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and Ingun Grimstad Klepp

Microplastic pollution from textiles: A literature review

SIFO
Consumption Research Norway

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UNIVERSITY COLLEGE
OF APPLIED SCIENCES

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Sammendrag

Formålet med rapporten er å gi en oversikt over dagens kunnskap om forurensning gjennom spredning av mikroplast. Vi fokuserer på mikroplastiske fibre (mikrofiber) fra tekstiler. Rapporten er en del av et større arbeid med å bedre inkluder klærs bruksfase i livssyklusanalyser (LCA). De siste ti årene har oppmerksomheten mot spredning av mikroplast. Det er nå signifikant bevis for negativ påvirkning på liv i vann, mens mindre er kjent om innvirkning på menneskers helse. Estimater antyder at så mye som 20% til 35% av alle primære mikroplastkilder i havmiljøet var fibre fra syntetiske klær, og mengden øker.

Mikrofiber spres gjennom primære kilder som inkluderer fiber som løsner fra syntetiske klær og tekstiler under bruk og vask eller gjennom sekundære kilder, hovedsakelig nedbrytning og fragmentering av syntetisk tekstilavfall. Syntetiske fibre utgjør nå mer enn 60% av den globale tekstilproduksjonen. Rapporten evaluerer nåværende forståelse av nivået av mikroplast, inkludert mikrofiber fra tekstilforurensning og dens innvirkning. Den oppsummerer kunnskap omkring hvilke tekstiler og vaskemetoder som bidrar til mest spredning, og drøfter hvordan problemet omkring mikrofiber kan trekkes inn i livssyklusanalyser. Det gir også råd om mulige strategier for å redusere forurensning av mikrofibre i tre kategorier:

1. Redusere produksjon og forbruk av klær
2. Forbedre forbrukspraksis i bruksfasen av syntetiske plagg
3. Erstattet bruk av syntetiske fibre med naturlige fibre.

Summary

The objective of this report is to give an overview of the current state of knowledge concerning microplastic pollution. We focus on microplastic fibres (microfibres) from textiles. The review is a part of a larger work towards better accounting for the use phase in Life Cycle Assessment (LCA) of apparel. Microplastic pollution of marine and freshwater environments has been identified as of concern for only about two decades, but there is now significant evidence of negative impacts on aquatic habitats and marine organisms, while less is known about impact on human health. Estimates suggest that as much as 20% to 35% of all primary source microplastics in the marine environment were fibres from synthetic clothing, and the amount is increasing.

Microfibres can enter the environment through primary sources that include fibres shed from synthetic apparel and textiles during use and washing or through secondary sources, predominantly degradation and fragmentation of larger pieces of synthetic textile waste. More than 60% of global textiles are now produced from synthetic fibres. The report reviews current understanding of the level of microplastic, including microfibres from textiles pollution, and its environmental impacts. It summarizes knowledge of which textiles and washing methods appear to contribute more significantly, and discusses challenges of including the microfibre problem in LCA studies of apparel and textiles. It gives a preliminary synthesis of strategies to reduce pollution of microfibres in three main categories:

1. Reducing production and consumption of clothing
2. Improving consumer practices in the use phase of synthetic garments
3. Replace use of synthetic fibres with natural fibres where possible.

Stikkord
Mikroplast, mikrofiber, bruksfase, klær, tekstiler, klesvask, LCA, livssyklusanalyse, syntetiske fiber, litteraturgjennomgang

Keywords
Microfibres, microplastic, use phase, apparel, clothing, textiles, laundry, LCA, synthetic fibres, literature review

Microplastic pollution from textiles:
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Preface

Australian Wool Innovation Limited (AWI) has commissioned Beverley Henry from Queensland University of Technology, Australia and Kirsi Laitala and Ingun Grimstad Klepp from Consumption Research Norway (SIFO) to conduct a literature review with the purpose of summarising current information on microfibre pollution from textiles and to evaluate the potential to include this environmental impact category to textile LCAs. We also gratefully acknowledge co-funding of the study provided by Cotton Research and Development Corporation.

The work has been done in close cooperation with Angus Ireland from AWI, Allan Williams from CRDC and Stephen Wiedemann from Integrity Ag Services, and we would like to thank them for good comments and follow-up during the project. We would also like to thank Tone Skårdal Tobiasson from nicefashion.org.

