27 (b) for CO and Figure 28 (b) for PES+CO) and "water temperature" (Figure 27 (a) for CO and Figure 28 (a) for PES+CO). Increasing the number of washing cycles, whether using detergent or not, had no significant impact on the maximum strength of the fabric. However, for a single cycle, the use of detergent didn’t affect the fabric's maximum strength. Similarly, when using a washing temperature of 60 ºC and increasing the number of cycles, the fabric's strength decreased, but for a single cycle, the choice of higher or lower temperature had no significant influence on the fabric's strength.

Figure 27 – Interaction profiles max strength of courses for CO. Interaction between (a) water temperature x cycles number, (b) cycles number x detergent quantity, (c) cycles number x fabric softener quantity, (d) water temperature x detergent quantity, (e) water temperature x fabric softener quantity, (f) detergent quantity x fabrics softener quantity.



Source: by the author.

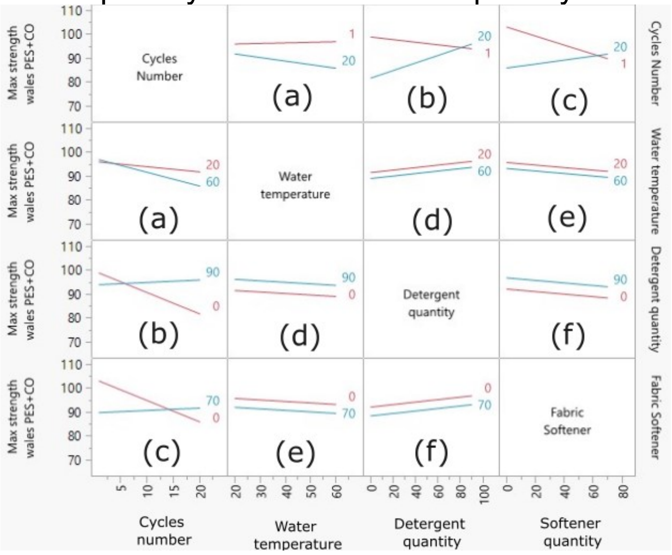
Figure 28 – Interaction profiles max strength of courses for PES+CO. Interaction between (a) water temperature x cycles number, (b) cycles number x detergent quantity, (c) cycles number x fabric softener quantity, (d) water temperature x detergent quantity, (e) water temperature x fabric softener quantity, (f) detergent quantity x fabrics softener quantity.



Source: by the author.

In the wales direction, stronger interactions were observed between "cycles number" and both "detergent quantity" (Figure 29 (b)) and "softener quantity" (Figure 29 (c)) for polyester and cotton blend fabrics. These interactions played a more significant role in affecting the fabric's properties in this direction.

Figure 29 - Interaction profile factors for max strength of wales for PES+CO. Interaction between (a) water temperature x cycles number, (b) cycles number x detergent quantity, (c) cycles number x fabric softener quantity, (d) water temperature x detergent quantity, (e) water temperature x fabric softener quantity, (f) detergent quantity x fabrics softener quantity.

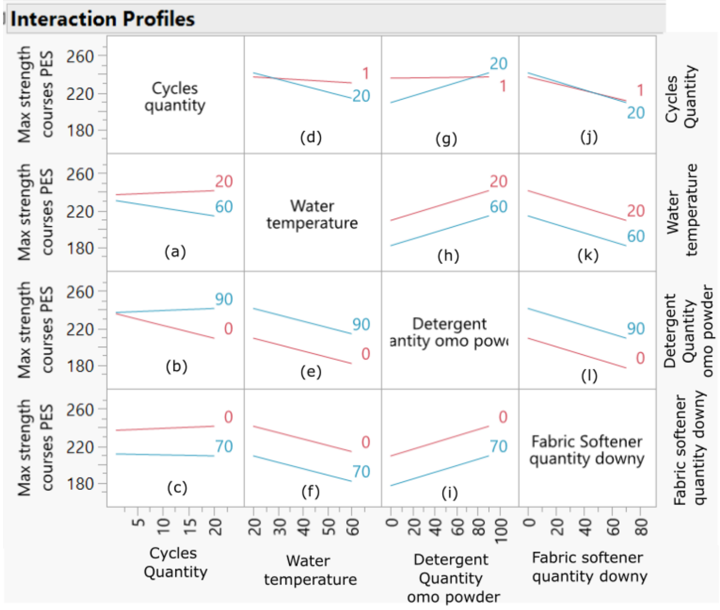


Source: by the author.

Conversely, for polyester fabric (

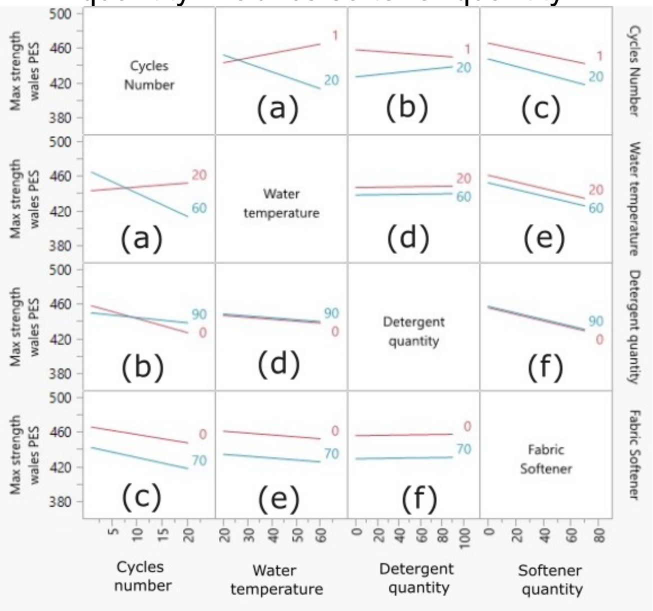
Figure 30 and Figure 31), weaker interactions were observed in both directions, indicating that the factors analyzed had a comparatively lesser impact on the fabric's properties.

Figure 30 – Interaction profile factors for max strength of courses for PES. Interaction between (a) water temperature x cycles number, (b) cycles number x detergent quantity, (c) cycles number x fabric softener quantity, (d) water temperature x detergent quantity, (e) water temperature x fabric softener quantity, (f) detergent quantity x fabrics softener quantity.



Source: by the author.

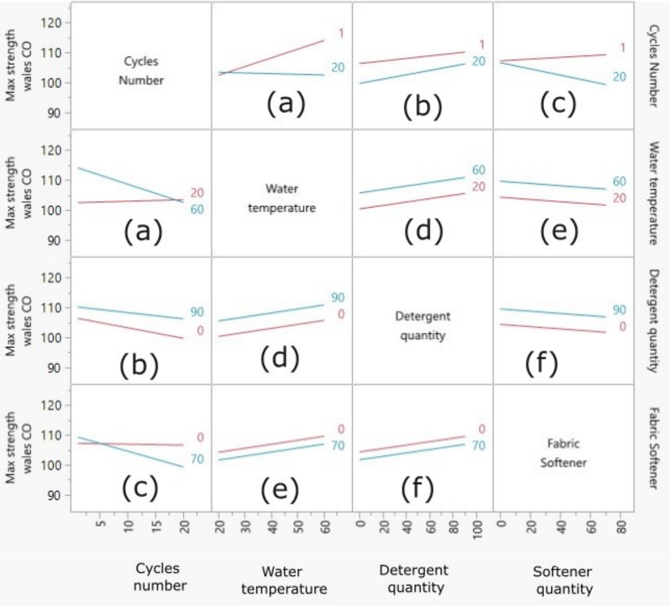
Figure 31 - Interaction profile factors for max strength of wales for PES. Interaction between (a) water temperature x cycles number, (b) cycles number x detergent quantity, (c) cycles number x fabric softener quantity, (d) water temperature x detergent quantity, (e) water temperature x fabric softener quantity, (f) detergent quantity x fabrics softener quantity.



