UNIVERSITY OF BORÅS

Impact of Yarn Constructions on Microplastic Fibre Release

Maria Persson, Julia Hellmark Killick, Nils-Krister Persson

2024-06-27

Authors: Maria Persson, Julia Hellmark Killick, Nils-Krister Persson, University of Borås

Funded by: The Swedish Environmental Protective Agency (Naturvårdsverket)

© University of Borås 2024

Allégatan 1, 503 32 Borås

Preface

This report has been commissioned by the Swedish Environmental Protection Agency (Naturvårdsverket) with the aim to investigate the potential influence of yarn construction on the fragmentation of microplastic fibres in textile fabrics in order to contribute to the Ecodesign requirements proposed by the European Union (EU). Julia Taylor has reviewed the report, and the authors are solely responsible for the content and conclusion in the report.

Sammanfattning

Betydelse av garnets konstruktion för hindrande av torr mikroplastemission hos textil

Denna rapport har gjorts på uppdrag av Naturvårdsverket för att undersöka en något förbisedd faktor, nämligen garnkonstruktionen, som en aspekt av textilier, och hur denna faktor inverkar på mikrofiberfällningen (s.k. shedding), från textilier i torrt tillstånd.

Kort sammanfattat kan sägas:

Att spunnet garn (så kallat stapelgarn) hade en ökad benägenhet att avge fiberfragment jämfört med filamentgarn.

Viskosgarn, oberoende av om det var spunnet eller filamentgarn, visade lägre fiberemission jämfört med polyestergarn.

Kemiskt återvunnet polyestergarn visade en tendens att avge fler fiberfragment jämfört med oanvänt polyestergarn.

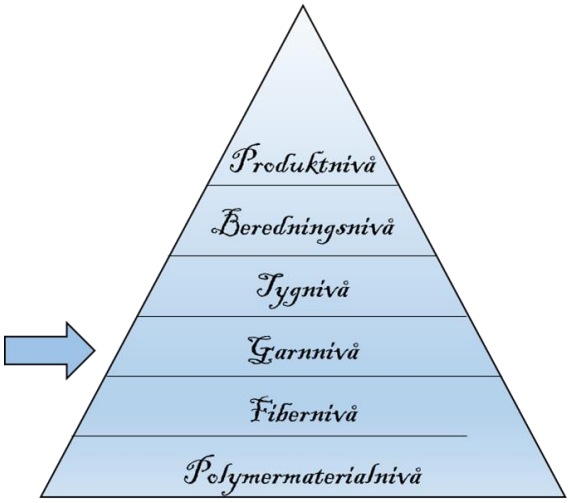
Studien uppmärksammar också att antalet partiklar av storleksordningen under µm dvs i nanometerområdet kan vara betydande.

Det går inte att rekommendera att på bred front gå över från spunnet garn till filamentgarn eftersom spunnet garn har en sådan grundläggande betydelse för värme- och kylisolering i plagg. En övergång skulle också ge favör till syntetiska garn som väsentligen är fossilbaserade. Däremot kan slutsatsen dras att garnkonstruktionen spelar roll och bör undersökas vidare vad gäller dess kvalitet, exempelvis med avseende på hur hårt garnet är spunnet, stapellängd och hårighet.

Att textilier kan vara en källa till mikroplaster har i den vetenskapliga litteraturen uppmärksammats tämligen sent. Andra källor såsom kosmetik (inklusive tandkräm och skrubbkrämer), däck och konstgräsmattor uppmärksammades länge mer.[1] Detta trots att det är naturligt att förknippa många typer av textiler med stor hårighet och i sin tur med risk för fibersläpp. Att ett lager av utstickande trådar och trådändar binder luft så denna blir stillastående används för att göra textilen värmeisolerande (i stickade tröjor, koftor, täckjacksvadd, täckisolering, filtar) vilket kanske är textilens enskilt viktigast funktion som teknisk artefakt.

Många faktorer kan påverka en textil. Textil, förutom något undantag, kan alltid sägas bestå av ett polymert material. Det kan vara naturligt (ull, bomull) eller syntetiskt (polyester, polyamid (nylon)) eller ett sorts mellanting, s.k. regenererad cellulosa (viskos m.fl.) som har ett naturligt råämne i form av cellulosa men som behandlats kemiskt för processabilitet. Det finns sålunda alltid en grundläggande *polymermateriell nivå* när man talar om textilier generellt och mikrofiberfällning speciellt. Här ingår faktorer som materialval, värmeutvidgningsegenskaper (upprepad värmeexpansion och kylkontraktion vilka utgör grund för sönderflagning), nedbrytningskänslighet vid närvaro av vatten och/eller värme, kemikalietålighet, risk för mikrosprickbildning (grundat i mikromorfologi), nötningstålighet osv. Här kan också inkluderas katalysrester från polymerisationen som kan tänkas släppas under användning.[1] I litteraturen har denna nivå varit i fokus för många studier, där inte minst jämförelser gjorts mellan naturliga och syntetiska typer.

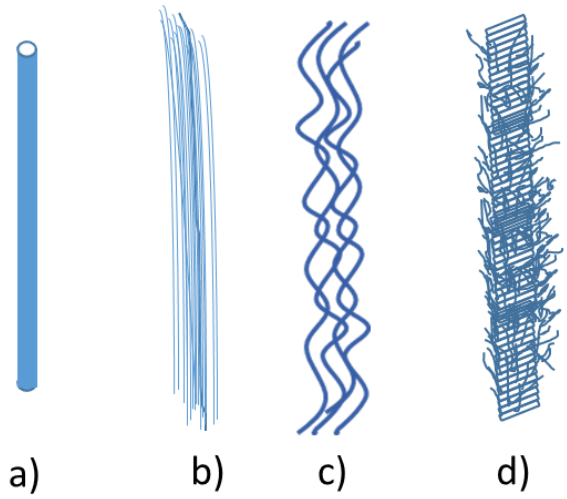
Per definition består textil alltid av fibrösa strukturer som skapats av det polymera materialet. I diagrammet i figur 1, benämns detta fibernivå, som är nästa steg i en hierarki (figur 1) Här kommer faktorer som olika fibertvärsnitt (med olika känslighet för nötning och smutsomslutning) in. Eventuella additiv kommer här också in. Det är inte bara så att en fiber består av polymer och det av en sort. Tvärtom adderas en rad andra kemikalier, inte sällan är de av låg molekylär vikt dvs små och kan löpa risk att migrera till ytan och lösas ut av olika nedbrytningsprocesser.



Figur 1. *Textilhierarkin, från beslut om polymermaterial till slutprodukt. Genom att navigera i textilhierarkins lager kan forskare och yrkesverksamma inom industrin få värdefulla insikter i textilproduktionens komplexitet och möjliga vägar för utsläpp av mikrofibrer eller fiberfragment inom textilstrukturer. I denna studie fokuserar vi på påverkan garnnivå, vilket indikeras med en pil.*

När det gäller mikrofiberfällning orsakad av egenskaper och processer på fibernivån är detta betydligt mindre studerat än vad gäller egenskaper och processer på polymermateriell nivå. Fibrerna sätts sedan samman till garn och vi har egenskaper och processer på *garnnivå*, se figur 1. Hur garnet är konstruerat,

figur 2, är helt centralt för egenskaperna (till exempel styrkan, tjockleken, vikt, utseende, komfort osv.), hos den slutliga textila produkten. Möjligen något förvånande är detta i många fall viktigare än vilket typ av polymert material som använts. Man kan till exempel tänka sig att sticka en blus i ett polyestergarn av så kallad multifilament typ och en blus i ett polyestergarn av stapeltyp. Alltså bägge gjorda av samma polymertyp. De kommer att få helt olika komfortegenskaper. Den senare kommer att bli behaglig att ta på sig. Den kommer att bli mycket mer lik en blus gjord i bomullsgarn. Garnkonstruktion är en värld i sig. I figur 2 visas de huvudtyper man talar om.



Figur 2. En aspekt av garnkonstruktion är garntypen. Här visar vi bara några få: a) monofilament; b) multifilament garn; c) texturerat multifilament garn; d) spunnet garn

Spunna garner (spun yarns) består av hopspunna korta fibrer, ofta benämnda *stapel (stapelgarn* blir då en synonym till spunnet garn). Att man har dessa begränsade längder är förväntat när det gäller naturfibrer. Såväl bomull som ull har ju begränsad naturlig fiberlängd. Eftersom det är omöjligt att väva och sticka alltför korta delar återstår bara att forma ihop stapeln till sammantvinnade garn om stapeln skall kunna användas till textil. Då får man garn som är processerbart till tyg. Garnet kommer att få fyra värdefulla egenskaper: 1) man nyttjar korta delar (stapeln) till att få fram en längre processerbar enhet (garn); 2) man får en sammanhållning (kohesion) i denna struktur; 3) man får en hårighet, vilket dels låser in luft så denna blir stillastående i ett lager runt garnet, dels ger en mindre kontakt med huden och också på så sätt skapar ett stillastående luftlager närmast huden och verkar termiskt isolerande; och 4) man får kaviteter i det spunna garnet som kapillärt kan transportera bort fukt från huden som annars sänker komforten. Stapeln i spunna garner kan ha längd från några millimeter upp till några centimeter. Om de fibrer man använder är långa (100 tals meter) talar man i stället om *filamentgarn*. Ett garn kan bestå av ett eller upp till hundratals filament. I det förra fallet talar man om *monofilament*. I det senare talar man om *multifilamentgarn*.[2] Sådana garn används till andra ändamål än spunna garner, ofta till tekniska textilprodukter. Isoleringsförmågan är inte lika stor eftersom det inte finns samma slags av luftinneslutningsförmåga som hos spunna garner. I gengäld kan draghållfasthet bli mycket hög, liksom

regn- och vindtäthet. Filamentgarn används till kavajfoder, idrottsplagg, täckjackor, barnoveraller, bland mycket annat. Filamentens böjlighet är en viktig aspekt för garn och en faktor på garnnivån. Så också deras finlek. Multifilamentgarn kan vidare vara texturerade. [3]Med detta menas att filamenten inte ligger packade parallellt varandra utan det finns en tendens till lite olika böjning sinsemellan (figur 2 c). Garnet kommer då vilja ta plats – också när det är invävt eller instickat - och kan på så sätt få en viss luftinneslutningsförmåga. Den resulterande textilen är ofta starkare, mjukare, mer vattenbeständig och mer hållbar än textilier av vanliga, släta och obehandlade garn. En annan faktor som delvis hör till garnkonstruktionen är fibrernas tvärsnitt. De kan vara av en rad olika typer; runda, trekantiga, lobala, tillplattade etc, Tvärsnittet påverkar packningsgraden och därmed den interna nötningen filament till filament. [4]

Garn stickas och vävs till tyg. Det finns hundratals olika stick- och vävmönster[1] dvs topologier ett tyg kan framställas i. Dessa kan vara olika tåliga mot olika sorters belastningar såsom friktion och skjuvning som har stor riktning i och parallellt med ytan eller å andra sidan penetrationspåverkan, mer eller mindre vinkelrät mot tyget. För mikrofiberfällning är det förra fallet troligen intressantast. Det finns sålunda en mängd faktorer på *tygnivå*. Också här har många studier fokuserat på mikrofiberfällning och tygnivåns inverkan. Det finns sålunda flera studier på slitage på barnkläder, fleece har utpekats som en källa till textila mikrofiber osv.

Färgning och s.k. beredning (flamskydd, skrynkelbehandling, vattenavstötning etc.) kan göras på flera nivåer. Om vi antar att det görs på ett tyg återfinns det en ”*beredningsnivå*” i hierarkin (figur 1). Man kan tänka sig att det här finns stor känslighet för att processerna görs rätt för att få god vidhäftning och undvika att kemikalier släpper vid användning.

Av tyg gör man plagg eller andra typer av textil (mattor, sängkläder, kuddar). Detta kallar vi *produktnivå*. Många av studierna om mikrofiberfällning är faktiskt på denna nivå. Man jämför (ofta inköpta) plagg och ibland tillkommer rent numerära, absoluta resultat i stället för relativa. Ett plagg si och så släpper si och så många partiklar. Detta kan vara intressant ur medial synpunkt att få braskande rubriker men säger inget vetenskapligt om orsakssamband och hur vi skall jämföra och utifrån det förstå och minska uppkomsten av mikrofibermission. Då behövs i stället att jämföra emitterad massa per massa fiber eller massa tyg eller ytstorlek.