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Abstract

Microplastic particles, including the subset, microsynthetic fibres commonly referred to as microfibres, are now ubiquitous in aquatic and terrestrial ecosystems globally. Without active intervention, the abundance of these particles <5mm in diameter is set to increase as consumption of plastics and use of man-made fibres in clothing expands to meet rising demand as world population and regional incomes grow. Microplastics can enter the environment through primary sources, which include tyre abrasion on road surfaces, fibres shed from synthetic apparel and textiles during washing and plastic microbeads from cosmetics and other personal cleaning products, or through secondary sources, predominantly degradation and fragmentation of larger pieces of plastic waste.

As yet, the impacts of microplastic pollution in the environment are not well understood, but there is growing evidence that ecosystem impacts potentially occur through both physical and chemical pathways. Physical effects occur when organisms ingest microplastic particles or fibres mistaking them for food with consequently lower intake of essential nutrition due to gut-fill. Chemical impacts may be direct when harmful compounds are leached from plastic (sometimes referred to as plastic toxicity) or indirect via adsorption of chemicals in solution onto the hydrophobic surface of microplastics which can be ingested by organisms and released or transferred up the food chain. Fibre-shaped microplastics appear to be of greater environmental consequence than more regular shaped particles due to a tendency for entanglement in the digestive tract that can lead to blockages and higher chance of compromised growth, reproduction or even starvation. Chemical impacts may also be enhanced since the larger surface area of fibres potentially allows greater sorption of harmful compounds and a higher retention in the gut allows more time for leakage of plastic additives. Organic contaminants of concern include polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons, petroleum hydrocarbons, organochlorine pesticides, polybrominated diphenyl ethers alkylphenols and bisphenol A.

While research is only beginning to provide any clarity on the potential for humans to be exposed to physical, chemical or biological risks from microplastics in the environment, concern is growing as evidence for exposure increases. There are three main mechanisms for impacts on human health:

(1) Microplastics may enter the human body through the food chain and drinking water with a small proportion thought to be retained. As for other organisms, textile microfibres may pose a higher risk than other particles due to their shape;
(2) The high relative surface area of microfibres and its hydrophobic nature facilitates adsorption of chemicals from surrounding water, raising the risks of human exposure to sorbed carcinogenic and non-carcinogenic compounds when consuming seafood;
(3) Biological risks occur when microplastics host bacteria, including some linked with human gastrointestinal infections.

Despite uncertainty due to the lack of standard measurement and monitoring protocols, experimental results quantifying microfibre loss during washing of synthetic clothing provide an indication of the scale of the global environmental problem with increasing consumption of synthetic clothing. Factors affecting the abundance of fibres in washing machine effluent include the type and quality of the fabric, age of the garment, type of washing machine (top-loading vs front-loading) and filters and the effectiveness of sewage waste-water treatment plants. A study by Bren School of Environmental Science & Management, University of California for Patagonia stressed the need for "further research on shedding characteristics of apparel and the development of mitigation measures by producers, consumers, waste managers, and policy makers towards addressing the issue of microfibre pollution." There is a fundamental need for standardised procedures for sampling, quantifying and monitoring microplastic prevalence in habitats

and methods for assessment of impacts on ecosystem and human health in order to assemble robust data for mitigation responses.

Life cycle assessment (LCA) is the tool most widely applied to monitoring environmental performance of products but review of the literature revealed no LCA studies that have attempted to include impacts of microplastic pollution. We discuss the research and data needs for development of methods to assess environmental impacts and encourage better performance through initiatives such as the Sustainable Apparel Coalition's Higg Index. Current LCA methods for estimating eco-toxicity and human toxicity categories provide a possible avenue for including chemical impacts when data become available, but preliminary evaluation indicates that physical impacts would require a new approach to develop a suitable indicator for the range of microplastic particles and fibres entering terrestrial, freshwater and marine ecosystems.

In summary, more research is needed to better understand the contributions to microplastic pollution from textiles, and effective options for management and mitigation. However, work to date provides some insights, including:

- Manufacturers and consumers of synthetic textiles should invest in higher quality garments which appear to shed less in the wash than low-quality products, and which are constructed to be more durable so are used longer and kept out of landfill hence reducing secondary sources of microplastics.
- Use of front-loading washing machines and gentler cycles are preferred as they result in lower fibre shedding than alternative laundry practices.
- Shedding of microfibres will likely be lower if garments are washed less often with milder detergents.
- Developing technology such as improved filters in washing machines together with education of consumers and businesses on their management will reduce the amount of microfibres entering laundry effluent.
- Wastewater treatment plants filter much of the microfibre load from effluent but the range of effectiveness varies from 65–92 % offering significant scope for reduction in amounts released into the environment through improvements in lower-end facilities.
- A key action to reduce microsynthetic fibre pollution must be maximising the proportion of natural fibre in global textile products since there is evidence that these biodegrade relatively rapidly and do not accumulate in the environment in the same way as synthetics such as polyester and nylon.
- In addition to fibre biodegradability, the natural properties of wool apparel and textiles such as odour resistance and stain repellent surface characteristics favour less shedding to the environment due to less frequent, lower impact washing, greater durability, and established pathways for recycling.