Source: by the author.

In the wales direction for cotton fabrics weaker interactions were observed between "cycles number" and both "softener quantity" (Figure 32 (c)) and "water temperature" (Figure 32 (a)). With a single cycle, whether using fabric softener or not had no significant effect on the fabric's strength. However, when subjected to 20 cycles, the use of fabric softener resulted in a decrease in the maximum strength. Other variables didn't show significant interactions for cotton fabrics.

Figure 32 - Interaction profile factors for max strength of wales for CO. Interaction between (a) water temperature x cycles number, (b) cycles number x detergent quantity, (c) cycles number x fabric softener quantity, (d) water temperature x detergent quantity, (e) water temperature x fabric softener quantity, (f) detergent quantity x fabrics softener quantity.



Source: by the author.

Overall, the findings highlight the importance of considering various factors and their interactions when evaluating fabric properties in different directions and fabric types.

5.1.2.6 Best condition according to the model

The models generated in this study predict that for polyester fabric, the optimal washing combination is achieved by using 90g of detergent, washing at 20ºC, and abstaining from the use of fabric softener. This combination effectively minimizes the loss of the fabric's resistance and enhances its durability.

Regarding cotton fabric, it is recommended to wash it at 60ºC, using detergent but without adding fabric softener. However, in the case of cotton fabric, the impact of using detergent on the fabric's resistance is only marginally increased.

For polyester-cotton blend fabric, the same washing approach as for pure polyester fabric is advised: washing with cold water at 20ºC, using detergent, and avoiding fabric softener.

By following these washing recommendations tailored to each fabric type, users can optimize the longevity and performance of their clothes.

5.1.3 Factors effects on shrinkage

Regarding cotton fabrics, the R² was 83% in the courses direction (Table 14**Error! Reference source not found.**) and 96% in the wales direction (Table 15), representing a good percentage of adjustment but slightly lower than that observed for polyester. This difference can be attributed to the inherent natural properties of cotton, such as variations in fiber diameter, yarn count, and molecular structure, which are more pronounced compared to synthetic fibers like polyester. The greater natural variability of cotton makes it more challenging to replicate consistent behavior.

Table 14 - CO fabric model statistical summary for shrinkage in the courses direction.

R²	Mean of response (%)	Term	Effect (%)	Standard error	p-value
0.83	0.03	Cycles number	-0.93	0.24	0.1881
		Detergent quantity	0.78	0.24	0.2406
		Fabric softener quantity	-0.62	0.24	0.3138
		Water temperature	-0.36	0.24	0.5295

Source: by the author.

Table 15 - CO fabric model statistical summary for shrinkage in the wales direction.

R²	Mean of response (%)	Term	Effect (%)	Standard error (%)	p-value
0.96	-2.66	Cycles number	-1.70	0.14	0.0275
		Detergent quantity	-0.74	0.14	0.1247
		Water temperature	-0.68	0.14	0.1381
		Softener quantity	-0.56	0.14	0.1829

Source: by the author.

The model for polyester fabrics in the courses direction demonstrated a coefficient of determination (R²) of 95% (Table 16), while for the wales direction, it reached 99% (Table 17). These high R² values indicate a substantial level of adjustment to the experimental data.

Table 16 - PES fabric model statistical summary for shrinkage in the courses direction.

R²	Mean of response (%)	Term	Effect (%)	Standard error (%)	p-value
0.95	-1.07	Cycles number	-1.72	0.16	0.0339
		Water temperature	-0.27	0.16	0.4850
		Detergent quantity	-0.01	0.16	0.9729
		Softener quantity	-0.01	0.16	0.9838

Source: by the author.

Table 17 - PES fabric model statistical summary for shrinkage in the wales direction.

R²	Mean of response (%)	Term	Effect (%)	Standard error (%)	p-value
0.99	-3.60	Cycles number	-2.02	0.04	0.0023
		Water temperature	-1.57	0.04	0.0038
		Detergent quantity	0.13	0.04	0.2930
		Softener quantity	0.02	0.04	0.9818

Source: by the author.

Polyester-cotton blended fabrics exhibited similar coefficients of determination to pure cotton fabrics, with values of 80% for the courses direction (Table 18) and 99% for the wales direction (Table 19). While these values indicate a good fit for the experimental data, they are not as high as those observed for pure polyester.

Table 18 – PES + CO fabric model statistical summary for shrinkage in the courses direction.

R²	Mean of response (%)	Factor	Effect (%)	Standard error (%)	p-value
0.80	0.10	Detergent quantity	0.64	0.18	0.2148
		Cycles number	-0.51	0.18	0.2947
		Water temperature	-0.51	0.18	0.2982
		Softener quantity	0.07	0.18	0.8552

Source: by the author.

Table 19 - PES + CO fabric model statistical summary for shrinkage in the wales direction.

R²	Mean of response (%)	Factor	Effect (%)	Standard error (%)	p-value
0.99	-3.39	Cycles number	-1.70	0.05	0.0065
		Water temperature	-0.24	0.05	0.1419
		Softener quantity	-0.13	0.05	0.3258
		Detergent quantity	0.02	0.05	0.8468

Source: by the author.

The mean response for polyester fabric in the courses direction was -1.60%, while for cotton, it was 0.03%. Notably, the polyester-cotton blend presented an average of 0.10%, which is very similar to that of the cotton fabric. Further analysis in subsequent sessions will explore the reasons behind these results in greater depth.

The shrinkage of fabrics was higher in the wales direction, but even so, the percentage of shrinkage was very low, with the average for polyester at -3.60%, cotton at -2.66% and the polyester-cotton blend at -3.39%.

5.1.3.1 Effect of detergent quantity on the shrinkage

The detergent quantity factor was not statistically significant, and its effect on the dimensional alteration of the fabric was minimal for all fabrics studied. Therefore, whether detergent is used or not does influence the shrinkage of the fabrics in this study.

5.1.3.2 Effect of water temperature on shrinkage

Regarding polyester fabrics in the wales direction, the water temperature demonstrated statistical significance and contribute to shrink fabric in -1.57%. Nevertheless, the temperature of 60 ºC used for washing still remains below the Tg (glass transition temperature) in the water of this polymer, which is approximately ~85 ºC. Therefore, this temperature can be deemed suitable for washing without encountering substantial issues. It is worth noting that despite being the most affected fabric among those studied, polyester displayed only a minor degree of shrinkage. (Fan; Hunter, 2009)

However, it is advisable to rinse the fabric with cold water to reduce the possibility of deformation during the centrifugation step, which could be induced by the movement of the polymer chains at higher temperatures.