Det finns en rad nedbrytande processer som kan tänkas ligga bakom mikrofiberfällning. Cykliska svällningar och återhämtningar orsakade av termisk påverkan (kyla eller värme), cykliska svällningar och återhämtningar orsakade av fukt och vatten, hydrolys, påverkan av ultraviolett ljus, smuts som kan

[1] *Mönster* används i minst två olika betydelser inom textil. Vanligt hos gemene är att man talar om att man syr ett plagg efter ett visst mönster, med olika mönsterdelar såsom ärmar, frontpanel, ryggpanel osv. En annan betydelse är att när man stickar eller väver (maskinellt eller för hand) ordnas garnen på olika sätt i förhållande till varandra, i ett *mönster*. Textilteknologisk talar man om väv- och stick*konstruktioner*. Med dessa menas här tuskaft, satin eller rib och jersey, för några exempel.

verka som lösningsmedel såsom fetter, rent mekanisk påverkan genom friktion, dragbelastningar och böjningar som introducerar såväl drag (tensile) som tryck (compression) påverkan osv. Speciellt för textilier som är kläder är att de tvättas. Tvätt har också varit det som vetenskapliga studier mest riktat in sig mot.[5-15] Detta bygger på en hypotes att de faktorer som då verkar på plagget är stora. De brukar sammanfattas under namn av Sinnerfaktorer (eng. *Sinner's Circle*) och är *mekanisk påverkan, kemisk påverkan, temperatur* och *tiden* plaggen exponeras för dessa. Det finns inte tydliga studier som jämför tvättens betydelse med den dagliga användningen, vad som i vår studie kallas torr (dry) användning, och kvantifiering av respektives betydelse. Det har inte heller varit vårt syfte. Däremot önskar studien lyfta fram att kläder också slits *mellan* tvättar och att detta resulterar i mikroplastemission. Mikrofibrerna kan sedan följa olika spridningsvägar. Inomhus kan en del fångas upp genom dammsugning och våttorkning. Utomhus har mycket långa transportsträckor noterats då mikrofibrer har upptäckts på avlägsna platser där människor inte vanligtvis vistas. [16, 17] }Vattendrag riskerar att bli slutrecipienter. [1]Också att bidra till kartläggningen av hur mikrofibrer sprids utomhus ligger utanför studien.

Vad som däremot är fokus i studien är att se på mikrofiberfällningen från textilier i torrt tillstånd för att adressera den dagliga användningen med ständiga böjningar, kontakt med möbler friktion textil-textil och där olika garnkonstruktioner jämförs.

För att testa mikrofiberfällning kan man gå tillväga på väsentligen två olika sätt. Man kan å ena sidan försöka efterlikna de olika exponeringar som en textile, ett plagg säg, utsätts för under sin livstid. Dessa parametrar kan vara tvättning, exponering till UV ljus eller nötning. Man skulle kunna följa ett antal från början identiska plagg och förse ett antal användare med dem. Användarna får sedan bruka plaggen under lång tid. Med någon lämplig metod (mikroskopering, fotografering och bildanalys) följer man slitaget. En kontroll till en sådan studie kan vara helt oanvända plagg. Mätningen sker i vad som skulle kunna kallas *negativ mode* (man mäter bortfall av material). En sådan studie tar lång tid, vilket är helt utom räckhåll för aktuellt projekt. Det finns också problem om man skulle mäta vikt då det troligen är mycket svårt att följa ett plaggs massförändring över tid när det är hos konsument. Det andra sättet är att kontrollerat i lab påverka och kontrollerat mäta plagg oberoende om detta återspeglar verklig användning eller ej. Tack vare jämförelse mellan de parametrar man är intresserad av – såsom garnkonstruktion – kan man få uppfattning av vilka typer som har hög benägenhet att fälla mikroplaster och de som har låg. Detta är möjligt att genomföra inom tidsramarna för projektet. Denna strategi genomförs i *positiv mode* dvs partikulära emissionen är det som mäts, inte förslitningen.

Sålunda, för att simulera slitage i form av nötning och få förståelse utfördes fem test; *nötning* (s.k. abrasion), *noppbildning* (s.k. pilling), *luddbildning* (s. k linting), *hårighetsanalys*, samt ett *tvättest*. Det sista gjordes som en jämförelse med ofta förekommande studier av inverkan av tvätt i samband med mikrofiberproblematik. Testerna utgick från *ISO standarder* för nötning och noppbildning (SS-EN ISO 12945–2:2000 och SS-EN ISO 12945-1:2000, luddbildning (SS-EN ISO-9073:10:2025), och tvättning

(SS-EN ISO 4484-1:2023), samt *ASTM standard* D5647 för hårighetsanalys. Detta har fördelen att resultaten enkelt och tydligt kan jämföras med resultat från andra studier. Det är en fördel som understödjer vetenskapliga krav på transparens och reproducerbarhet. Det går dock inte att uttala sig om vi sliter mer eller mindre än ett plagg av materialet skulle utsättas för under ett visst tidsspann i daglig användning.

Analyserna genomfördes på flera tyger med identiska konstruktioner men tre olika typer av garnkonstruktioner, nämligen *oanvänt spunnet garn*, *oanvänt multifilamentgarn* och *kemiskt återvunnet multifilamentgarn garn*. Två olika polymerbaserade material användes; viskos (cellulosaursprung) och polyester (syntetiskt material). Resultaten kan sammanfattas enligt följande.

Spunnet garn har en ökad benägenhet att avge fiberfragment jämfört med filamentgarn, särskilt märkbart under nötningstester såsom noppbildnings- och nötnings-test, samt under tvättprocesser. Viskosgarn, oberoende av om det var spunnet eller filamentgarn, visade lägre fiberemission jämfört med polyestergarn. Det spelar sålunda roll för mikrofiberfällningen vad för garnkonstruktion som används i en textil. Detta understryker vikten av att ta hänsyn till garnkvalitén i kommande krav på ekodesign som föreslås av EU kommissionen, för att effektivt minska miljöpåverkan. De tester som använts; nötning, noppbildning och linting befinns vara användbara då de har fördel av vara standardiserade och sålunda kan genomföras på många ställen.

Dessutom visade kemiskt återvunnet multifilament polyestergarn en tendens att avge fler fiberfragment jämfört med oanvänt polyestergarn. I takt med ökat intresse för cirkularitet och återvinning bör man uppmärksamma hur återvunna garn framställs för att undvika att de blir en ny källa till mikrofiberfällning. Studien uppmärksammar också att antalet emitterade partiklar av storleksordningen under µm dvs i nanometerområdet kan vara betydande vid torr användning. Deras karaktär har inte kunnat undersökas inom projektet. De kan vara additiv av olika slag eller av polymertyp. Dock är det viktigt att framtida tester behöver kunna hantera partiklar i denna storleksordning.

Det går inte att rekommendera att på bred front gå över från spunnet garn till filamentgarn eftersom spunnet garn har sådan stor betydelse för värme- och kylisolering i plagg. En sådan övergång skulle också ge favör till syntetiska garn eftersom det enda naturliga filamentgarnet är silke som har en ytterligt liten del av den totala världsmarknaden av garn. Men syntetiska garner är väsentligen fossilbaserade, som har sina nackdelar. Det i förstone enkla begreppet *kvalitet* blir betydelsefullt. Kvalité definieras ofta som något i stil med ”alla sammantagna egenskaper hos en produkt eller en företeelse som ger den dess förmåga att uppfylla uttalade och underförstådda behov”. Detta är en *relativ* definition - relativ till en kunds behov. Men om kunden inte har behov av annat än att bli attraherad av ett plagg vid köptillfället kommer aldrig miljömässiga aspekter komma upp och inkluderas i kvalitetsbegreppet. I synnerhet inte förmåga hos garn eller plagg att motstå att fälla mikrofiber. Garnkvalitet behöver inkluderas när man diskuterar mikrofiberemissioner– det visar studien - med ett kvalitetsbegrepp som är *absolut* snarare än

relativt. Väl spunna, kardade, kammade garn behöver även kvantifieras när det kommer till mikrofiberemissioner. För detta behövs vidare studier göras. Närmast för handen ligger då jämförelsestudie över olika garnspinningstekniker, tvisttal (antal varv per längdenhet), hårighet och hur dessa relaterar till mikroplastfällning.

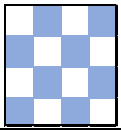
Abstract

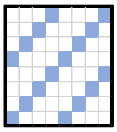
This report has been commissioned by the Swedish Environmental Protection Agency (Naturvårdsverket) with the aim to investigate the potential influence of yarn construction on the fragmentation of microplastic fibres (MPF) in textile fabrics. The analyses were conducted on multiple fabrics with identical constructions but utilizing different types of yarn, such as spun yarn and filament yarn. These fabrics underwent various test simulating the wear experienced throughout a fabric's lifecycle, including washing, abrasion, and pilling. The research findings highlight the significant influence of yarn type on shedding behaviour. Specifically, spun yarn demonstrates a heightened propensity to shed fibre fragments compared to filament yarns, particularly noticeable during flat abrasion test such as pilling and Martindale, as well as during laundry processes. In contrast, regardless of being spun- or filament yarn, viscose yarn demonstrated lower fibre shedding rates compared to polyester yarn. Furthermore, the chemical recycled polyester yarn showed a tendency to shed more fibre fragments than primary polyester yarn. The conclusions drawn from this report underscores the importance of incorporating yarn quality considerations into eco-design requirements, as suggested by the EU Commission, to effectively mitigate environmental impacts. Further research is essential to enhance our understanding of the factors influencing fibre shedding and to develop efficient strategies for sustainable product design and regulation.

Contents

Sammanfattning 4
Abstract 11
Terms and Definitions 13
1. Introduction 15
1.1 The Textile Hierarchy 15
2. Different sources of Fibre Fragment Shedding 17
2.1 Laundering: A Known Source of Microplastic Fibres 17
2.2 Wear: A Forgotten Source of Microplastic Fibre 19
1.3 Summary state of the art 20
1.4 Study aims 21
2. Material and Method 21
2.1 Materials 21
2.2 Fabric Construction 21
2.3 Yarn Hairiness test 22
2.4 Wear simulation using ICI pilling-box 22
2.5 Wear simulation using Martindale 25
2.6 Microscopic analysis of shedded fibre fragments 25
2.7 Fibre fragment shedding during linting test 26
2.8 Fibre fragment shedding during laundry 26
3. Results 27
3.1 Fibre fragment shedding during wear simulation using ICI Pilling-box 27
3.2 Comparative analysis of knitted polyester spun yarn and filament fabrics 30
3.2.1 Yarn Hairiness 30
3.2.2 Fibre fragments shedded during wear simulation using Martindale 30
3.2.3 Fibre fragments shedded during linting test 31
3.2.4 Fibre fragments shedded during laundry 32
4. Discussion 33
5. Conclusions 35
6. Further Recommendations 36
References 37

Terms and Definitions

Additive	A supplementary material combined with a base (polymeric) material to provide special properties. For example, pigments are used as dope additives to give colour in mass dyeing.
decitex (dtex)	Mass in gram per 10 000 m
Fibre Fragment	Fragments of textile fibres that are shed from product during production, use, and after-use phase
Fibril	A tiny threadlike element of a synthetic or natural fibre
Fibrillation	A phenomenon that occurs in textile fibres, resulting in the exposure and fraying of individual fibrils on the surface of the fibre.
Filament	A fibre of an infinite r extreme length.
Filament yarn	A yarn composed of continuous filaments assembled with or without twist.
Hairiness	Describes excessive fibre ends on a yarn's surface that may create problems in fabrication or in consumer use because they are more sensitive to abrasion and pilling
Knitting	A method of constructing fabric by interlocking a series of loops of one or more yarns.
Lint	Particles and short fibres that fall from a textile product during stresses of use
Microplastic	According to the Swedish Environmental Protective Agency, microplastics refer to solid particles of plastics and rubber regardless of form (such as beads, flakes, and fibres", which are between 1 nm and 5 mm in their largest dimension and are insoluble in water.
Microplastic fibre	According to the Swedish Environmental Protective Agency, microplastic fibres are defined as polymeric fibres of length between 3 nm and 15 mm, and a length-to-diameter ratio of > 3.
Nm	Normal metric yarn count. Defined as the number of meters per kilogram.
Plain weave	One of the three fundamental weaves: plain, twill and satin. Each filling yarn passes successively over and under each warp yarn, alternative each row. 
Polymer	A very large molecule made by connecting many small "building blocks", or monomers, together.
Shedding	Shedding is defined as release of particulate matter from a textile. It is a general term comprising polymeric fibre shaped materials as well as additives and loss of earlier attached dirt particles, skin particles etc.
Spun yarn	A yarn consisting of staple fibres usually bond together by twist
Staple fibre	Is any natural or of manufactured fibre produced in or cut to a short length (cm - dm). measured in inches or centimetres

Twill weave	A fundamental weave characterized by diagonal lines produced by a series of floats staggered in the warp direction. 
Weaving	The method or process of interlacing two yarns of similar materials so that they cross each other at the right angles to produce woven fabric.