Executive Summary

Microplastic pollution – Overview

Microplastics are most commonly defined as particles less than 5 mm at their smallest diameter.

- Plastic production and consumption have increased almost exponentially over the past 50 years with an estimated 200-fold increase in use in that time.
- As availability of plastics has increased and cost has decreased, consumption has grown and the generation of waste has likewise expanded. Plastic degrades slowly to smaller and smaller particles but does not break down to its component elements and so the total amount of waste is growing. It is difficult to quantify this waste because of its dispersed and variable nature. Fragmentation of plastic waste is a secondary source of microplastics. Major primary sources of microplastics, purposeful or inadvertent, arise from tyre abrasion on road surfaces, fibres shed from synthetic clothing during use, particularly washing, and microbeads specifically produced for personal cosmetic and hygiene products.
- Analyses and documentation of the presence of microplastics has focused on aquatic systems (marine and freshwater) and shorelines, but measurements have also been made in terrestrial habitats including agricultural land treated with sludge and effluent from sewage waste water treatment plants (WWTPs), and in household dust.
- Rates of deposition of microplastics in water columns and of accumulation in gyres have been estimated but there is incomplete understanding of the fate and distribution of microplastics once they enter ecological systems and measurements of quantities of particles per volume of water or sediment have been difficult to relate to a source. However, several studies have concluded that they are now very likely to be ubiquitous in marine environments.
- The environmental impacts of microplastics in any habitat are not well-understood but are likely to be related to abundance, size, shape and encounter rates, and there is evidence for physical, chemical and biological effects from their presence and encounters with organisms.
- Sampling of organisms from zooplankton to filter feeders and vertebrates clearly demonstrates ingestion of microplastics and point to multiple mechanisms of harm.
    - Physical impacts include displacement of food intake and filling the digestive tract, even to the extent of causing starvation.
    - Chemical impacts occur due to microplastics providing a vector for toxic compounds either through release from the plastic itself of substances such as finishes on clothing textiles, or through preferential bonding of organic compounds (persistent organic pollutants, PoPs) and other harmful chemicals to the hydrophobic surface of microplastics.
    - Biological effects may also occur where microplastics host bacteria, potentially exposing organisms to new infection risks.
- The potential for toxins and microorganisms to travel through the food chain is a particular concern for ecosystem health and for human health. Research on the human health implications of consumption of seafood and drinking water contaminated by microplastics and on respiratory intake of airborne particles and fibres is still in its infancy.

Microplastic fibres

Microplastic fibres (also referred to as microfibres or microsynthetic fibres) are microplastic particles that are fibrous in shape. There is no clear definition of their diameter but it is generally accepted as less than 20 micrometres (1 micrometre (µm) is one-millionth of a metre (m) or one-thousandth of a millimetre (mm)); the length may be greater than 5 mm.