Furthermore, drying appears to have played a role in the dimensional changes of all fabrics studied. Specifically, for polyester, it is recommended to employ a low drying temperature (<60ºC) to avoid more significant issues related to dimensional changes.

5.1.3.3 Effect of softener quantity on the shrinkage

The softener quantity factor exhibited no statistically significant impact on the shrinkage of the various fabrics under investigation, regardless of fabric type.

5.1.3.4 Effect of cycles number on the shrinkage

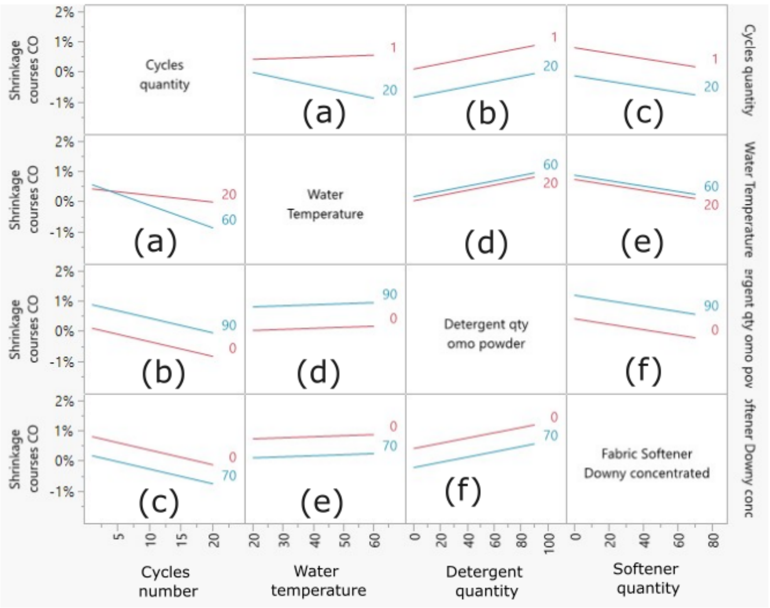
The number of cycles was found to have statistical significance for cotton (CO) and polyester-cotton blend (PES+CO) fabrics in the wales direction, as well as for pure polyester (PES) fabrics in both directions (wales and courses). It is important to consider that the number of cycles directly correlates with the duration the fabric is exposed to the washing temperature. Anand *et al.* (2002) reported that knit fabrics are notably affected by centrifugation during washing, which can contribute to shrinkage, along with the movement of the drum during drying.

Another noteworthy aspect related to the number of cycles is that it can lead to shrinkage due to the relaxation of tensions that were not previously relaxed. However, the observed shrinkage was minimal, less than 4%, for all combinations of factors studied in this research.

5.1.3.5 2nd order interactions among factors

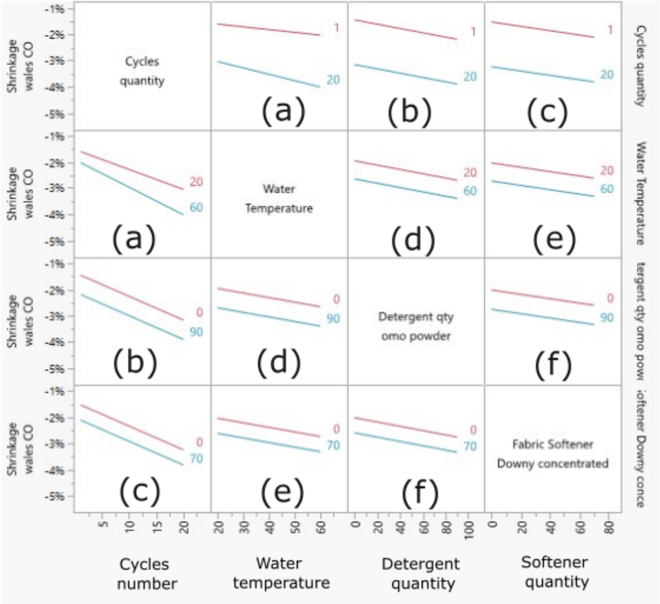
For cotton fabrics (Figure 33 and Figure 34) in both the wales and courses directions, as well as for polyester (Figure 35 and Figure 36) and polyester-cotton blend (Figure 37 and Figure 38) fabrics in the courses direction, no variables displayed significant interactions. However, in the wales direction for polyester (Figure 35 (a)) and polyester-cotton blend (Figure 38 (a)) fabrics, the cycles number and water temperature showed a stronger interaction. This means that increasing the number of cycles using a washing temperature of 60ºC results in greater shrinkage. Therefore, for older clothes or garments where preserving dimensions is a concern, it is better to opt for cold-washing cycles.

Figure 33 - Interaction profile factors for shrinkage of courses for CO. Interaction between (a) water temperature x cycles number, (b) cycles number x detergent quantity, (c) cycles number x fabric softener quantity, (d) water temperature x detergent quantity, (e) water temperature x fabric softener quantity, (f) detergent quantity x fabrics softener quantity.



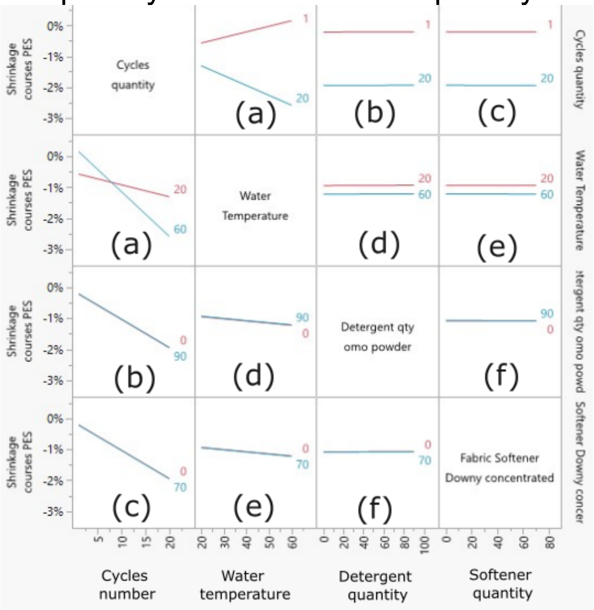
Source: by the author.

Figure 34 - Interaction profile factors for shrinkage of wales for CO. Interaction between (a) water temperature x cycles number, (b) cycles number x detergent quantity, (c) cycles number x fabric softener quantity, (d) water temperature x detergent quantity, (e) water temperature x fabric softener quantity, (f) detergent quantity x fabrics softener quantity.