1. Introduction

The release of microplastic fibres from textile materials also denoted as fibre fragment shedding has emerged as a significant environmental concern due to its implications for air and water quality, as well as for animal and human health. These fibres, which originate from synthetic or natural textiles, have been identified as a pervasive source of microplastic pollution in various environmental settings, including both indoor and outdoor environments.[18, 19] Fiber fragmentation occurs throughout the entire life cycle of textile materials, irrespective of their synthetic or natural origin. However, synthetic fibre fragment is particularly concerning due to their resistance to degradation, leading to their accumulation over time. Specifically, the fibres released during wear contribute to the presence of airborne microplastics.

While wastewater treatment plants effectively capture many fibres released into the wastewater[1,20], (such as those released during laundry) airborne fibres evade filtration and collection processes. Airborne microplastic can travel long distances and ultimately accumulate in soil and bodies of water, posing a significant environmental risk as they can act as carriers or sorbents of other pollutants.[21-23] Given the current prominence of this issue, it is crucial to identify the specific areas where the greatest impact of microplastics pollution is projected to occur, with the aim to efficiently mitigating its effects on the environment. One driver behind this issue is the European Union (EU), which has initiated an EU strategy for Sustainability and Circular Textiles.[24] This strategy aims to tackle the various stages of the lifecycle during which synthetic fibres are released into the environment through a series of preventive and reduction measures. Notably, the EU intends to implement binding design requirements under the Eco-design for Sustainable Products Regulation to enforce sustainable practice in the textile industry.[24] Another significant driver from the EU is the Zero Pollution Action Plan[25], which states that a 30% reduction in microplastic emissions is achievable by 2030 through the new regulations implemented and enforced by REACH since October 17th 2023[26]. This regulation prohibits the intentional addition of microplastics in products such as glitter, cosmetics, detergents, and plant protection products.

1.1 The Textile Hierarchy

In order to understand the mechanisms through which microplastic fibres can be shed from textiles structures, a comprehensive understanding of the textile hierarchy is essential. Textile products, ranging from, t-shirts and carpets to pillows and airbags, are intricate assemblies of various building blocks, each serving as a potential source of microplastic pollution. The textile hierarchy, illustrated in Figure 1, provides a structured framework to elucidate the journey of a textile product from its inception to its final form.

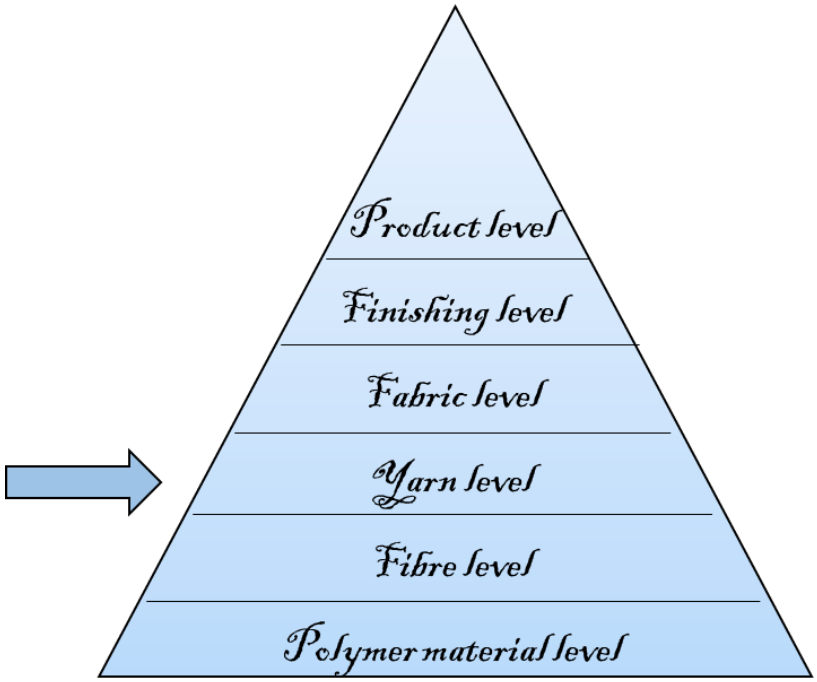


Figure 1. *The textile hierarchy, starting from the polymer material decision towards the final product. By navigating the intricate layers of the textile hierarchy, researchers and industry professionals can gain valuable insights into the complexities of textile production and the potential pathways for microplastic fibre or fibre fragment shedding within textile structures. In this study we are focusing on the impact on yarn level as indicating with an arrow.*

At the foundation of any textile product lies the selection of the polymer material, *polymer material level.* This critical stage involves decisions regarding the choice of polymer, molecular weight, copolymerization, and other additives. The properties of the polymer material dictate fundamental characteristics such as *fibre level*, where parameters such as linear density, diameter, shape, additives, crystallinity, and length of the staple fibre or filament plays a role.

From fibres yarns are spun at the *yarn level*, with considerations encompassing various yarn constructions and characteristics. Figure 2 illustrates key aspects of yarn types, while decisions at the yarn level involve factors like twist number, yarn density, thickness, texturizing processes, and spinning methods such as ring spinning, open-end spinning, and air jet spinning. Through knitting and weaving processes, yarns are transformed into fabrics at the *fabric level,* where properties like stretch, floats, weft density, warp density and smoothness are crucial considerations.

Following fabric production, the *finishing steps* are undertaken, encompassing process such as dyeing (if not utilizing dope dyed yarn), functionalization for properties like water repellence, odour resistance, and wrinkle resistance, as well as treatments for colour fastness and potential corona of flame treatments. Textile products often comprise a system of diverse fabrics and components, with the assembly process falling under the product level, shaping the final characteristics and functionality of the product.

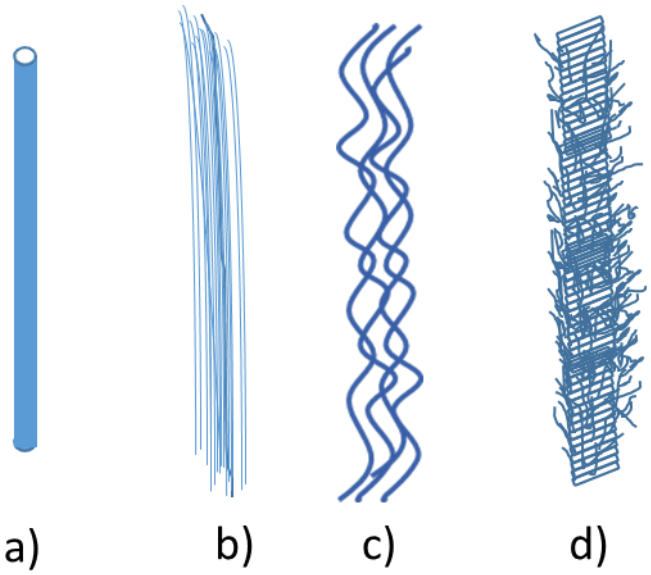


Figure 2. *An aspect of the yarn construction is the yarn type. Here we show just a few, a) monofilament; b) multifilament untextured; c) multifilament texturized; d) spun yarn with protruding parts.*

2. Different sources of Fibre Fragment Shedding

2.1 Laundering: A Known Source of Microplastic Fibres

Laundering, specifically washing and drying, has been established as a primary factor contributor to the shedding of fibre fragmentation, ultimately leading to the release of microplastic fibre fragments into natural water systems via wastewater.[18, 19] The first study to announce that domestic laundry can be a source of fibre fragments was conducted as late as 2011 by Browne, et al.[18] . Since then, a growing number of studies have been conducted in order to understand the impacts of microplastic release during washing.[27-32] For instance Kelly et al (2019)[29] conducted a comparative analysis of fibre release from a generic t-shirt, under varying conditions, including temperature, water-to-fabric ratio, use of detergent (liquid), and degree of agitation, in both closed and open washing systems (Tergotometer and domestic washing machine). Their findings indicated that the water-to-fabric ratio was the primary determination of shedding, with higher water quantity relative to fabric quantity leading to greater shedding. While the use of detergent was reported as a determining factor by some authors. [33-37], other found less shedding to occur with the use of detergent [30, 38, 39] Additionally, higher temperatures [30, 34, 35, 40], greater agitation[34], longer durations [30, 31, 34], less filled washing machines[30, 41], as well as whether the machine is top-loaded as opposed to front-loaded[42, 43] have been identified as factors contributing to greater fibre loss in various studies.

The mechanical processes involved in washing textiles, including stretching, friction against other textiles, and compression, contribute to fibre damage, leading to fibrillation[44] and eventual fragmentation into microplastic fibres.[45-47] The extent to which a fabric is damaged in the process varies depending on the durability of the material. However, no textile fabric is immune to attrition, and all textiles will inevitably undergo wear and tear. For instance, the tendency of a fibre to fibrillation is influenced by the shear strength and tensile strength of the fibre. Excessive shear stress can induce fibrillation regardless of the fibre's properties, but whether this is followed by breakage depends on the fibre's shear strength. Weaker fibres are more prone to immediate fracture, while stronger materials may continue to fibrillate before eventually breaking.[48] As an example, wool fibres are weak and stretch easily when wet, requiring special care when washed. In contrast, synthetic fibres such as polyester have good wet strength and can therefore withstand mechanical action in laundry better [49]. Aramid fibres, such as p-aramid, are commonly used in protective wear such as uniforms and workwear. These fibres will fibrillate during washing, resulting in a frosty surface of the fabric[50]. Therefore, tensile strength also plays a role in determining whether the fibre will fracture and deform due to attenuation and thinning (Figure 3)

Figure 3. *Cotton sock showing signs of thinning at the toes when worn.*

Bending rigidity is another important material property that can result in fibre fragmentation during laundry. The bending rigidity of a fibre, which describes its propensity to withstand repeated bending, depends on the fibre's shape, modulus, density and the fineness [51]. Rigid fibres (high module) are more resistant to bending and therefore more susceptible to breakage if they are exposed to bending forces [52]. Likewise, coarser fibres, being less flexible, are more susceptible to breakage due to bending. Conversely, finer fibres are more likely to have lower tensile strength compared to fibres of greater linear density. The characteristics of fibres are dependent on their chemical composition, including the polymer backbone and any incorporated additives.[52]

It is worth noting that many of the damaging effects discussed above can also occur in a dry state of a textile material. Additionally, the yarn structure type and fabric constructions (weave, knit, braid or nonwoven) also contributes to mechanical strength of the textile [53]

2.2 Wear: A Forgotten Source of Microplastic Fibre

The comprehensive loss of fibres through various means is commonly known as wear. In the absence of moisture and water as well as detergents, as in the case of laundry, the term "abrasion resistance" is typically used to characterize a textile material's ability to endure deterioration from wearing. Fabrics with high abrasion resistance can maintain their structure integrity and appearance even when subjected to repeated rubbing and frictional forces, which indicate a strong cohesion within the fabric system.[54] Fibre cohesion refers to the ability of fibres to stick together and resist separation. Consequently, factors influencing yarn cohesion also impact abrasion resistance.

In spite of everybody's everyday experience that fibrous dust is accumulated in homes, in corners and under furniture, the scientific interest for this has been moderate and late. Textile fibre dust was first studied from a perspective of occupational medicine [55] and hygiene.[56]

Incorporating longer fibres into a fabric enhances abrasion resistance, as they are more difficult to dislodge from the fabric structure. Similarly, filament yarns exhibited better abrasion resistance compared to spun yarns made from the same material[54], and one can therefore assume that filament yarns have a lower tendency to release fibre fragments. .

Furthermore, the utilization of finer fibres in yarn production increases the fibre count in the cross section, leading to heightened cohesion and improved abrasion resistance. Therefore, fabrics composed of finer fibres demonstrate superior abrasion resistance when compare the fabric made of courser yarn.[54]

Abrasion of a fabric can also led to pilling, a surface defect characterized by the formation of small, fuzzy balls or clusters of entangled fibres on the surface of clothing. [44, 57, 58] . Choi et al[6] investigated the impact of physical and chemical properties on pilling and observed fibre fragmentation due this phenomenon. Pilling can cause fibres to be worn or pulled away from the fabric surface because of mechanical action such as during wearing or washing.

Another common term used in the textile industry describing short fibre separation from fabric is linting. These fibres tend to accumulate in the lint trap of dryers[59] . Notably, textile production generates lint, particularly from fabrics composed of staple fibre and hence spun yarn. Staple fibres, which are typically short in length (typically order of mm to cm), are the predominant form of natural fibres, with the exception of silk. In contrast, synthetic fibres as well as manmade fibres are filaments. Filament yarn require an additional production step to be shaped into staple fibres, involving the cutting, and crimping

of the fibres.[2] The crimping process is essential to enhance the cohesion between the fibres during yarn production.[60, 61]

The lint generation during textile production is a significant concern due to its potential to cause respiratory and allergic symptoms, such as wheezing, phlegm, and hypersensitive pneumonitis [62-66] Lint also poses a risk of contaminating the final textile products, affecting their quality,[67] and sometimes even leading to the discharge of the entire batch. In order to avoid cross-contamination of lints, it is important to have dedicated factories for each fibre type and maintain a good housekeeping.