- In this review the term microfibres is used to refer generally to the subset of microplastics and focusses on fibres shed from clothing made from synthetic fabrics. The term 'microfibre' has also been used specifically for synthetic fibre finer than one denier or decitex e.g. used in microfibre fabrics such as fine polyester or polyamides. These fabrics may also contribute to microplastic pollution but in this review, we do not use the word with this meaning. Rather, we examine the broader issue of microscopic fibres from any plastic source.
- More than 60% of global textiles are now produced from synthetic fibres. Based on reported analyses, microfibres appear to be ubiquitous in marine, freshwater and sediment habitats and recent studies provide evidence that microfibres preferentially accumulate at high concentrations in deep sea sediments. Microfibres dominate all waste affecting some coastal habitats, notably those close to dense human populations.
- New methods used to detect microfibres can identify the type of fibre. The few studies available indicate that the relative amounts of synthetic material reflect global production, i.e. amounts are dominated by polyester with acrylic and nylon also present. Studies have also identified microfibres of rayon, a cellulosic polymer.
- Experimental measurements of microfibres present on filters, in effluent or other discharge from washing machines have been made, providing an indication of the extent of pollution and potential impact. However, the lack of a standardized approach means these rates cannot be compared directly.
- More data are needed on the role of WWTPs in the release and fate of textile microplastic fibres in the environment. This is especially important where domestic or commercial washing machine effluent enters sewage discharge systems. In addition to developing filters or other methods to exclude microfibres from aquatic systems, methods of disposal of sludge containing trapped microfibres is important for understanding terrestrial contamination. Where sludge has been added to soils or beach sediments, microplastics may persist for decades.
- Microplastics, including fibres, have been found in many studies examining dissected digestive tracts of aquatic organisms and in seabirds that feed on them. There is evidence for microfibres causing a decline in energy for growth, blockages and starvation, and for more subtle effects, including changes in activity, behaviour and reproduction in fish under experimental conditions. These changes indicate likely negative outcomes for survival of individuals and possibly for species in regions of higher exposure.
- Some researchers have speculated on potential impacts on human health through consumption of marine organisms that have ingested microfibres. Specific research on the fibre component of microplastics has not been undertaken although concerns relate to possible intake of toxic compounds such as PoPs or other harmful compounds sorbed onto the fibres.
- There is some evidence for potential intake of airborne textile microfibres in laundry and other household dust but insufficient understanding of how these particles, once in human airways, may affect risks for tumours or other disease outcomes.

Microfibres from natural and manmade textiles

- Manmade plant-based fibres are a special category of textile microfibres that is poorly understood as a source of potential persistent micro-particle pollution. In some studies, they have not been distinguished from petroleum-based plastic fibres, but recent studies have begun to identify fibres of cellulosic polymers separately from synthetic textile fibres. Findings of rayon (viscose) and lyocell microfibres in the stomachs of tiny crustaceans from deep-sea trenches highlights the need for further research on these manmade materials.

- No studies were found that reported the presence of natural plant source or animal fleece fibres from textiles in studies of aquatic microplastic pollution. In some studies methods of analyses were targeting plastic compounds, but several researchers attributed the failure to detect natural fibres to their rapid biodegradation in terrestrial and marine environments rather than failure of analytical techniques.
- Preliminary data found that natural fibres accounted for 37.4% of the total microscopic litter in the digestive tract of terrestrial birds. A decline in the proportion of natural fibres from the oesophagus to stomach to intestine suggested that, unlike synthetic fibres, they may be digestible. This is consistent with terrestrial biodegradation studies but is based on a single study using a small sample size.
- While not all chemicals used in cotton and wool supply chains are harmful, chemicals used in production or finishing of natural fibre clothing may potentially contribute to eco-toxicity or human-toxicity impacts of microplastics. No information was found in the literature search for this review but if potentially harmful chemicals were sorbed onto the surface of microplastics it is possible they could be introduced into ecosystems from natural textiles. Research is required to determine whether wash-out of chemicals used in production of natural fibre textiles (e.g. in dyeing or finishing) occurs, whether these are potentially harmful, and whether they are sorbed onto microplastics.

Microsynthetic fibres and natural fibres in assessment of textile sustainability

- In order to manage the impacts of textile microfibres there is a critical need for robust protocols for quantifying and monitoring fibre losses from garments and their prevalence in the environment. There is also a need for better understanding of the impacts of microfibres on ecosystems and human health. These data and development of indicators of impacts are essential to be able to include this important environmental impact category in sustainability assessment of apparel and textiles and to develop mitigation options.

Potential microfibre mitigation strategies can be grouped into three categories

- *Reducing production and consumption of clothing*: The current ‘fast fashion’ trend results in an enormous volume of waste textiles in landfill. Because synthetics make up the highest proportion, this waste is a growing source of secondary microplastic pollution as garments gradually break down to micro-sized plastic particles;
- *Improving consumer practices in the use phase of synthetic garments*: In the use phase, the abrasive action of washing clothing and other textiles is a primary source of microfibre contamination of the environment, with preliminary evidence that man-made cellulosic fibres may also contribute to persistent microfibre pollution. Practices recommended to reduce microfibre shedding from textiles include:
  - less frequent washing over the life of a garment;
  - gentler, lower chemical use washing; and
  - extending the life of the garment.
- *Avoiding microplastic fibre pollution through increased use of natural fibres:* An effective strategy for consumers to reduce their contribution to microfibre pollution would be to choose garments made from natural fibres which are biodegradable and do not contribute to the build-up of microfibres in the environment.