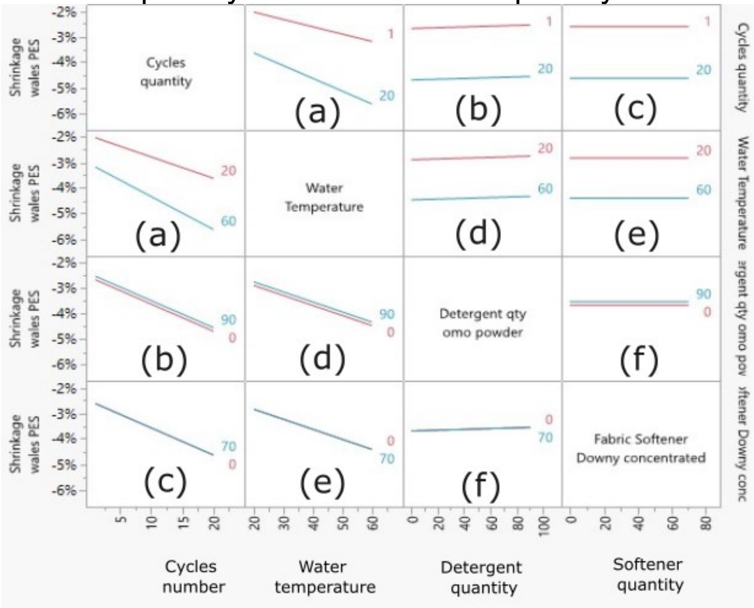
Source: by the author.

Figure 35 - Interaction profile factors for shrinkage of courses for PES. Interaction between (a) water temperature x cycles number, (b) cycles number x detergent quantity, (c) cycles number x fabric softener quantity, (d) water temperature x detergent quantity, (e) water temperature x fabric softener quantity, (f) detergent quantity x fabrics softener quantity.



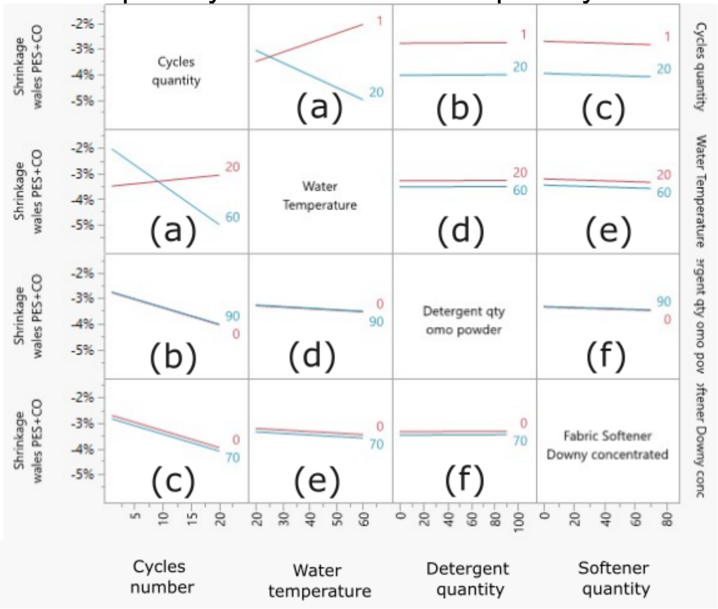
Source: by the author.

Figure 36 - Interaction profile factors for shrinkage of wales for PES. Interaction between (a) water temperature x cycles number, (b) cycles number x detergent quantity, (c) cycles number x fabric softener quantity, (d) water temperature x detergent quantity, (e) water temperature x fabric softener quantity, (f) detergent quantity x fabrics softener quantity.



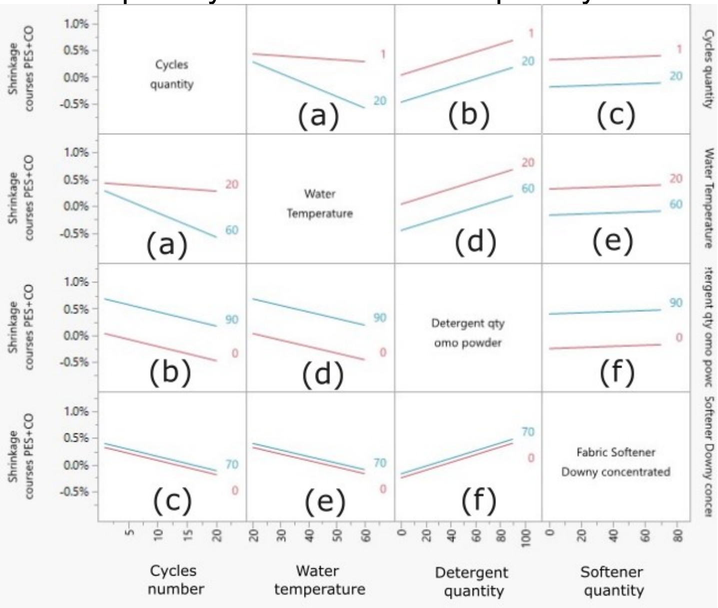
Source: by the author.

Figure 37 - Interaction profile factors for shrinkage of wales for PES+CO. Interaction between (a) water temperature x cycles number, (b) cycles number x detergent quantity, (c) cycles number x fabric softener quantity, (d) water temperature x detergent quantity, (e) water temperature x fabric softener quantity, (f) detergent quantity x fabrics softener quantity.



Source: by the author.

Figure 38 - Interaction profile factors for shrinkage of courses for PES+CO. Interaction between (a) water temperature x cycles number, (b) cycles number x detergent quantity, (c) cycles number x fabric softener quantity, (d) water temperature x detergent quantity, (e) water temperature x fabric softener quantity, (f) detergent quantity x fabrics softener quantity.



Source: by the author.

5.1.3.6 *Best condition according to the model*

The models developed in this study have revealed the optimal washing combination to minimize shrinkage for both polyester and cotton fabrics is washing at 20ºC. Interestingly, the use of detergent or fabric softener did not show any significant influence on shrinkage for either fabric type. Therefore, for polyester and cotton fabrics, a cold wash at 20ºC with detergent is recommended, and the choice of using fabric softener or not seems to have no impact on dimensional stability.

Furthermore, the study found that an increase in the number of washing cycles does lead to some degree of shrinkage. Therefore, it is advisable to avoid excessive washing cycles to preserve the dimensions of the clothes for a longer period. However, it is worth noting that the effect of multiple washing cycles on shrinkage is relatively low and not a major concern.

5.1.4 Factors effects on mechanical index

Table 20 presents the statistical summary of the prediction model developed in this study for the mechanical index response. The coefficient of determination (R^2) for the prediction model was 99%, indicating high accuracy and a good fit for the experimental data.

Table 20 – Mechanical Index estimates, standard error, and probability T-student.

R²	Mean of response	Term	Effect	Standard error	p-value
0.99	579.5	Cycles number	427.50	6.06	<.0001
		Water temperature	28.00	6.06	<.1042
		Softener quantity	13.00	6.06	<.3624
		Detergent quantity	7.50	6.06	<.5802

Source: by the author.