The propensity of fabrics to release lints is also a substantial concern when utilized in clean rooms and hospitals, primarily due to the potential risks associated with lint contamination.[68] Lint has the potential to compromise the cleanliness and sterility of environments and products used in these environments, thereby significantly impacting the quality of the products and the safety of the patients.[69] Additionally, lint contamination can interfere with the performance of sensitive equipment and instruments in clean room environments, potentially leading to operational issues and compromised results.[70]

1.3 Summary state of the art

The literature study has revealed that the impact of textile characterisation on microplastic formation or fibre fragments shedding has not been consistently and comprehensively explained, although certain trends have emerged. For instance, the majority of the peer-reviewed scientific articles on the topic have focused on fibre fragmentation during laundry.[6-15] There is a scarcity of publications related to fibre fragmentation in the dry state, such as abrasion, pilling, and linting, which are concerning when considering fibre fragment shedding into the air.

Trends observed from the literature study, as also discussed in a recent review article[5], indicate that natural and synthetic fibres exhibit distinct behaviours regarding fibre fragment shedding, with natural and man-made fibres tending to shed more fibre fragments than synthetic counterparts [7-9]. Fabric samples composed entirely of synthetic fibre blends generally shed fewer fibre fragments compared to those made from mixed fibre blends[10, 11]. It is notable that there is no significant disparity when comparing various types of synthetic fibres.[6, 8, 10, 12]

Fabrics made from spun yarns of synthetic origin are more likely to release fibre fragments than those made from filament yarns. [11, 13, 14]Additionally, woven fabrics shed fewer fibre fragments than fabrics with a knitted structure. [11, 15] Yarn construction appears to have a more significant impact on fibre fragment shedding than the overall textile design.[13, 14] However, there is a gap in the literature regarding the precise building blocks of textile structure, making study repeatability challenging. The understanding of how textile properties, including yarn structure, interact and influence the fibre fragment release, is not well understood. With fragmented knowledge scattered in the scientific literature, it becomes challenging to compile sufficient information to ascertain the specific

characteristics of eco-design requirements of a textile product. In addition, the question remains: what constitutes a large amount of fibre fragmentation, and what is considered low in the context of a textile garment.

1.4 Study aims

It is evident that fibre fragments, lint, microplastic fibres and, potentially, particulates from any additives within and on the textile, are released both during washing and wear processes. The mechanisms behind are plenty; hydrolysis, mechanical pressure, friction, skewing and dissolution.[52, 53] Material properties are of course important, so is user behaviour. But what is often lacking is investigation of yarn construction. The effective area at the yarn level is many orders of magnitude larger than at the fabric level where the textile is regarded as a flat smooth surface. And it is from surfaces that the release of particles is happening. Therefore, **this study aimed to investigate the influence of yarn construction on the shedding of fibre fragments within textile fabrics to enhance understanding for future environmental labels and eco-design requirements as suggested by the EU commission.** The report explores the possibility of establishing design requirements at the fibre and yarn level as a first step towards increasing the understanding of where in the textile value chain eco-design requirements should be implemented to mitigate the production of textile products with a high propensity to shed fibre fragments. In order to investigate this potential approach, various yarn types were converted into fabrics and subjected to a range of wear and tear tests following standardized protocols, including washing, abrasion, linting and pilling.

2. Material and Method

2.1 Materials

The yarns utilized in the study consisted of polyester, or viscose yarns, as outlined in Table 1. The primary objective was to evaluate the fragmentation of fibres derived from a single synthetic material as well as a man-made fibre, in order to investigate the potential impact of yarn type to shedfibre fragments. .

2.2 Fabric Construction

All the fabrics used in the study were manufactured in house, at the Swedish School of Textiles. The knitted fabrics were knitted using an industrial standard Mayer & Cie (type OVJA 1.6 EE) circular-knitting double-jersey machine with E20 gauge (Figure 4). The structure used in this investigation was the interlock as commonly used in knitwear. The woven fabrics (plain or twill) were made on a CCI sample weaving machine (CCI Tech, Taipei, Taiwan). For detailed information about the fabric's specification, see Table 1.

Figure 4. Weaving machine from CCI (left), circular-knitting double-jersey machine Mayer & Cie in the (middle) and laboratory washing machine from Wascator FOM71 (right), all at the University of Borås.

All fabrics underwent a prewashing process using a Wascator FOM71 laboratory washing machine (Figure 4), following the guidelines outlined in ISO 6330 (*Domestic washing and drying procedures for textiles testing)*. The prewashing was conducted at 60°C to eliminate spin oils, foreign fibre matter, and other forms of contamination from the fabrics. Prior to and between the prewashing cycles, the washing machine was run at 90°C for a duration of 70 minutes, using 10 ± 0,5 grams phosphorous-free, type A powder reference detergent (Non-Phosphate Reference, Detergent A, James Heal, England). Following the prewashing, the fabrics were air-dried and subsequently wrapped in aluminium foil for storage before being utilized for further experiments.

2.3 Yarn Hairiness test

The hairiness of the polyester spun yarn (P-SY) and polyester filament (P-F48) yarn was determined using the ASTM D5647 (*standard guide for measuring hairiness of yarn by the photo-electric apparatus*) test method on a Mesdan S.p.A MT (Puegnago sul Garda, Italy) hairiness tester. A test length of 100 m was fixed for measuring the hairiness, (H) while the take-up roller speed was maintained at 30 m/min. The fibre measuring length was set at 1 mm. To ensure statistical reliability, ten tests were conducted per sample.

2.4 Wear simulation using ICI pilling-box

The initial wear simulation of all fabrics was conducted using an ICI pill box apparatus (James H. Heal & Co. Ltd, Halifax, England), following the standardized procedures outlined in the SS-EN ISO 12945-1:2020 for the determination of fabric propensity to surface pilling, fuzzing or matting. The ICI-pilling box apparatus (Figure 5) is commonly used for knitted fabric and is designed to gently rub the test specimens against each other and the cork-lined body of the box to stimulate wear.

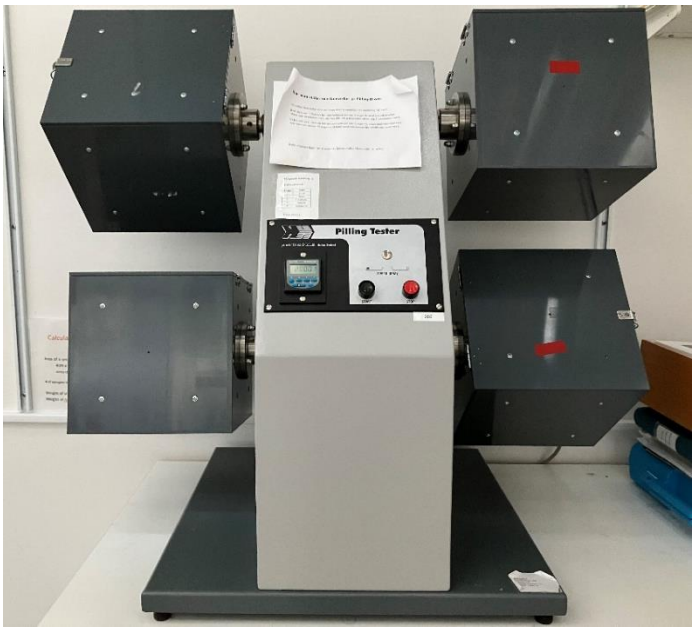


Figure 5. ICI pilling box from James H. Heal & Co. Ltd at the University of Borås

Four specimens, each measuring 125 mm x 125 mm, were cut from the fabric and folded inwards before being securely sewn using a sewing machine at a distance of 12 mm from the edge. Subsequently, the sewed samples were everted, ensuring that the front side faced outwards, and then placed on polyurethane sample tubes, which were secured in place using PVC tape. Prior to commencement of the experiment, the pilling box was meticulously cleaned using a vacuum cleaner, and circular double-glued tape (d=24 mm) was fixed to the centre of each wall within the box (Figure 6).

To minimize loose fibres, the four sets of tubes were gently blown with air before being positioned in the pilling box. The ICI pilling test was initiated, and the fabrics underwent 18,000 rotations during the test. The test was conducted as a controlled temperature of 20°C ± 2°C and RH of 60 ± 10%. Following the completion of the test, the tape was removed and carefully placed between transparency paper for further analysis.

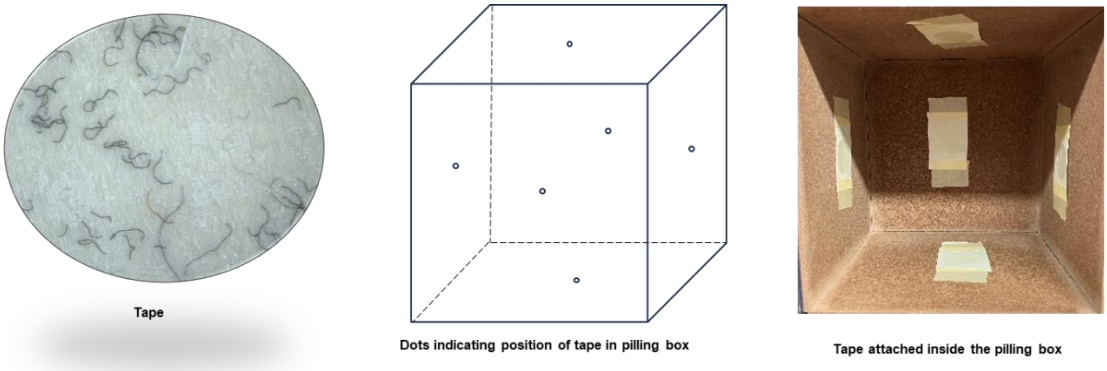


Figure 6. *Schematic representation of the ICI-Pilling box and the positioning of the tape for collecting released fibre fragments during the testing.*

Table 1. Yarn and fabric specification. P = polyester (synthetic yarn). V= viscose (regenerated yarn). SY = spun yarn. F = multifilament. r = recycled. -T = twill (a weave construction). –P = plain (a weave construction). Z = twist direction (where that yarn follows the direction of the middle part of the letter "Z")

Abbreviation	Material	Yarn number		Yarn type	Yarn Twist [Twists per meter]	Tensile strength [cN/dtex]	Yarn Manufacturer	Fabric construction	Fabric weight [g/m^2]	Included in test
		Nm	dtex							
P-SY	Polyester	51/1	-	Spun yarn (Ring spinning)	Z - 600	19,7 ± 2,5	PT. Indorama Synthetics Tbk.	Interlock	160	2.3, 2.4. 2.5, 2.6, 2.7, 2.8
P-F48	Polyester	-	167/48/1	Filament yarn	-	32,5 ± 1,0	Cofitex S.A Spain	Interlock	130	2.3, 2.4. 2.5, 2.6, 2.7, 2.8
P-F144	Polyester	-	167/144/1	Filament yarn	-	39,6 ± 4,8	Cofitex S.A Spain	Interlock	140	2.4
rP-F48	Chemical Recycled Polyester*	-	167/48/1	Filament yarn	-	38,2 ± 2,9	Cofitex S.A Spain	Interlock	140	2.4
V-SY	Viscose	51/1	-	Spun yarn (Ring spinning)	Z - 600	15,1 ± 1,5	Cofitex S.A Spain	Interlock	140	2.4
V-F44	Viscose		167/44/1	Filament yarn	-	15,2 ± 2,1	Cofitex S.A Spain	Interlock	130	2.4
P-F48-T	Polyester	-	167/48/1	Filament yarn	-	32,5 ± 1,0	Cofitex S.A Spain	1/3 Twill	90	2.4
P-F48-P	Polyester	-	167/48/1	Filament yarn	-	32,5 ± 1,0	Cofitex S.A Spain	Plain	80	2.4

* *Chemical recycled polyester from PET.*

2.5 Wear simulation using Martindale

A 6-station Martindale tester (James H. Heal & Co. Ltd, Halifax, England) was used to conduct rubbing test on fabric samples, following the procedure from SS-EN ISO 12945-2:2000. To ensure that all shedded fibre fragments analysed originated from the same source, identical fabrics were utilized as both specimens and abradants, representing a deviation from the ISO method. Leather sheets with a thickness of 1.5 mm were employed as substitution for the standard woven felt textile and polyether urethan foam materials, serving as the base underlays for the abradant and specimen. This substitution was implemented to prevent the introduction of extraneous fibres into the test system. Prior to the experiment, the apparatus underwent a thorough cleaning process, including washing, rinsing, and drying, to maintain optimal experimental conditions. Furthermore, to minimize potential contamination a custom-made Plexiglas box was built to cover the Martindale in order to preventing the influence of external fibres on the test results.