- Several jurisdictions have now banned the use of microbeads in personal products. A similar regulatory action is not feasible at this time for synthetic clothing due to much stronger societal implications, but there is a possibility of expanded legislative initiatives to help control microplastic pollution.
- Future regulatory or market pressures to restrict microplastics may increase the proportion of clothing from natural fibres. The positive attributes of wool in terms of durability, recyclability and low impact care (less frequent washing, at lower temperatures with less detergent/conditioner) are consistent with strategies to minimize shedding of microfibres to the environment.
- Life cycle assessment (LCA) is the tool most widely applied to monitoring environmental performance of products at this time but, to date, no known LCA studies have included impacts of microplastic pollution and, this review discusses research and data requirements. At this time, development of methods or mid-point indicators for microfibres in LCA is hampered by the data and knowledge gaps for quantifying emissions and understanding mechanisms of action. Current LCA methods for estimating eco-toxicity and human toxicity categories provide a possible avenue for including chemical impacts when data become available. Preliminary evaluation indicates that physical impacts would require a new approach for indicators covering the range of microplastic particles and fibres entering terrestrial, freshwater and marine ecosystems. Key unknowns are whether mass or a count of microfibres is more closely aligned to impacts and the relative importance of aquatic and airborne sources in determining exposure.

Sammendrag (Norwegian summary)

Bekymringen for og kunnskapen om spredning av mikroplast er økende. Det er nå bevis for negativ påvirkning på liv i vann, mens mindre er kjent om innvirkning på menneskers helse. Denne rapporten gir en oversikt over dagens kunnskap om spredning av mikroplast fra tekstiler, også kalt mikrofiber. Den kunnskapen vi har i dag tilsier at så mye som 20% til 35% av primære kildene til mikroplast i havet er mikrofiber fra syntetiske klær og tekstiler. Til sammenligning, andel av mikroplast fra kosmetikk er anslått å være 2 – 3,7%. Mengden mikrofiber er økende. Rapporten evaluerer nåværende forståelse av nivået av mikroplast. Den oppsummerer kunnskap omkring hvilke tekstiler og vaskemetoder som bidrar til mest spredning, og drøfter hvordan problemet omkring mikrofiber kan trekkes inn i livssyklusanalyser (LCA) for tekstiler. Det gir også råd om mulige strategier for å redusere forurensning fra mikrofibre. Rapporten er en del av et større arbeid med klærs bruksfase i livssyklusanalyser (LCA), se rapport «Use phase of apparel: A literature review for Life Cycle Assessment with focus on wool».

Mikrofiber er mikroplast i fiberform

Mikroplast er definert til biter mindre enn 5 mm i diameter. For mikrofiber er det ikke en klar definisjon, men det er vanlig å bruke begrepet om mikroplast med en diameter mindre enn 20 mikrometer (1 mikrometer (µm) er en milliondel av en meter) og en lengde på over 5 mm. Begrepet mikrofiber brukes også om syntetiske materialer som er laget med spesielt tynne fiber f. eks. til klær eller kluter. Slike tekstiler bidrar, som alle andre syntetiske stoffer, til spredning av mikroplast, men vi vil ikke bruke 'mikrofiber' om denne typen produkter her. Fokuset er på mikrofiber som en undergruppe av mikroplastforurensning.

Mikrofiber spres fordi fiber løsner i bruk og vask av syntetiske klær og gjennom nedbrytning og fragmentering av syntetisk tekstilavfall. Slikt avfall kan f. eks være garn og tauverk fra fiske og havbruksnæringer. Globalt er søppelfyllinger en viktig kilde til spredning, fordi syntetiske tekstiler brytes ned til mikrofiber og spres til jord og vann. Syntetiske fibre utgjør nå mer enn 60% av den globale tekstilproduksjonen og vokser raskt både fordi tekstilforbruket vokser, og fordi andelen syntetiske materialer vokser. Forbruket av plast øker raskt, og de siste 50 år har vi 20 ganget forbruket. Syntetiske tekstiler, som annen plast, degraderes svært langsomt, og brytes ned til mindre og mindre fiber og partikler. Dermed 'forsvinner' plasten og blir usynlige for oss. Det er vanskelig å estimere mengdene av plastavfall, men vi vet at mengden både synlig og usynlig plast vokser raskt.