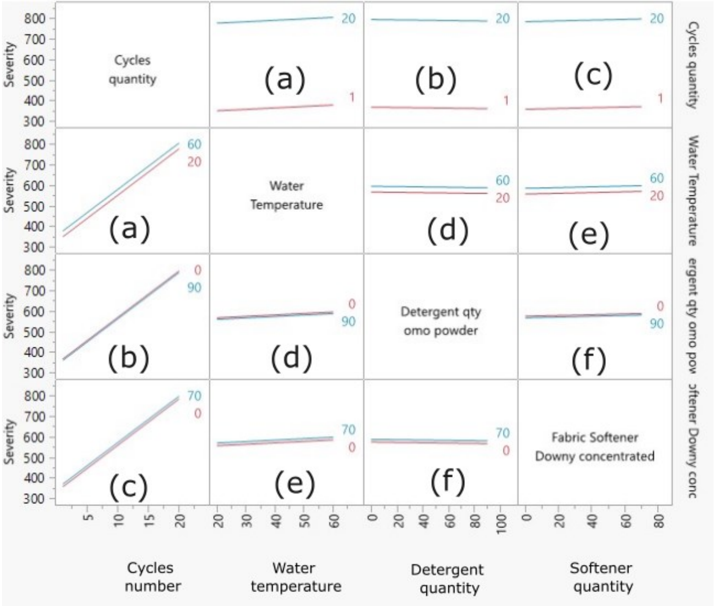
Regarding the effects of water temperature, detergent quantity, and softener quantity on the mechanical index, they were not statistically significant and had minimal impact. This was expected since the primary parameter affecting the mechanical action is the agitation and spinning during washing, which is closely related to the cycles number. As a result, the cycles number factor had a significant influence on the mechanical index.

The impact of interactions between the factors was small and was not considered in the regression model. As shown in

Figure 3939, there were no significant interactions between any of the factors. This further confirms that the cycles number is the dominant factor influencing the mechanical action index.

In summary, the prediction model for the mechanical index demonstrated high accuracy, and the cycles number factor had a significant impact on the mechanical action during washing. The other factors (water temperature, detergent quantity, and softener quantity) did not show statistically significant effects, as their influence was overshadowed by the cycles number factor. Moreover, no significant interactions between the factors were observed, indicating that their individual effects were relatively independent of each other in determining the mechanical index.

Figure 39 - Interaction profile factors for mechanical index. Interaction between (a) water temperature x cycles number, (b) cycles number x detergent quantity, (c) cycles number x fabric softener quantity, (d) water temperature x detergent quantity, (e) water temperature x fabric softener quantity, (f) detergent quantity x fabrics softener quantity.



Source: by the author.

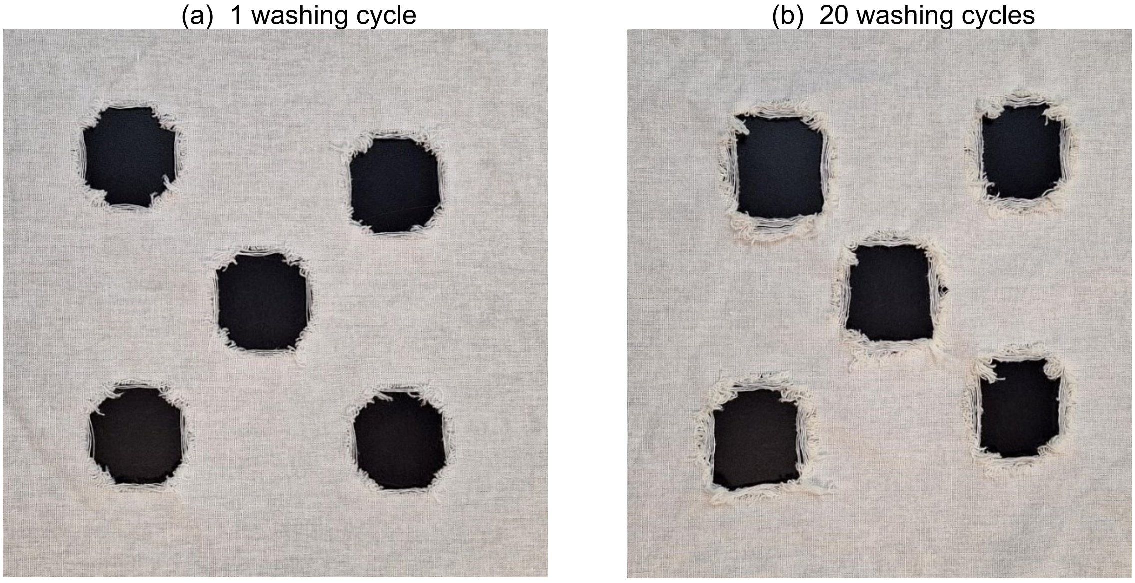
5.1.4.1 *Effect of cycles number on mechanical index*

The factor that had the most significant impact on the increase in the mechanical action index (427.50) was the number of cycles. In this test, a plain-woven fabric with open holes and no finishing was used, making it highly susceptible to mechanical agitation and friction with other fabrics during washing.

Figure 4040 clearly demonstrates the difference between 1 washing cycle and 20 washing cycles, highlighting the evident influence of mechanical action on this particular fabric type. The fabric without seams can suffer significant damage due to repetitive washing cycles.

However, when comparing this measurement with the maximum strength of fabrics, it becomes apparent that the number of cycles factor was not as significant for maximum strength as it was for the mechanical index. Interestingly, there was no correlation between the mechanical index and the maximum strength of the single jersey knit fabrics studied in this work. This indicates that the mechanical index cannot be used as a predictor of strength loss for this type of fabric.

Figure 40 – Picture of the 5-hole garment.


(a) 1 washing cycle (b) 20 washing cycles

Source: by the author.

The interaction profiles for this response (

Figure 39) showed weaker effects across all variables, and the interaction between the number of cycles and the softener quantity was so minimal that it was removed from the analysis.

In conclusion, the number of cycles had a significant impact on the mechanical action index for the plain-woven fabric studied, but it did not show the same level of significance in predicting the maximum strength of single jersey knit fabrics. Further exploration of the mechanical index's relationship with other fabric properties could provide valuable information for assessing overall fabric performance and durability.

5.2 OPTICAL MICROSCOPIC ANALYSIS OF FABRICS

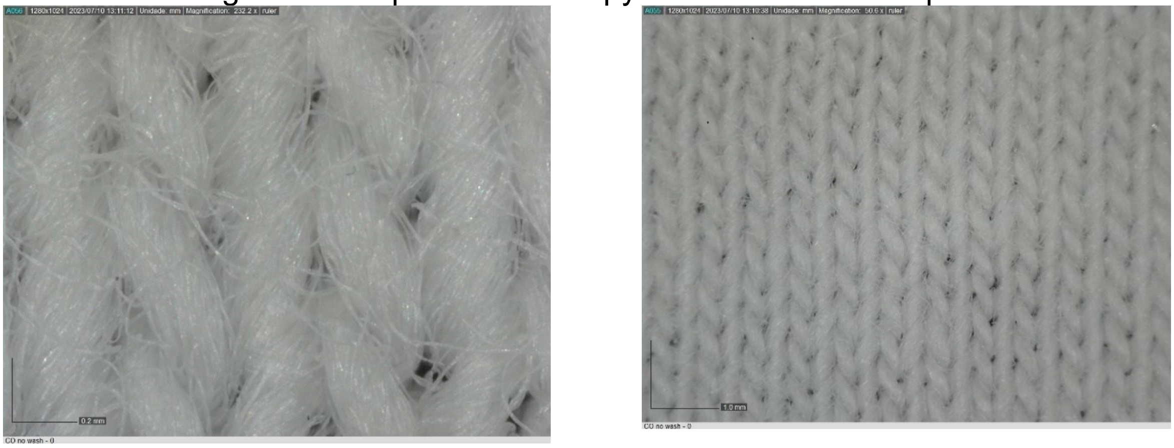
Figure 4141, Figure 422, and Figure 433 display the micrographs of the fabrics investigated in this study. A comparison between cotton (Figure 41) and polyester (Figure 42) reveals the expected differences. Polyester, being a multifilament yarn, exhibits a smooth and glossy surface. Conversely, cotton, composed of short fibers and ring-spun, displays numerous fibrils on its surface.