The pilling test was conducted under a pressure of 12 kPa and test was done at 1000, 5000, 7000 and 14000 cycles, in contrast to the standard protocol which recommends stopping after 7000 or 14 000 cycles. After the pilling experiment, tape was positioned at the centre of the lower holder in the Martindale, and a pressure of 12 kPa was applied for 10 seconds before the pressure and tape were removed (Figure 7). This step was designed to collect loose fibres and fibrils present on the fabrics surface. The collected tape samples were then placed between two transparent papers for further analysis. Quadruplets (n=4) were performed for each fabric type, and the test order of the fabrics was randomized to mitigate potential biases.

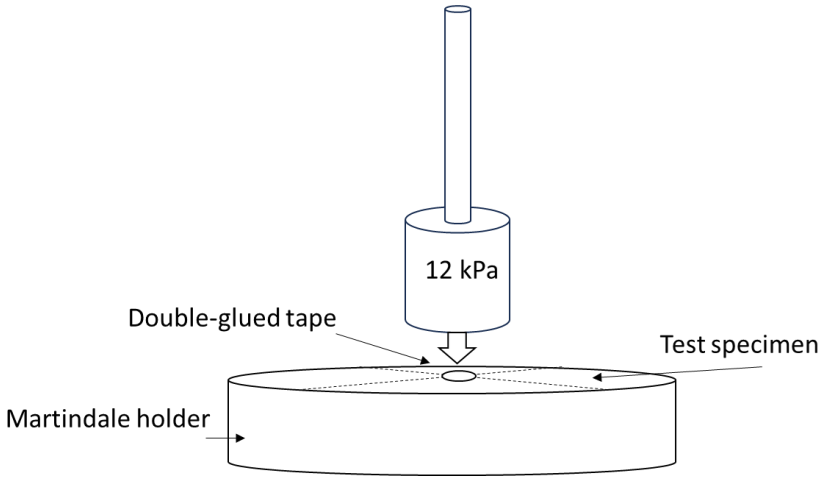


Figure 7. *Schematic representation of the Martindale pilling experiment and the positioning of the tape for collecting released fibre fragments after the testing.*

2.6 Microscopic analysis of shedded fibre fragments

The assessment of microplastic fibres was conducted using an optical microscope. Each tape specimen underwent analysis Nikon SMZ800 and NIS-Element image analysing software following calibration.

The microscope operated at a magnification of x1. Subsequently, the obtained images were subjected to area fraction analysis of the fibres adhering to the tape using Image J version 1.54d. After opening the image in Image J, the image was converted to binary mode and calculating the area fraction (Figure 8).

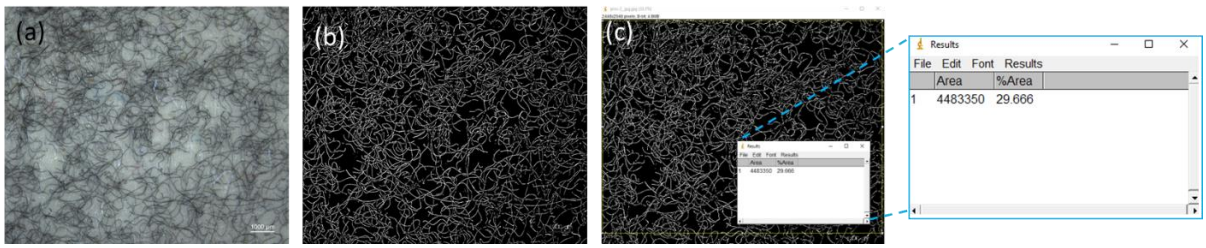


Figure 8. *Illustration of the process analysing the optical microscope image and calculate the area fraction [%]. Image (a) depicts the original microscope image, which was subsequently converted to black and white (binary mode) as shown in image (b). The area fraction of the fibres was then calculated using Image J, as demonstrated in image (c).*

2.7 Fibre fragment shedding during linting test

The assessment of fibre lint release from the polyester spun yarn (P-SY) and polyester filament (P-F48) knitted fabric was conducted in accordance with the standard SS-EN ISO 9073-10:2005 "*Textiles - Test methods for nonwovens*". Pre-conditioned fabrics were carefully positioned within a closed, dust-free chamber to minimize external interference and were subjected to controlled movement to induce particle release. The released particles, spanning a size range from 0.3 µm to > 25 µm, were quantified and characterized using MET ONE 3400 particle counter manufactured by Beckman Coulter, Inc United State. 10 samples were tested per material, five specimens on each side.

2.8 Fibre fragment shedding during laundry

The determination of fibre loss from the polyester spun yarn (P-SY) and polyester filament (P-F48) knitted fabrics during washing was carried out in accordance with the guidelines outlined in SS-EN ISO 4484-1:2023. A total of four specimens were utilized for the experimental procedure. Prior to washing each specimen's edge was folded into a double rolled hem (type 6.03.01) and secured by stitching along all edges using lock stitch type 301 and 100% polyester continues filament yarn. The washing was conducted at a temperature of 40 °C, utilizing 360 mL of water, with a duration time of 45 minutes. A single wash cycle was performed, with the inclusion of 50 steel balls. No washing detergent was utilized during the experimental procedure. For the subsequent analysis, a Whatman Glass fibre filter, GF/A, CAT No: 1820-047, with a 1.6 µm pore size and 47 mm diameter was employed. The analytical balance utilized for the measurement was a Kern & Sohn, ABJ 80-4M, WB1030109, with a precision of 0.1 mg. The percentage of fibre fragment release of each specimen was calculated using the equation:

$$\mathrm{Pf} = \frac{Mf}{Sm1}\ x\ 100 \qquad (1)$$

Where:

P_f = percent of fibre released (%)

M_f = mass of fibre released (g)

S_{m1} = mass in grams of specimen before testing (g)

3. Results

3.1 Fibre fragment shedding during wear simulation using ICI Pilling-box

In the conducted study, all fabric samples underwent testing utilizing the ICI pilling test to simulate wear conditions. To capture the microfibres released during the test and gain insights into the significance of yarn construction, the method involving double glued tape was designed for collection. This approach aimed to provide an understanding of the fabric's performance under simulated wear, shedding light on the impact of yarn structure and fibre fragment release during gentle abrasion.

The first test aimed to compare the release of fibre fragments from polyester spun yarn (P-SY) with filament yarn of the same linear density of 167 dtex but with different numbers of filaments in the yarn, specifically 48 (P-F48) and 144 (P-F144). The results, as shown in figure 9a and 9b, clearly indicate that the spun yarn releases more fibre fragments compared to the filament yarn. Furthermore, the results also demonstrate that there was no significant difference in the release of fibre fragments between yarns made from 48 or 144 dtex. To ensure the reliability of the results, the area fraction was normalized with the fabric weight, as illustrated in figure 9b.

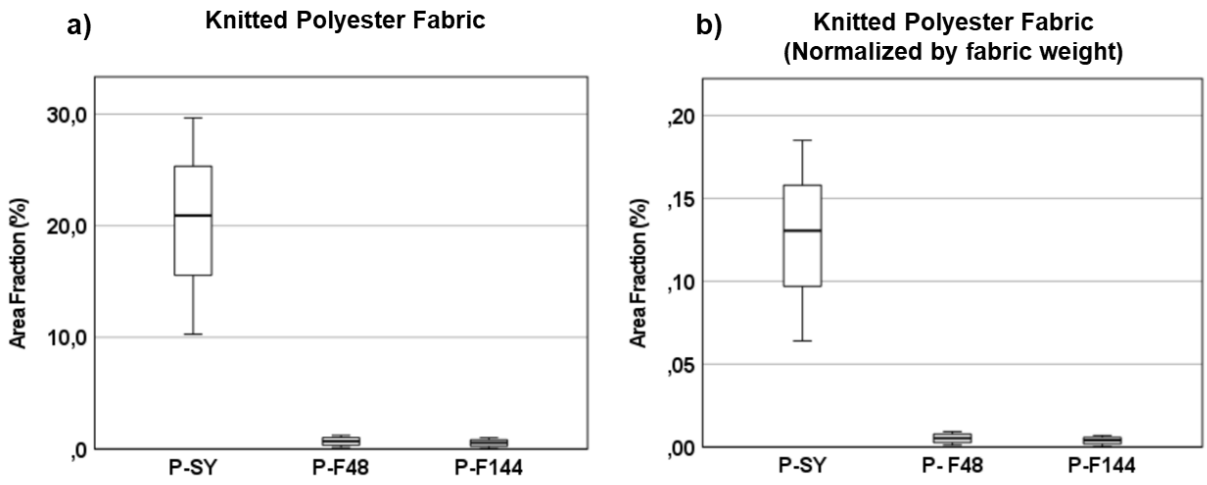


Figure 9. *Box plot illustrating the percentage of the area fraction corresponding to the release of fibre fragments from knitted polyester fabric. The fabric samples were produced using spun yarn (P-SY) and filament yarn with a*

linear density of 167 dtex, derived from 48 filaments (P-F48) or 144 filaments (P-F144). Panel a) presents the area fraction percentage of the shedded fibre fragments, while panel b) depicts the area fraction percentage normalized with respect to the fabric weight. The box plot visually represents the distribution of fibre shedded across the different yarn compositions, with the central line indicating the median value, the box encompassing the interquartile range, and the whiskers extending to the minimum and maximum values.

In the subsequent test, the impact of fabric construction was assessed using polyester filament yarn (P-F48), and the outcomes are shown in Figure 10. The findings illustrate the significance of fabric construction in relation to fibre fragmentation during simulated wear. While the woven fabric's construction, whether twill or plain, has relatively minor effect, it is evident that knitted fabric releases a greater quantity of fibre fragments. The results confirm that loose fabric constructions, such as knitted fabric, shed a significant greater quantity of fibre fragments despite being made of filament yarn.

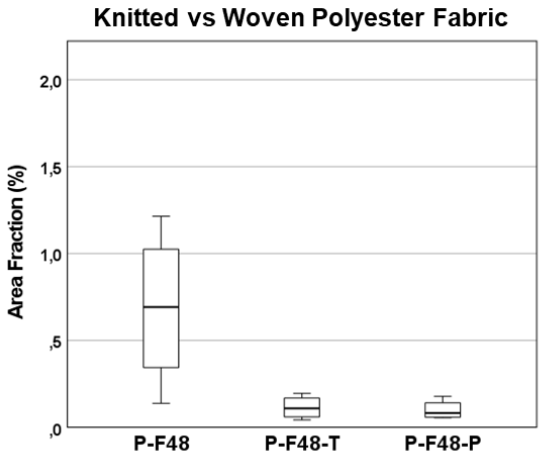


Figure 10. *The box plot visually represents the proportion of area fraction attributed to the fibre fragments shedding from knitted polyester fabric (P-F48) and woven polyester fabric constructed in either twill (P-F48-T) or plain (P-F48-P) weaves. These fabrics were manufactured using identical filament yarn with linear density of 167 dtex, derived from 48 filaments.*

The fibre fragmentation during simulated wear of knitted fabrics made of polyester filament yarn (P-48) was additionally compared to a recycled filament yarn (rP-F48), with the results presented in Figure 11. The recycled polyester yarn shed a significantly higher amount of fibre fragments compared to the primary, also known as virgin, filament yarn. This is somewhat surprising as the yarn's tensile strength is higher for the recycled yarn compared to primary yarn, i.e., 38 cN/dtex vs 32 cN/dtex.

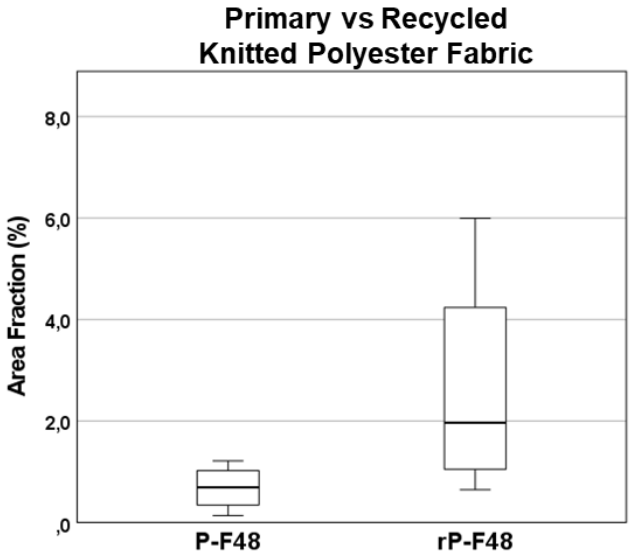


Figure 11. *The box plot visually represents the proportion of area fraction attributed to the fibre fragments shedding from knitted polyester fabric manufactured with primary yarn (P-F48) and knitted polyester fabric manufactured with chemical recycled yarn (rP-F48). Both fabric types were produced using filament yarn with a linear density of 167 dtex, derived from 48 filaments.*

In order to determine whether the yarn construction had a comparable impact when derived from a material other than polyester, fabrics made from viscose yarn were examined. One yarn was made from a spun yarn (V-SY), and the other from a filament yarn (V-F48). The results illustrated in Figure 12, indicate that the spun yarn has a greater propensity to shed fibre fragments compared to filament yarn. This once again underscores the significance of yarn construction in studying the phenomenon of fibre fragmentation.