Det syntetiske tekstilmateriale som brukes mest er polyester etterfulgt av polypropylen, polyamid (nylon) og akryl som til sammen utgjør 98% av alle syntetiske fibrene. Studier av mikroplast i hav og sedimenter viser at forholdet mellom de mikrfibrene som finnes der og den globale produksjonen av syntetiske tekstiler er proporsjonal. Det er med andre ord mest avfall fra polyester. Enkelte studier tyder på at det er mer akryl i mikrofiberform enn andelen slike klær. Dette kan ha sammenheng med at dette materialet er relativt svakere. I slike undersøkelser finnes også fiber som stammer fra regenererte fiber som viskose (hvor det som ofte omtales som bambus også er med), men kunnskapen omkring deres nedbryting og påvirkning på livet i havet er begrenset. Naturfiber mister også fiber i bruk og vask, men disse nedbrytes raskere i naturen og i dyrs fordøyelsesorganer, i motsetnings til de syntetiske fibrene.

Negativ påvirkning på levende organismer

Mikroplast, inkludert mikrofiber, finnes i dag både i økosystemer i havet og på land. Det er påvist mikroplast i en rekke levende organismer, i sjøvann over alt på jorden og i drikkevann. Foreløpig er kunnskapen om hvordan mikroplast påvirker miljøet mangelfull. Vi vet likevel en del. Mikroplast påvirker økosystemer både fysisk, kjemisk og biologisk. Når organismer forveksler mikroplast med mat tar plasten opp den plassen som mat skulle ha i fordøyelsen og kan også blokkere for den naturlige transporten gjennom fordøyelsesorganene. Dette er en fysisk påvirkning. Kjemisk påvirkning skyldes derimot at farlige stoffer lekker ut av plasten og tas opp i levende organismer. Kjemisk påvirkning kan også skyldes at farlige stoffer har festet seg til overflaten på plastpartiklene og derfra trenger inn i næringskjedene. På samme måte kan bakterier og andre organismer festes til plasten og spres med den. Dette er da en biologisk forurensning.

Mikrofiber synes å ha større negativ påvirkning på miljøet enn annen mikroplast. Dette skyldes at fibrene lettere setter seg fast inne i fordøyelsesorganene og dermed blokkerer for normal sirkulering. Konsekvensen av dette blir manglende opptak av føde, som igjen fører til redusert vekst eller død. Også kjemisk er mikrofiber mer problematisk enn annen mikroplast. Den store overflaten på fibrene gir mer plass for å absorbere skadelige stoffer. Det er også en sammenheng mellom disse to problemstillingene. Jo lenger mikroplasten forblir inne i en levende organisme, jo større er også sjansen for at stoffene lekker ut av plasten og over inn i organismen. Dermed vil fibre, som lettere blir hengende fast, utgjøre et større problem enn plast som lettere glir igjennom organismen. Tekstiler inneholder i utgangspunktet en rekke miljøgifter. Bekymringen for lekkasje fra mikroplast omfatter stoffer som polyklorerte bifenyler (PCB), polysykliske aromatiske hydrokarboner (PAH), petroleum hydrokarboner (PHC), klororganiske pesticider, polybromerte difenyletere (PBDE), alkylfenoler og bisfenol A (BPA).

Mikroplast inkludert mikrofiber har blitt funnet i undersøkelser av fordøyelsesorganene til marine organismer og i sjøfugl. Effekten av dette er både lavere opptak og dermed lavere energinivå og vekst. En annen effekt er endringer i adferd og reproduksjon. Dette er vist i eksperimenter med fisk.

Analyse og dokumentasjon av mikroplast har så langt fokusert på vann, både ferskvann og saltvann samt strandsonen. Forskning på konsekvenser av inntaket av mikroplast via drikkevann og sjømat vokser raskt. Men spredningen omfatter også husstøv, jordsmonn og luft. Det er manglende kunnskap om hvordan mennesker og dyr reagerer på innånding av mikroplast. Det potensiale det er for at miljøgifter tas inn i næringskjeden gjennom mikroplast, er en viktig bekymring som kan påvirke både menneskers og dyrs helse.

Livssyklusanalyser (LCA) er det mest brukte verktøyet for sammenligninger av miljøbelastninger av produkter. Til tross for at det er hevet over tvil at mikroplast og mikrofiber er uønsket i næringskjedene, og høyst sannsynlig er et stort miljøproblem, er det ingen eksisterende LCAer av tekstiler som tar denne faktoren med i betraktning. Rapporten inneholder en diskusjon om hvilke data som vil være viktige for å endre på dette.

Hvilke klær bidrar mest?