Notably, this distinction in brightness is evident in the polyester-cotton blend fabric (Figure 43 (a) and (b)), where both cotton and polyester yarns were knitted together. The polyester yarn stands out with its enhanced brightness, and the intercalation of the yarns is evident in the microscopic images.

After 20 washes, the fabrics containing polyester (Figure 42 (c) and (d), Figure 43 (c) and (d)) experienced a loss of shine. This change occurred because loose fibrils emerged on the surface due to friction with other garments and the washing machine. Consequently, the surface texture became less smooth, aligning with the reduction in the whiteness index of these fabrics when washed with softener.

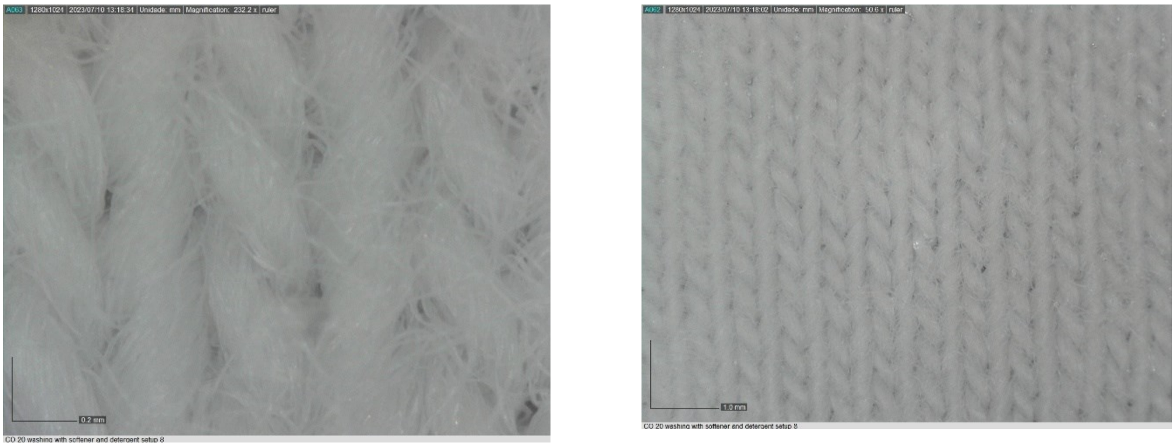
Moreover, the polyester-cotton blend fabrics exhibited a decrease in loop spacing after washing (Figure 43 (c) and (d)), resulting in a higher coverage factor and reduced dimensions, which aligned with their observed shrinkage.

Figure 41 – Optical microscopy of cotton fabric samples.



(a) Cotton no washing - magnitude 230x

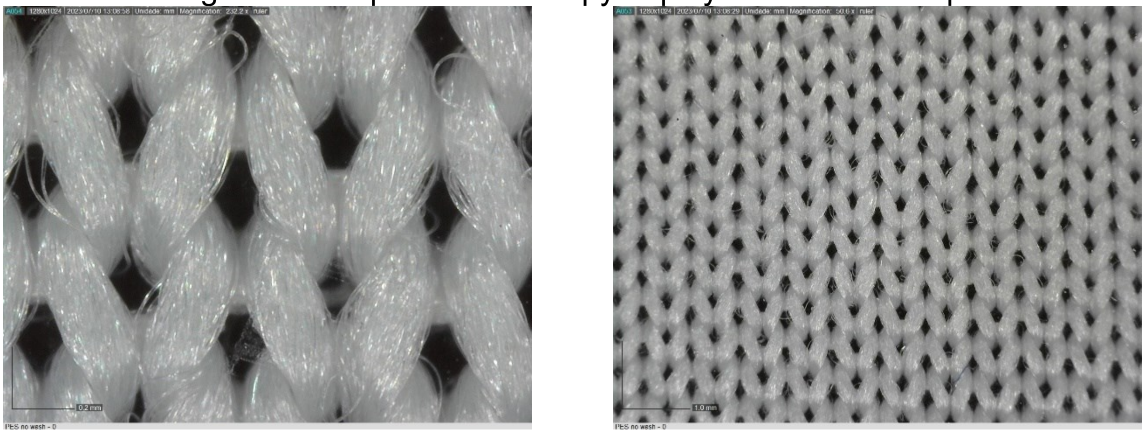
(b) Cotton no washing – magnitude 50x



(c) Cotton 20 washings setup 8 – magnitude 230x

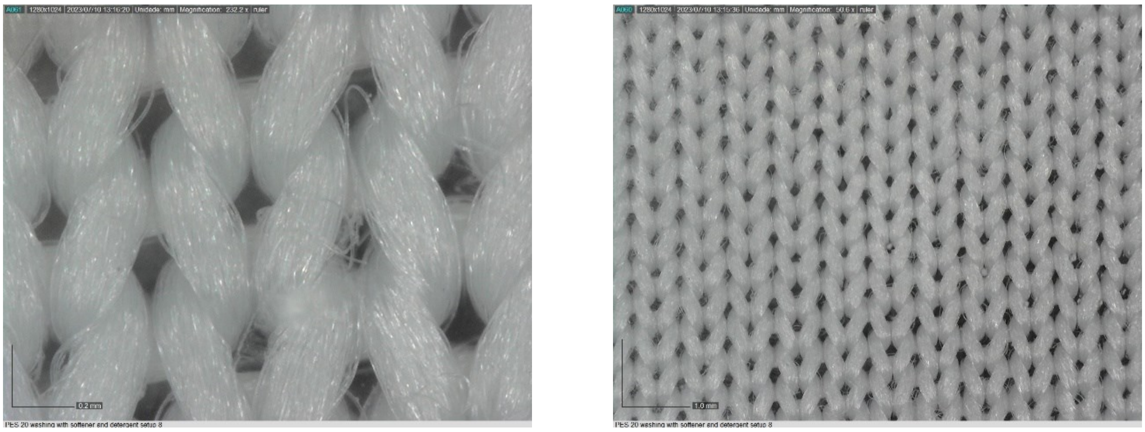
(d) Cotton 20 washings setup 8 - magnitude 50x

Figure 42 – Optical microscopy of polyester fabric samples.