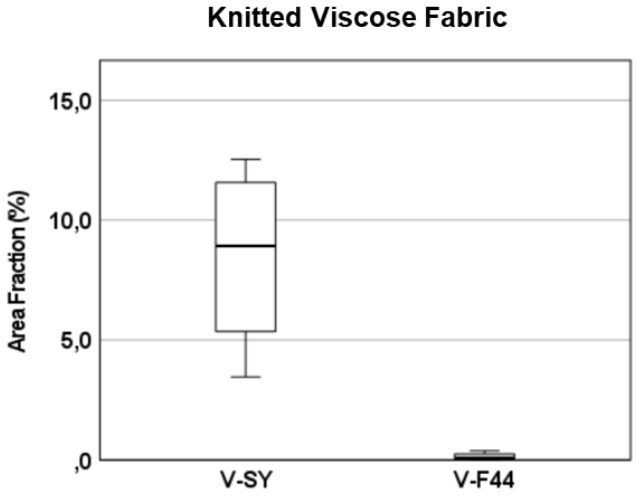


Figure 12. *Box plot illustrating the percentage of the area fraction corresponding to the release of fibre fragments from knitted viscose fabric. The fabric samples were produced using spun yarn (V-SY) and filament yarn with a linear density of 167 dtex, derived from 48 filaments (V-F48).*

3.2 Comparative analysis of knitted polyester spun yarn and filament fabrics

3.2.1 Yarn Hairiness

Consistent with expectations a noticeable disparity in yarn hairiness was evident between the polyester filament yarn and the polyester spun yarn, as illustrated in figure 13. This observation aligns with the findings of the yarn hairiness test (refer to table 2), indicating a higher level of hairiness in the spun yarn compared to the filament yarn.

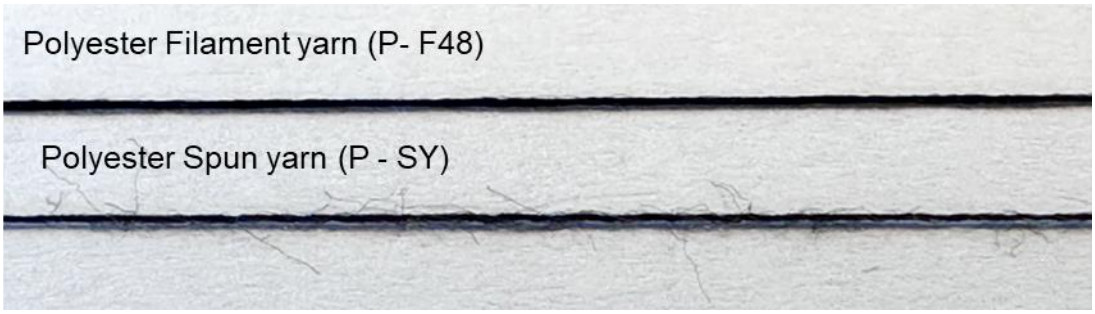


Figure 13. *Single yarn strand image of polyester filament yarn 167 dtex (P – F48) and polyester spun yarn (Nm 51/1 (P-SY)). The image shows protruding fibre ends from the spun yarn.*

Table 2. Yarn hairiness (H) results of polyester filament yarn (P-F48) and polyester spun yarn (P-SY)

Sample	Yarn number	CV (%)	Hairiness (H)
P-F48	167 dtex	3,74	1,70
P-SY	Nm 51/1	13,31	2,75

3.2.2 Fibre fragments shedded during wear simulation using Martindale

The results comparing shedding behaviour between polyester spun yarn (P-SY) and polyester filament yarn (P-F48) using the Martindale test to simulate are shown in Figure 14. The shedding of fibre fragments was quantitatively evaluated at various intervals during the Martindale test. The data revealed a consistent pattern where the spun yarn polyester fabric exhibited higher shedding rates compared to the filament yarn fabrics across all cycle counts. This trend persisted regardless of the test duration, indicating a fundamental difference in fibre shedding behaviour between the two yarn types.

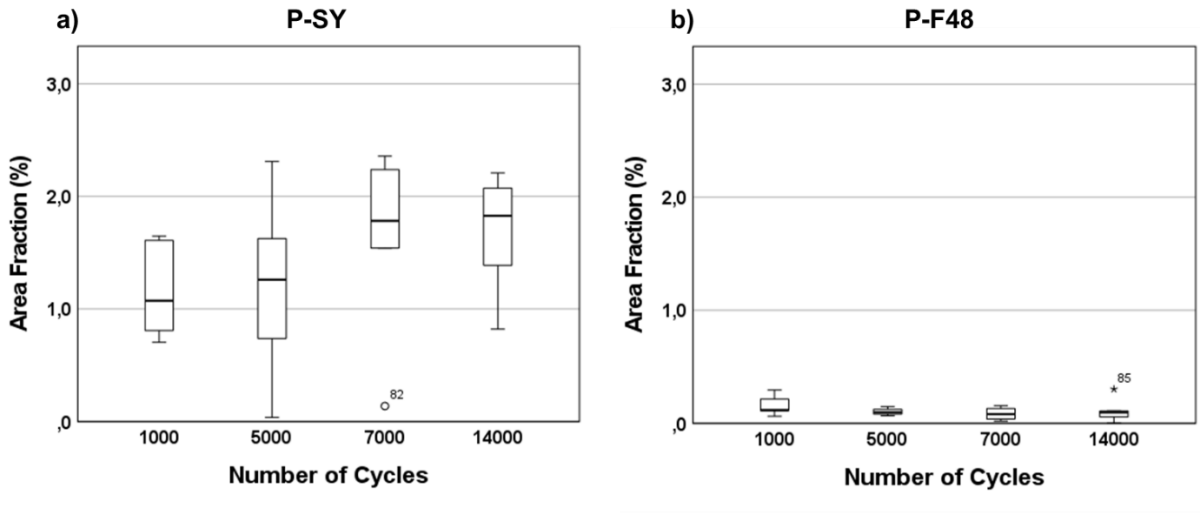
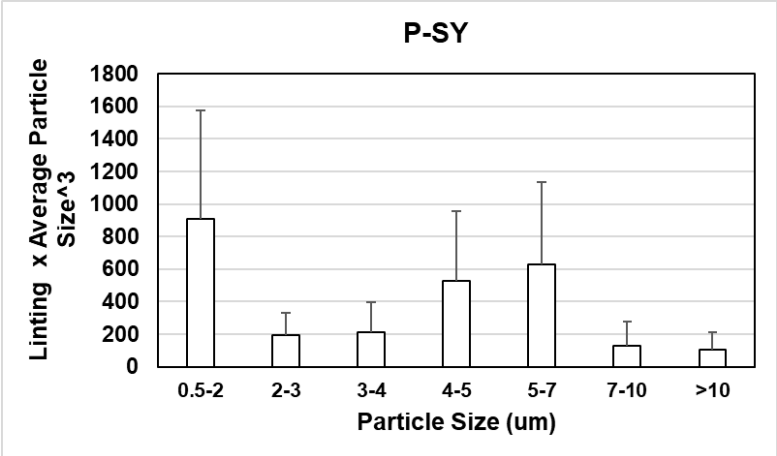


Figure 14. *Shedding propensity between the two types of polyester yarn, a) spun yarn (P-SY) and b) filament yarn (P-F48). The results consistently demonstrate that spun yarn polyester knitted fabric shed more fibres than filament yarn knitted fabrics, irrespective of the number of cycles.*

3.2.3 Fibre fragments shedded during linting test

The results from the linting test are illustrated in Figure 15a and 15b, illustrating the total linting particles generated and released into the air during the test. These findings are of significant interest for several reasons. Firstly, the test results are based on quantifying the *number* of particles released into the air, during movement, and secondly, the particles are categorized based on their *size*. The test's high sensitivity enables the measurement of particle release down to the nano-scale. Figure 15a illustrates that the polyester spun yarn (P-SY) released a significant number of particles in the micrometer range, particularly large particles, based on their mass. However, a notable portion of particles in the *nano size* range of 0.5-2 µm are also released during the test. Particularly intriguing are the results from the polyester filament yarn, as illustrated in Figure 15b, where the fabric predominantly releases particles in the nano size range, with a conspicuous absence of particles in large size categories.



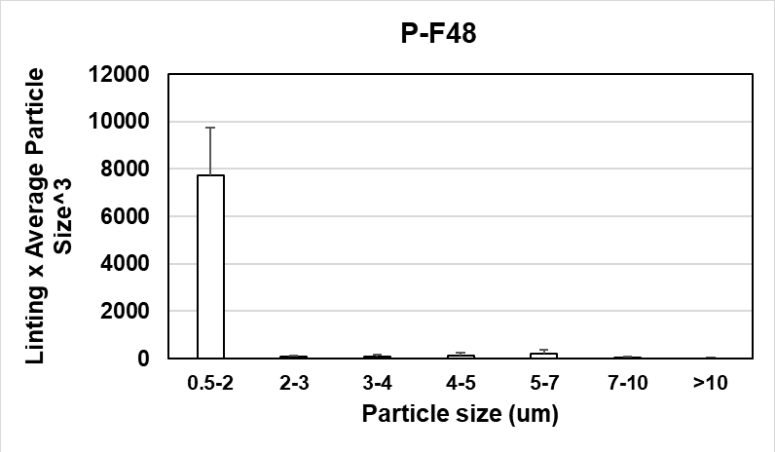


Figure 15. *Lint and other particles were generated in the dry state following testing according to ISO 9073-10:2025. The graph illustrates the number of particles released from knitted polyester fabric manufactured using spun-yarn (a) and from knitted polyester fabric manufactured using filament yarn (b). To represent the mass of the particles, the total number of particles was multiplied by the average particle size^3 within each size group. For instance, the average particle size for each group was determined as follows, e.g., average particle size of group 0,5 – 2 µm = 1,25 µm, 2-3 µm = 1 µm, 4-5 µm = 3,5 µm, 5-7 µm = 6 µm, 7-10 µm = 8 ,5 µm and > 10-25 µm = 17,5 µm.*

3.2.4 Fibre fragments shedded during laundry

The fibre loss results from laundry of two types of polyester fabric (i.e., spun yarn fabric and filament fabric) are presented in table 3, while Figure 16 visually represents the shedded fibres. The results indicate that the knitted polyester spun yarn fabric exhibited a higher number of shed fibres compared to the knitted fabric manufactured from polyester filament yarn.

Table 3. Determination of fibre loss during laundry of knitted polyester spun yarn (P-SY) and knitted polyester filament (P-F48) fabric.

Sample	**Mf** Mass of fibre release (mg)	**Pf** Fibre release (%)
P-SY	1,28 ±0,10	0,013 ± 0,0001
P-F48	0,63 ± 0,05	0,009 ± 0,0008

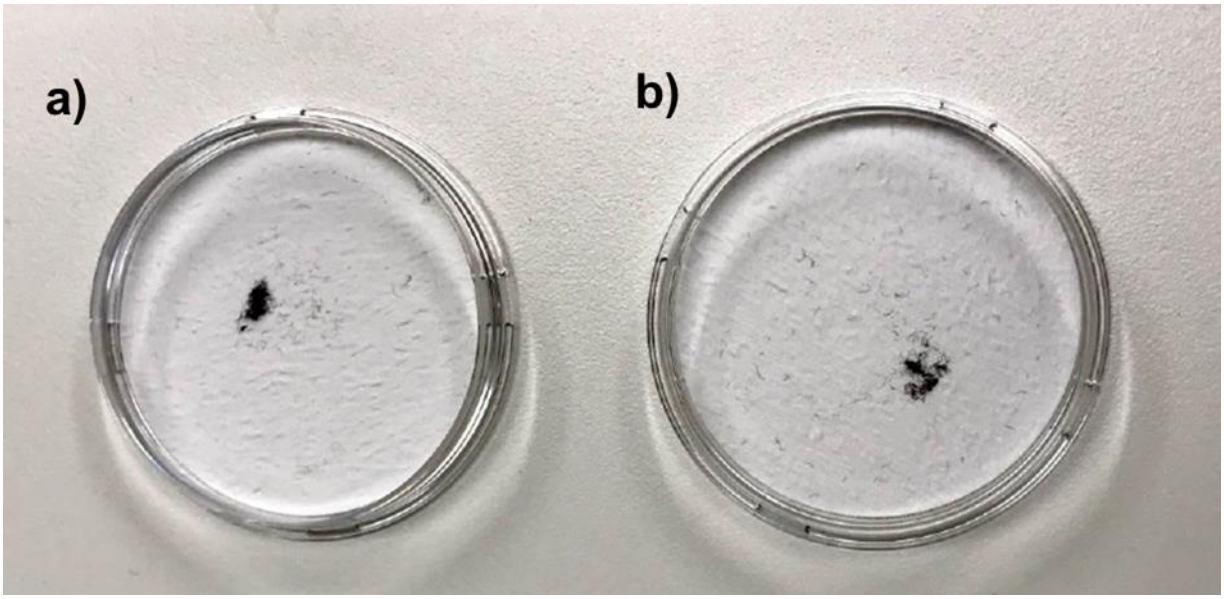


Figure 16. *Visual example of filter tray with fibre from 2) knitted polyester filament (P-F48) and b) knitted polyester spun yarn (P- SY) fabric.*

4. Discussion

This study explores the relationship between fabric and yarn construction and their impact on shedded fibre fragments during simulated wear processes such flat abrasion (pilling, Martindale), flex abrasion (linting) and laundering. A detailed investigation was conducted comparing polyester spun yarn and polyester filament yarn. Our primary hypothesis suggested that fabrics, regardless of their construction and yarn type, would shed fibres over their entire lifecycle, with yarn construction playing a significant role in release of fibre fragments. Additionally, we hypothesized that spun yarn, characterized by short fibres twisted together, would demonstrate a higher propensity for shedding fibre fragments compared to filament yarn. This assumption is of paramount importance given the relatively unexplored influence of textile material structure. Within the realm of microplastics fibres and fibre fragmentation from textiles, a common issue arises where detailed specifications of the composition are lacking, leading to a scarcity of comprehensive descriptions of the textile aliquot necessary for study replication.