Det er mye usikkerhet omkring mengder og spredning, ikke minst fordi måleenheter og standardiserte metoder mangler. Fra ulike eksperimenter vet vi likevel en del. Alle plagg mister fiber i bruk og vask. Hvor mye påvirkes av mange ting, blant annet type fiber og den kvalitet plagget har. Syntetiske plagg av høyere teknisk kvalitet mister mindre fiber i vask enn plagg i lavere kvalitet. Det er plagg laget for lang levetid som mister minst fiber. Samtidig mister eldre plagg mer enn nye. Det skjer altså en nedbrytning av plaggene over tid som bidrar til at mer fiber løsner. Også vaskemaskinen påvirker spredningen. Bruk av frontmatet vaskemaskin, slik det er vanlig å bruke i Norge, og bruk av programmer med mindre mekanisk bearbeiding, bidrar til å redusere spredningen. Spredningen blir også mindre om klærne vaskes sjeldnere og med milde vaskemidler.

Mulige måter å samle opp mikrofiber

Renseanleggene filtrer allerede i dag ut mikrofiber, men effektiviteten varierer veldig. Uansett bidrar dette likevel ikke nødvendigvis til å hindre spredning fordi slammet (med mikroplasten) brukes som gjødning og jordforbedring. Mikrofiber vil dermed ikke tas ut, men tvert imot spres videre. Det er mulig at vi i fremtiden vil kunne filtrere ut mikrofiber fra vaskemaskinene gjennom mekaniske filter eller liknende. Hvor effektivt dette eventuelt vil bli, og i hvilken grad det samtidig også påvirker vaskeresultat og driftssikkerhet av maskinene vet vi foreløpig ikke noe om. Effekten av slike filtre vil også avhenge av at de tømmes og kastes på en slik måte at plasten destrueres. Filtre i vaskemaskin vil ikke forhindre spredning via luft og husstøv.

Tiltak mot spredning av mikrofiber

Flere land har innført, eller diskuterer å innføre, forbud mot bruk av mikroplast i kosmetikk og hygieneprodukter. Dette gjøres til tross for at dette er produkter som i langt mindre grad enn tekstiler, veidekke, bildekk og kunstgressbaner bidrar til spredning. Det er likevel ikke grunn til å tro at forbud mot bruk av syntetiske klær vil komme. Grunnen til dette er at de samfunnsmessige konsekvenser av et slikt forbud vil bli mye større enn av å forby mikroplast i kosmetikk. På sikt vil trolig merkeordninger bidra til at forbrukere lettere kan velge produkter som i mindre grad enn andre bidrar til spredning, men det er lang vei frem til at dette kommer på plass.

Det forbrukere foreløpig kan gjøre, kan deles i tre ulike typer tiltak

1. Redusere forbruk av klær og tekstiler

Vi har de seneste tiårene hatt en eksplosjonsartet vekst i produksjon og forbruk av tekstiler, særlig i syntetiske materialer. Som for annen plast bidrar det høye forbruksnivået i seg selv til stor fare for at produkter kommer på avveie. Det er også stor avfallsproduksjon gjennom hele verdikjeden i land med mangelfull avfallsbehandling og dårlig rensing av vann. I Norge bruker vi i liten grad fyllinger til tekstilavfall, men dette er i bruk i store deler av verden, og jo mer syntetiske klær – og annen plast som er i avfallet – jo mer vil brytes ned til mikrofiber. En omlegging fra «fast fashion» og «ta tre betal for en» til klær med høyere kvalitet og levetid vil ikke bare være gunstig i forhold til å redusere spredning av mikroplast, men også andre miljøproblem knyttet til tekstiler.

2. Forbedringer i bruksfasen av syntetiske plagg

Gjennom bruk og ikke minst vask bidrar bruken av syntetiske tekstiler til spredningen av mikroplast. I tillegg er det indikasjoner på at også de regenererte cellulose fibrene kan utgjøre et miljøproblem i form av mikroplast. Forbrukere og andre brukere av tekstiler kan redusere spredningen av mikroplast gjennom å:

- Vaske syntetiske tekstiler sjeldnere
- Vaske med mer skånsomt program
- Vaske dem med mildere vaskemidler
- Anskaffe syntetiske klær av høyere teknisk kvalitet og beholde dem lenger.

3. Erstattet bruk av syntetiske fibre med naturlig fiber

Ved å erstatte bruken av syntetiske klær og andre syntetiske tekstiler med klær og tekstiler i naturmaterialer, er det mulig å redusere spredningen av mikroplast. Det viktigste vil være å redusere av syntetiske tekstiler som vaskes ofte.