(a) PES no washing – magnitude 230x

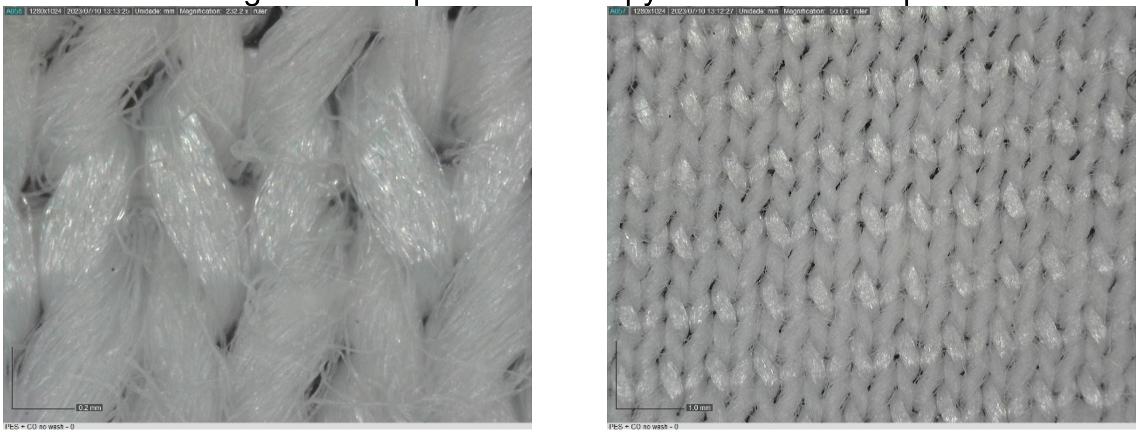
(b) PES no washing – magnitude 50x



(c) PES 20 washings setup 8 – magnitude 230x

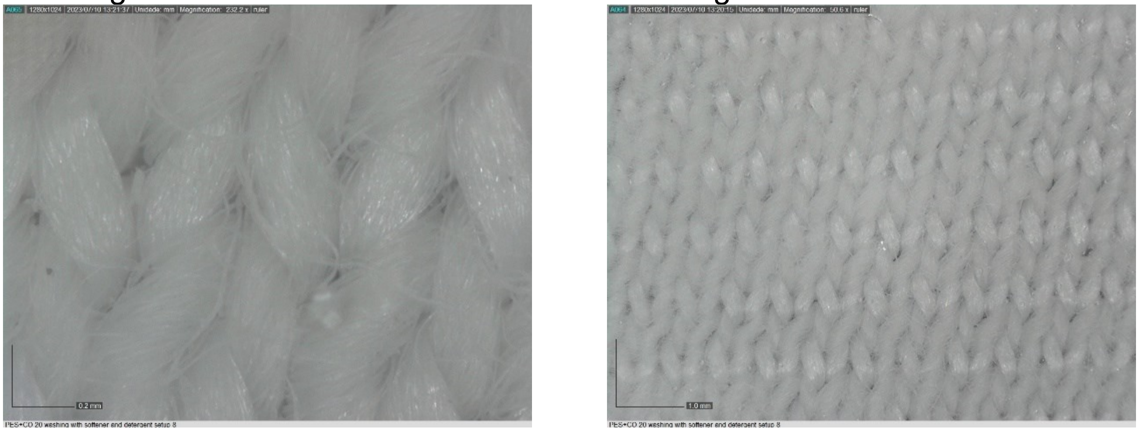
(d) PES 20 washings setup 8 – magnitude 50x

Figure 43 – Optical microscopy of PES+CO samples.



(a) PES + CO no washing – magnitude 230x

(b) PES + CO no washing - magnitude 50x



(c) PES + CO 20 washings setup 8 – magnitude 230x

(d) PES + CO 20 washings setup 8 – magnitude 50x

5.3 FOURIER-TRANSFORM INFRARED SPECTROSCOPY OF FABRICS

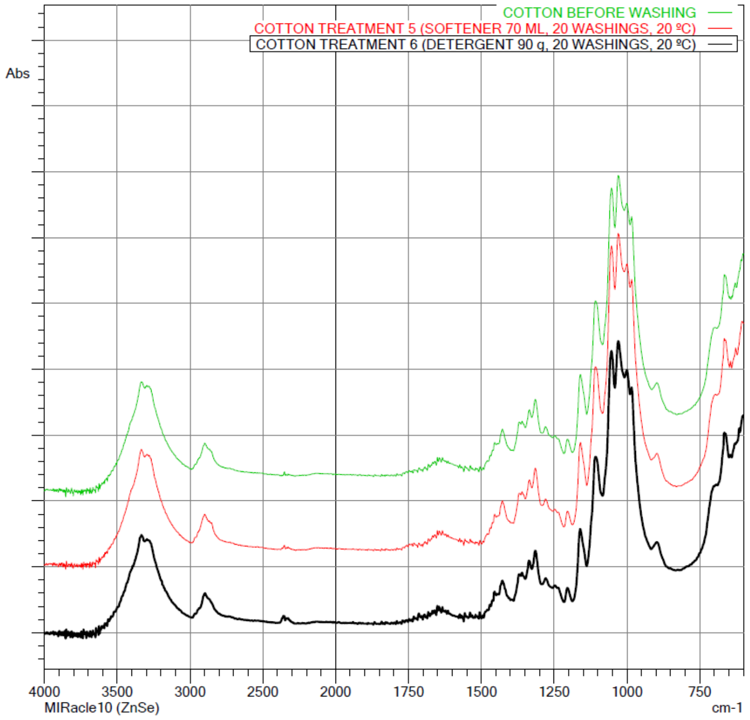
The Fourier-transform infrared spectroscopies (FTIR) of the fabrics, conducted before washing, after 20 wash cycles with Omo detergent, and after 20 wash cycles with fabric softener, are depicted in Figure 44, 45 and 46.

Fabrics containing polyester exhibited characteristic peaks of the ester C=O functional group at 1712 cm^{-1}; 1407 cm^{-1} (aromatic ring); 1340 cm^{-1} and 1018 cm^{-1} (carboxylic ester or anhydride); 970 cm^{-1} (C=C); 872 cm^{-1} (five substituted H in benzene); 847 cm^{-1} (two neighboring H in benzene); and 721 cm^{-1} (heterocyclic aromatic ring). (Fang *et al*., 2021; Dalla Fontana; Mossotti; Montarsolo, 2020; Kumar; Senthil Kumar, 2020)

The vibration peak at 3335 corresponds to intramolecular hydrogen bonding, such as $C_{(3)}OH\cdots O_{(5)}$ and $C_{(6)}O\cdots(O)H$, and 3284 corresponds to intermolecular hydrogen bonding, such as $C_{(3)}OH\cdots C_{(6)}O$, characteristic of cellulose I present in cotton. (Abidi; Cabrales; Haigler, 2014)