The textile matrix is inherently dynamic and offers nearly infinite variability. Expecting the industry to accurately replicate a textile sample becomes challenging when critical information is absent, including the material of polymer type (e.g., polyester, cotton, viscose), yarn count or linear density, fibre length for staple fibres, number of fibres in a yarn for filament fibres, twist per unit length, twist direction, and relevant spinning method details. Ideally, any finishes or post-treatment processing should also be documented. The absence of one or more of these crucial details significantly hampers the reproducibility of a study. Furthermore, the bill of materials in this study remains incomplete. For example, the yarn utilized in the research was sourced from the yarn stock at the Swedish School of Textiles, University of Borås. However, details regarding the yarn such as information pertaining to any

finish applied to the yarn or details on the yarn dyeing process were notable absent. Nonetheless, we maintain confidence that our material specifications (as listed in table 1) are adequately described to validate the data underpinning this study.

The results derived in this study from the wear simulating test utilizing the pilling box consistently demonstrated that spun yarn, regardless of material type, confirmed a greater propensity to shed fibre fragments in comparison to filament yarn (see Figure 9 and Figure 12). This outcome aligns with our initial expectations and is supported by previous studies indicating that filament yarn has stronger fibre cohesion, making it more challenging to dislodge fibres from the fabric construction.[54] Similar findings were observed between knitted and woven fabric, as illustrated in Figure 10, indicating that a tighter structure, such as woven fabric, shed fewer fibre fragments compared to a looser structure, such as knitted fabric. This observation aligns with our previous research findings, where we also demonstrated that looser constructions such as knits tend to be more prone to shedding. [37] Filament yarn and compact structures, such as woven fabrics, are very common in fabrics and garments that require wind- and water resistance. However, compactness becomes a disadvantage when bulk and absorbency are necessary for comfort. [71]

An interesting discovery emerged from the study comparing chemical recycled polyester filament yarn with primary polyester yarn, as shown in Figure 11. The test results revealed a broader distribution of shedded fibres for the recycled polyester filament yarn compared to the primary polyester yarn. While the exact reason for this disparity may vary, it is worth noting that the recycled polyester yarn demonstrated a slightly higher tensile strength, suggesting potential imperfections in the polymer structure can be excluded. Factors influencing fibre cohesion, such as residual spin finish from inadequate pre-cleaning or variations in fibre surface characteristics and, should therefore be considered. The cross-sectional profile of the filament is another parameter to investigate, as different profiles will impact the movement of the individual filament in the yarn. As a result, this can affect the bending properties as well as surface roughness of the fabric.[4] This, in turn, can also give rise to different fibre shedding during the simulated wear test in the ICI pilling box test.

An additional observation from this study reveals that fabrics manufactured from polyester yarn, whether filament or spun yarn, shed more fibre fragments compared to viscose yarn of similar type. This outcome underscores the superior fibre cohesion within the viscose yarn in contrast to polyester yarn.

In the context of abrasion resistance in textiles, the length of fibres plays a crucial role as stated earlier. Longer fibres contribute to improved abrasion resistance by reducing the irregularity of the yarn surface and minimizing fibre ends protruding from the surface. The results from this study have shown that utilizing filament yarn is advantageous in reducing fibre fragmentation at the micro-level. One common method utilized in the textile industry to assess the uniformity of yarn and the presence of fibre ends, is by measuring the yarn's hairiness. A lower hairiness value indicates a more even yarn with fewer ends

sticking out, which is desirable in reducing the shedding of fibre fragments from a fabric.[72, 73] While low hairiness is typically preferred for this reason, it is important to note that some level of hairiness do have positive effects on the fabric. Hairiness contributes to the textile character of the material, providing comfort, skin-friendliness, and not least heat insulation. Fabrics with higher hairiness levels can therefore offer enhanced warmth due in part to the presence of hairiness. [72]

The most notable findings from this study pertains to the results obtained from the linting test, as illustrated in Figure 15, revealing that filament yarn exhibited a significantly higher release of particles in the nano-size range. Unlike the other test conducted in this study, which focused on assessing the shedding of fibre fragment based on mass at specific time points, the linting test specifically quantified the number of particles shed.

Upon excluding particles within the range of 0,2-0,5 µm from the linting test results illustrated in Figure 15, it can be inferred that the outcomes of this test are consistent with the overall findings of the study. Specifically, fabrics manufactured from spun yarn were observed to shed more fibre fragments compared to those made from filament yarn. However, without further investigation, it remains uncertain whether the particles released in the nano-size range originates from fibres, fibrils, spin finish, or residues such as calcium deposits resulting from the use of non-phosphate detergents during washing[3].

The results presented in Figure 15 underscores the importance of delving into the investigation of particles shed in the nano-size range, in addition to focusing on the micro and macro scales as previously examined. With a limited number of samples, it would be interesting to perform the linting test according to ISO 9073-10:2005 in order to study the outcome on different particle levels of textile structures made from various yarn types and materials.

5. Conclusions

In order for the European Union to implement binding design requirements on the fibre and yarn lever under the Eco-design for Sustainable Products Regulation further research is needed. In this study we can conclude that the quality and construction of the studied yarns have an impact on fibre fragment shedding. In order to establish Eco-design requirements, a more comprehensive systematic study, including a design of experiments, is necessary to draw a scientific correlation between yarn construction and microplastic fibre release. The results from this study mark the beginning of this crucial work. The conclusion drawn from this study are as follows:

- Spun yarn tends to shed more fibre fragments compared to filament yarn during simulated wear through flat abrasion test such as pilling and martindale
- Spun yarn also tends to shed more fibre fragments during laundry.

- Viscose yarn, regardless of whether it is spun yarn or filament yarn, sheds less fibre fragments compared to polyester yarn.
- Chemical recycled polyester yarn shows a tendency to shed more fibre fragments compared to primary yarn.

6. Further Recommendations

The findings of this study underscore the need for further research on the yarn quality and its release of fibre fragments into the air. For instance, a more in-depth analysis of the fibre cohesion within the yarn and between the yarn and fabric structures could elucidate the relationship with fibre fragments. Given the propensity of fibre fragments to shed from fabrics throughout their lifecycle, additional studies on airborne fibre fragments are recommended. These fragments have the potential to reach water sources through the air and during wastewater when they are discharged in the sewage, such as during wet floor cleaning. Airborne fibre fragments fibres pose a significant concern due to the challenges in capturing them compared to filtration methods used in water treatment plants. It is also recommended to increase the number of samples being tested including a larger number of yarn types than tested in this study. Other parameters not including in this study is the impact of yarn twist, ply yarn, texturized yarn as well as different yarn types of spun yarn processes.

Enhanced knowledge in the area of airborne fibre fragments is crucial as society transitions towards a circular economy, with an anticipated increase in the use of recycled (mechanical or chemical) material in textiles. Despite the modest finding in this study, it revealed that chemical recycled polyester filament yarn shed more fibres compared to virgin filaments. Further investigation into mechanically recycled yarn is essential, as these yarns are likely composed of shorter fibres, leading to reduced fibre cohesion and potentially easier dislodgment from the surface. Finally, the study suggests a need to explore nano-fibre fragmentation in addition to micro-fibres, as this area remains largely unexplored. More knowledge in this area will support the textile industry in defining which quality parameters should be tested to assess a product's impact on fibre fragment release. The earlier we can specify the requirements in the textile value chain, the better, in order to prevent the production of a large quantity of material that is ultimately tested and determined if it pass a certain design requirement. For instance, the consumer industry could learn from the personal protective clothing industry, which has requirements at both fabric level and on final garment performance.

References

1. European Environmental Agency, Microplastics from textiles: towards a circular economy for textiles in Europe. https://www.eea.europa.eu/publications/microplastics-from-textiles-towards-a
2. Hearle, J. W. S., Textile fibers: a comparative overview. *Encyclopedia of Materials: Science and Technology* **2001**, 9100-9116.
3. Hatch, K. L., *Textile Science*. West publishing company Minneapolis/Saint Paul, 1993.
4. Bueno, M. A.; Aneja, A. P.; Renner, M., Influence of the shape of fiber cross section on fabric surface characteristics. *Journal of Materials Science* **2004,** 39, (2), 557-564.
5. Gliaudelyte, U., Persson, M., Daukantiene, V., Impact of textiles composition, structure, and treatment on microplastic release during washing: a review. *Textile Research Journal* **2024**; 0(0).
6. Choi, S.; Kim, J.; Kwon, M., The effect of the physical and chemical properties of synthetic fabrics on the release of microplastics during washing and drying. *Polymers* **2022,** 14, (16), 3384.
7. Sudheshna, A. A.; Srivastava, M.; Prakash, C., Characterization of microfibers emission from textile washing from a domestic environment. *Science of The Total Environment* **2022,** 852, 158511.
8. Cesa, F. S.; Turra, A.; Checon, H. H.; Leonardi, B.; Baruque-Ramos, J., Laundering and textile parameters influence fibers release in household washings. *Environmental Pollution* **2020,** 257, 113553.
9. Sillanpää, M.; Sainio, P., Release of polyester and cotton fibers from textiles in machine washings. *Environmental Science and Pollution Research* **2017,** 24, 19313-19321.
10. Yang, L.; Qiao, F.; Lei, K.; Li, H.; Kang, Y.; Cui, S.; An, L., Microfiber release from different fabrics during washing. *Environmental Pollution* **2019,** 249, 136-143.
11. De Falco, F.; Di Pace, E.; Cocca, M.; Avella, M., The contribution of washing processes of synthetic clothes to microplastic pollution. *Scientific reports* **2019,** 9, (1), 6633.
12. Celep, G.; Tetik, G. D.; Yilmaz, F., Limitations of Textile Recycling: The Reason behind the development of alternative sustainable fibers. In *Next-Generation Textiles*, IntechOpen: 2022.
13. Choi, S.; Kwon, M.; Park, M.-J.; Kim, J., Analysis of microplastics released from plain woven classified by yarn types during washing and drying. *Polymers* **2021,** 13, (17), 2988.
14. Berruezo, M.; Bonet-Aracil, M.; Montava, I.; Bou-Belda, E.; Díaz-García, P.; Gisbert-Payá, J., Preliminary study of weave pattern influence on microplastics from fabric laundering. *Textile Research Journal* **2021,** 91, (9-10), 1037-1045.
15. Vassilenko, E.; Watkins, M.; Chastain, S.; Mertens, J.; Posacka, A. M.; Patankar, S.; Ross, P. S., Domestic laundry and microfiber pollution: Exploring fiber shedding from consumer apparel textiles. *Plos one* **2021,** 16, (7), e0250346.
16. Carlsson, P.; Singdahl-Larsen, C.; Lusher, A. L., Understanding the occurrence and fate of microplastics in coastal Arctic ecosystems: The case of surface waters, sediments and walrus (Odobenus rosmarus). *Science of The Total Environment* **2021,** 792, 148308.
17. Bourdages, M. P. T.; Provencher, J. F.; Baak, J. E.; Mallory, M. L.; Vermaire, J. C., Breeding seabirds as vectors of microplastics from sea to land: evidence from colonies in Arctic Canada. *Science of the Total Environment* **2021,** 764, 142808.
18. Browne, M. A.; Crump, P.; Niven, S. J.; Teuten, E.; Tonkin, A.; Galloway, T.; Thompson, R., Accumulation of microplastic on shorelines woldwide: sources and sinks. *Environmental science & technology* **2011,** 45, (21), 9175-9179.