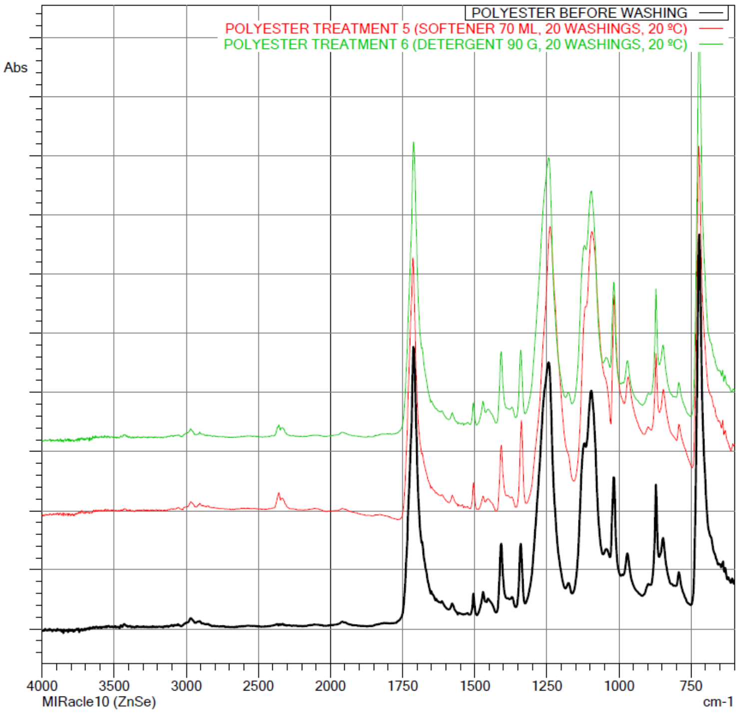
No significant differences were observed between the fabrics before and after washing with either detergent or fabric softener.

Figure 44 – FTIR spectroscopy results for cotton before washing and after treatments 5 and 6.



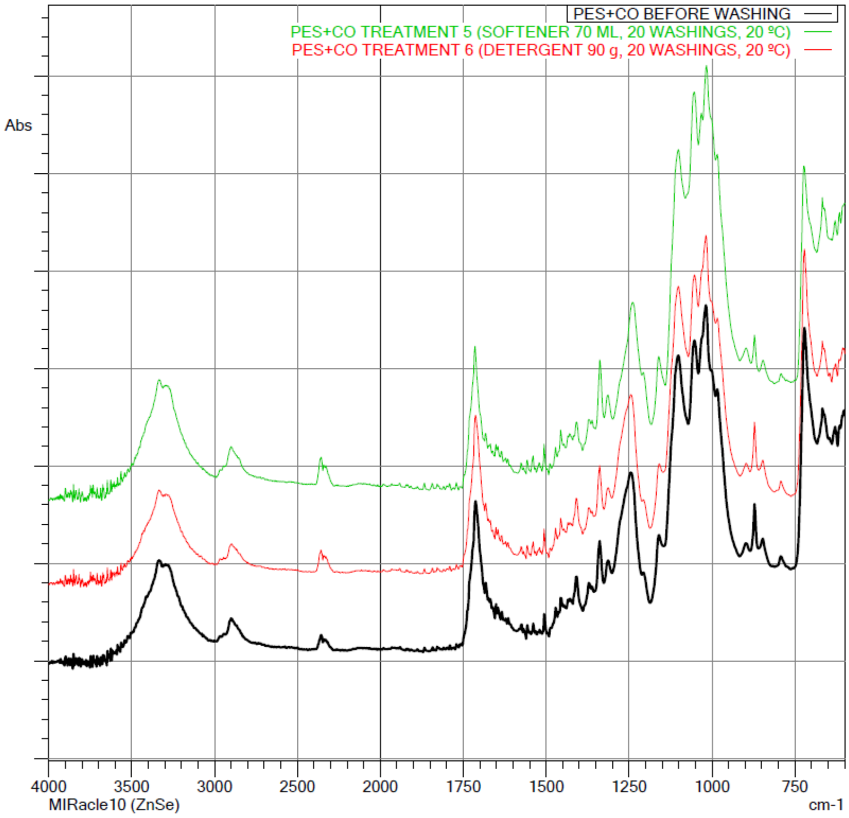
Source: by the author.

Figure 45 – FTIR spectroscopy results for polyester fabric before washing and after treatments 5 and 6.



Source: by the author.

Figure 46 - FTIR spectroscopy results for polyester fabric before washing and after treatments 5 and 6.



Source: by the author.

6 CONCLUSIONS

Through this study, a deeper understanding of the impact of different chemicals used during washing on the durability of knitted fabrics made of cotton, polyester, and a blend of both fibers was achieved. Durability, in this context, was defined by the fabric's resistance to stretching, retention of whiteness, and shrinkage.

Regarding tensile strength, it was observed that the softener had the most significant influence on strength loss. The softener creates a lubricating film on the fabric, leading to reduced strength. However, the use of detergent proved effective in preventing softener deposits on the fabrics, thereby enhancing their strength. For fabrics containing polyester, washing at higher water temperatures was not recommended. In contrast, cotton fabrics showed improved results when washed at 60ºC, likely due to the instability of the softener at higher temperatures, preventing its deposition on the fabric. Notably, cotton, being a non-thermoplastic polymer, was not affected by higher temperatures.

The study found that softener negatively affected the whiteness index of knitted cotton fabrics and was not recommended if preserving these characteristics is a priority. However, for 100% polyester fabrics, the softener had no impact on the whiteness index and can be used without restrictions. Washing the cotton fabrics at 60ºC improved their whiteness index, while detergent usage enhanced the whiteness index of all fabrics tested. Additionally, an increase in the number of washing cycles reduced the whiteness index of polyester-containing fabrics but increased the whiteness index of cotton fabrics, likely due to increased exposure to optical brighteners present in the detergent.

Shrinkage was not significant for the fabrics studied, and the factors that influenced it the most were washing temperature and the number of cycles. Washing temperature affected all fabrics, with polyester-containing fabrics being more affected. It is advisable to avoid washing or drying these fabrics at temperatures of 60ºC or higher. The study did not find any significant impact of the chemicals on dimensional stability.

Interactions between the factors were present, with varying strengths. Future studies should consider all the factors examined in this research, but some may be excluded depending on the specific response being investigated.

The mechanical action of the washing machine was also studied, and it was found that the number of cycles was the only relevant factor affecting this index. This result is reasonable as agitation and spinning in the machine increase friction between the agitator and fabrics, fabrics with other fabrics, and the washing machine drum.

Microscopic analysis of the fabrics revealed that after 20 washing cycles, the fabrics faded compared to their unwashed counterparts, supporting the finding that washing cycles decreased the whiteness index and affected the fabric's surface smoothness.

ATR-FTIR didn’t show significant differences between the fabrics before and after washing with either detergent or fabric softener.

In conclusion, the statistical model recommends washing fabrics containing polyester in cold water (20ºC), using detergent, and avoiding fabric softeners to increase their lifespan. For 100% cotton fabrics, it is recommended to use a higher temperature of 60ºC, with detergent, and without fabric softener. However, it is essential to note that fabric softeners are known to enhance fabric softness. Therefore, if durability is the priority, opting for fluffier clothes may not be feasible.

For future research, it would be valuable to introduce stains into the study to assess their influence on the results. Additionally, factors related to thermal comfort, such as air permeability, hydrophilicity, water vapor transmission, and hand feel, could be explored using a panel of trained individuals. Finally, other types of fabrics, chemicals and washing machines should also be considered in future studies.

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