19. Gasperi, J.; Wright, S. L.; Dris, R.; Collard, F.; Mandin, C.; Guerrouache, M.; Langlois, V.; Kelly, F. J.; Tassin, B., Microplastics in air: are we breathing it in? *Current Opinion in Environmental Science & Health* **2018,** 1, 1-5.
20. Baresel, C.; Magnér, J.; Magnusson, K.; Olshammar, M., Tekniska lösningar för avancerad rening av avloppsvatten. In IVL Svenska Miljöinstitutet: 2017.
21. Zhao, T.; Lozano, Y. M.; Rillig, M. C., Microplastics increase soil pH and decrease microbial activities as a function of microplastic shape, polymer type, and exposure time. *Frontiers in Environmental Science* **2021,** 9, 675803.
22. Yi, M.; Zhou, S.; Zhang, L.; Ding, S., The effects of three different microplastics on enzyme activities and microbial communities in soil. *Water Environment Research* **2021,** 93, (1), 24-32.
23. Hossain, M. N.; Rahman, M. M.; Afrin, S.; Akbor, M. A.; Siddique, M. A. B.; Malafaia, G., Identification and quantification of microplastics in agricultural farmland soil and textile sludge in Bangladesh. *Science of The Total Environment* **2023,** 858, 160118.
24. European Commision. Communication from the commission to the european parliament, the council, the european economic and social committee and the committee of the regions. https://environment.ec.europa.eu/document/download/74126c90-5cbf-46d0-ab6b-60878644b395_en?filename=COM_2022_141_1_EN_ACT_part1_v8.pdf
25. European Commission, E. Zero pollution action plan https://environment.ec.europa.eu/strategy/zero-pollution-action-plan_en
26. (ECHA), E. C. A. REACH Annex XVII Entry 78. https://echa.europa.eu/documents/10162/a5eaa862-fa4d-2e18-f5a5-3bda98e09ee7
27. Galvão, A.; Aleixo, M.; De Pablo, H.; Lopes, C.; Raimundo, J., Microplastics in wastewater: microfiber emissions from common household laundry. *Environmental Science and Pollution Research* **2020,** 27, 26643-26649.
28. Praveena, S. M.; Syahira Asmawi, M.; Chyi, J. L. Y., Microplastic emissions from household washing machines: preliminary findings from Greater Kuala Lumpur (Malaysia). *Environmental Science and Pollution Research* **2021,** 28, 18518-18522.
29. Kelly, M. R.; Lant, N. J.; Kurr, M.; Burgess, J. G., Importance of water-volume on the release of microplastic fibers from laundry. *Environmental science & technology* **2019,** 53, (20), 11735-11744.
30. Lant, N. J.; Hayward, A. S.; Peththawadu, M. M. D.; Sheridan, K. J.; Dean, J. R., Microfiber release from real soiled consumer laundry and the impact of fabric care products and washing conditions. *PLoS One* **2020,** 15, (6), e0233332.
31. Cotton, L.; Hayward, A. S.; Lant, N. J.; Blackburn, R. S., Improved garment longevity and reduced microfibre release are important sustainability benefits of laundering in colder and quicker washing machine cycles. *Dyes and Pigments* **2020,** 177.
32. Volgare, M.; De Falco, F.; Avolio, R.; Castaldo, R.; Errico, M. E.; Gentile, G.; Ambrogi, V.; Cocca, M., Washing load influences the microplastic release from polyester fabrics by affecting wettability and mechanical stress. *Scientific Reports* **2021,** 11, (1), 19479.
33. Hernandez, E.; Nowack, B.; Mitrano, D. M., Polyester textiles as a source of microplastics from households: a mechanistic study to understand microfiber release during washing. *Environ Sci Technol* **2017,** 51, (12), 7036-7046.
34. De Falco, F.; Gullo, M. P.; Gentile, G.; Di Pace, E.; Cocca, M.; Gelabert, L.; Brouta-Agnesa, M.; Rovira, A.; Escudero, R.; Villalba, R.; Mossotti, R.; Montarsolo, A.; Gavignano, S.; Tonin, C.; Avella, M., Evaluation of microplastic release caused by textile washing processes of synthetic fabrics. *Environ Pollut* **2018,** 236, 916-925.

35. Zambrano, M. C.; Pawlak, J. J.; Daystar, J.; Ankeny, M.; Cheng, J. J.; Venditti, R. A., Microfibers generated from the laundering of cotton, rayon and polyester based fabrics and their aquatic biodegradation. *Mar Pollut Bull* **2019,** 142, 394-407.
36. Napper, I. E.; Thompson, R. C., Release of synthetic microplastic plastic fibres from domestic washing machines: Effects of fabric type and washing conditions. *Mar Pollut Bull* **2016,** 112, (1-2), 39-45.
37. Carney Almroth, B. M.; Astrom, L.; Roslund, S.; Petersson, H.; Johansson, M.; Persson, N. K., Quantifying shedding of synthetic fibers from textiles; a source of microplastics released into the environment. *Environ Sci Pollut Res Int* **2018,** 25, (2), 1191-1199.
38. Cesa, F. S.; Turra, A.; Checon, H. H.; Leonardi, B.; Baruque-Ramos, J., Laundering and textile parameters influence fibers release in household washings. *Environmental Pollution* **2020,** 257.
39. Pirc, U.; Vidmar, M.; Mozer, A.; Krzan, A., Emissions of microplastic fibers from microfiber fleece during domestic washing. *Environ Sci Pollut Res Int* **2016,** 23, (21), 22206-22211.
40. Yang, L.; Qiao, F.; Lei, K.; Li, H.; Kang, Y.; Cui, S.; An, L., Microfiber release from different fabrics during washing. *Environ Pollut* **2019,** 249, 136-143.
41. Hanning, A.; Landin, R.; Rauch, S.; Schellenberger, S.; Jönsson, C. *MinShed, Design solutions for microplastics shedding from textiles*; 2022.
42. Hartline, N. L.; Bruce, N. J.; Karba, S. N.; Ruff, E. O.; Sonar, S. U.; Holden, P. A., Microfiber masses recovered from conventional machine washing of new or aged garments. *Environmental science & technology* **2016,** 50, (21), 11532-11538.
43. Jiang, L.; Yin, M.; Tang, Y.; Dai, R.; Mo, L.; Yang, W.; Liang, Y.; Huang, K., Microfibers shed from synthetic textiles during laundry: Flow to wastewater treatment plants or release to receiving waters through storm drains? *Process Safety and Environmental Protection* **2022,** 168, 689-697.
44. Okubayashi, S.; Bechtold, T., A pilling mechanism of man-made cellulosic fabrics—effects of fibrillation. *Textile research journal* **2005,** 75, (4), 288-292.
45. Cai, Y.; Yang, T.; Mitrano, D. M.; Heuberger, M.; Hufenus, R.; Nowack, B., Systematic study of microplastic fiber release from 12 different polyester textiles during washing. *Environmental Science & Technology* **2020,** 54, (8), 4847-4855.
46. Pušić, T.; Šaravanja, B.; Malarić, K.; Luburić, M.; Kaurin, T., Electromagnetic shielding effectiveness of woven fabric with integrated conductive threads after washing with liquid and powder detergents. *Polymers* **2022,** 14, (12), 2445.
47. Palacios-Marín, A. V.; Jabbar, A.; Tausif, M., Fragmented fiber pollution from common textile materials and structures during laundry. *Textile Research Journal* **2022,** 92, (13-14), 2265-2275.
48. Shibulal, G. S.; Naskar, K., Structurally different short aramid fiber–reinforced thermoplastic polyurethane. *Polymer composites* **2014,** 35, (9), 1767-1778.
49. Lau, L.; Fan, J., Laundry performance of fabrics and garments. *Eng. Appar. Fabr. Garments* **2009,** 1, 339-360.
50. Nayak, R.; Kanesalingam, S.; Houshyar, S.; Vijayan, A.; Wang, L.; Padhye, R., Effect of repeated laundering and Dry-cleaning on the thermo-physiological comfort properties of aramid fabrics. *Fibers and Polymers* **2016,** 17, 954-962.
51. Lee, K. W., Bending analysis of nonlinear material fibers with a generalized elliptical cross-section. *Textile research journal* **2005,** 75, (10), 710-714.
52. Bryant, G. M.; Walter, A. T., Stiffness and resiliency of wet and dry fibers as a functi of temperature. *Textile Research Journal* **1959,** 29, (3), 211-219.
53. Zambrano, M. C.; Pawlak, J. J.; Daystar, J.; Ankeny, M.; Cheng, J. J.; Venditti, R. A., Microfibers generated from the laundering of cotton, rayon and polyester based fabrics and their aquatic biodegradation. *Marine pollution bulletin* **2019,** 142, 394-407.

54. Özdil, N.; Kayseri, G. Ö.; Mengüç, G. S., Analysis of abrasion characteristics in textiles. *Abrasion resistance of materials* **2012**, 119-146.
55. Ogden, T. L.; Bartlett, I. W.; Purnell, C. J.; Wells, C. J.; Armitage, F.; Wolfson, H., Dust from cotton manufacture: changing from static to personal sampling. *The Annals of occupational hygiene* **1993,** 37, (3), 271-285.
56. Bao, L.; Li, D.; Qian, D.; Kemmochi, K.; Yamanaka, A., Measurement and evaluation methods for damage of fibers from dry sand erosion in a hot environment. *Textile Research Journal* **2012,** 82, (15), 1612-1617.
57. Jasinska, I.; Stempien, Z., An alternative instrumental method for fabric pilling evaluation based on computer image analysis. *Textile Research Journal* **2014,** 84, (5), 488-499.
58. Furferi, R.; Governi, L.; Volpe, Y., Machine vision-based pilling assessment: a review. *Journal of Engineered Fibers and Fabrics* **2015,** 10, (3), 155892501501000320.
59. Iroegbu, A. O. C.; Ray, S. S.; Mbarane, V.; Bordado, J. C.; Sardinha, J. P., Plastic pollution: a perspective on matters arising: challenges and opportunities. *ACS omega* **2021,** 6, (30), 19343-19355.
60. Akter, S.; Helali, M. M., The effect of mechanical crimp on the basic properties of jute yarn. *Materials Today: Proceedings* **2021,** 46, 425-432.
61. Goyal, A.; Nayak, R., Sustainability in yarn manufacturing. In *Sustainable Technologies for Fashion and Textiles*, Elsevier: 2020; pp 33-55.
62. Love, R. G.; Smith, T. A.; Gurr, D.; Soutar, C. A.; Scarisbrick, D. A.; Seaton, A., Respiratory and allergic symptoms in wool textile workers. *British journal of industrial medicine* **1988,** 45, (11), 727.
63. Too, C. L.; Muhamad, N. A.; Ilar, A.; Padyukov, L.; Alfredsson, L.; Klareskog, L.; Murad, S.; Bengtsson, C.; My, E. S. G., Occupational exposure to textile dust increases the risk of rheumatoid arthritis: results from a Malaysian population-based case–control study. *Annals of the rheumatic diseases* **2016,** 75, (6), 997-1002.
64. Kuzmickiene, I.; Stukonis, M., Lung cancer risk among textile workers in Lithuania. *Journal of Occupational Medicine and Toxicology* **2007,** 2, 1-5.
65. Lai, P. S.; Christiani, D. C., Long term respiratory health effects in textile workers. *Current opinion in pulmonary medicine* **2013,** 19, (2), 152.
66. Pauly, J. L.; Stegmeier, S. J.; Allaart, H. A.; Cheney, R. T.; Zhang, P. J.; Mayer, A. G.; Streck, R. J., Inhaled cellulosic and plastic fibers found in human lung tissue. *Cancer epidemiology, biomarkers & prevention: a publication of the American Association for Cancer Research, cosponsored by the American Society of Preventive Oncology* **1998,** 7, (5), 419-428.
67. Yuksekkaya, M. E., Fiber Fly Generation of 100% Acrylic yarns during weaving. *Textile Research Journal* **2010,** 80, (6), 508-515.
68. Romano, F.; Milani, S.; Joppolo, C. M., Airborne particle and microbiological human emission rate investigation for cleanroom clothing combinations. *Building and Environment* **2020,** 180, 106967.
69. Truscott, W., Lint fiber–associated medical complications following invasive procedures. *Biomedical Instrumentation & Technology* **2023,** 57, (s1), 5-10.
70. Watts, E. J.; Aerospace Corp El Segundo Ca Lab, O. In Garment selection for cleanrooms and controlled environments for spacecraft, *Institute of Environmental Sciences, Annual Technical Meeting*, 37 th, San Diego, CA, 1991; 1991.
71. Kadolph, S., Textiles. *Pearson New International Edition* Edinburgh Gate, 2014.
72. Periyasamy, A. P.; Tehrani-Bagha, A., A review on microplastic emission from textile materials and its reduction techniques. *Polymer Degradation and Stability* **2022,** 199, 109901.
73. Żurek, W., Fiber length distribution as a function of the number of fibers in a cross section of a yarn. *Textile Research Journal* **1962,** 32, (4), 255-257.