1. Introduction

1.1 Definition and scope of this review

The objective of this report is to give an overview of the current state of knowledge concerning microplastic pollution. We then focus on microplastic fibres (microfibres) from textiles. This is a relatively new but rapidly evolving area of research with significant gaps remaining in understanding the significance of this form of pollution for the environment and for human health. As such, the challenge of including the potential environmental impact of microplastics in tools such as life cycle assessment (LCA) which are used to quantify the sustainability of products has yet to be addressed. We discuss this challenge and possible future directions for measurement, monitoring and reporting to support mitigation strategies, while recognizing that more research and understanding are needed before reliable impact assessment is possible.

Microplastics are generally classed as plastic particles less than 5 mm in diameter (e.g. Bruce et al. 2016), although some studies reserve the prefix micro- for particles < 1 mm (e.g. Browne et al. 2010). In this review the more widely adopted threshold of 5 mm is assumed and exceptions will be noted where applicable. Cesa et al. (2017) summarized the data on size and characteristics of microplastics with a focus on studies concentrating on microfibre pollution as shown in Appendix A.

Eight per cent of global oil production is used to make plastic items. Microfibres, more precisely referred to as microplastic fibres or microsynthetic fibres, are the subcategory of microplastics that are fibrous in shape. In some regions, particularly near centres of population, microfibres have been found to be the most prolific form of microplastic contamination. Hence, it is important to expand our understanding of their impacts on natural ecosystems (Carson et al. 2011, McCormick et al. 2014) and on human health (e.g. Van Cauwenberghe and Janssen 2014) and the prospects for managing and mitigating the risks.

1.2 Overview

Microplastic pollution may derive from primary and secondary sources. When larger items of plastic litter in marine or freshwater or in landfill sites degrade micro- or nano-sized particles form secondary sources of microplastic contamination of waterways and soil. Primary sources include purposefully manufactured plastic items smaller than 5 mm such as microbeads used in personal cosmetic or hygiene products and industrial sources such as vehicle tyres that lose fibres with abrasion on road surfaces, and household or fashion textiles that shed fibres during production or washing (Browne et al. 2011). These primary products can pass through filters in waste water treatment plants (WWTPs) with a proportion of textile microfibres also passing through filters in washing machines.

Microplastic pollution of marine and freshwater environments has been identified as of concern for only about two decades, but there is now significant evidence of negative impacts on aquatic habitats and marine organisms (Besseling et al. 2014, Wegner et al. 2012; Wright et al. 2013a). Microplastic particles have also been found on beaches and in terrestrial environments, including in agricultural lands treated decades earlier with effluent from WWTPs and/or sludge from sewage treatment (Browne et al. 2011). Globally, the density of plastics on beaches has been estimated to be five times greater than in oceans at 2,000kg/km^2 (Eunomia 2016). A global study by the International Union for Conservation of Nature (IUCN) examined seven regions (Africa and Middle East, China, East Asia and Oceania, Europe and Central Asia, India and South Asia, North America and South America) and found releases of primary microplastics per region ranging from 134 to 281 kilotons per year. While some studies link microplastic levels to centres of population others found that per capita releases differed markedly between regions, ranging from 110 to 750 grams per person per year (Boucher and Friot 2017). Despite the strong evidence that levels are high and are increasing, investigations of the full environmental impacts and possible human health implications are still in their infancy.

Understanding the prevalence and fate of microplastic particles and fibres in the environment has been hampered by limitations in detection methods. As measurement techniques improve (Klein et al. 2015, Vandermeesch et al. 2015), research is revealing increasing cause for concern at the levels of accumulation, including for previously undetected levels of nano-size particles (<1mm) (Lambert and Wagner 2016), particularly in aquatic environments and shoreline habitats.

Research to support fate and exposure modelling of microplastics is still in the early stages. Together with the limitations on accuracy of sampling data and consequent prevalence in different environments, this means that attempts to quantify and attribute impacts to a product or organisation have a high level of uncertainty. Recent hydrological modelling by Besseling et al. (2016) reviewed information on possible transport and deposition of nanoplastic and microplastic particles carried in riverine systems to marine waters and discussed possible fate pathways along with evidence for accumulation in the food chain including in species used as human food.

The first part of this paper reviews current understanding of the level of microplastic pollution and its impacts. This is an active area of research, with results continuing to improve confidence in prevalence, exposure and links between impacts on organisms or human health and sources of microplastics, including microfibres from textiles.

2. Microplastics in the environment

2.1 Increasing microplastic pollution

Use of plastics has increased dramatically over the past six decades, in line with growth in availability, affordability and demand through population expansion and regional increases in income. In the 1950s global plastic production was a modest 1.5 Mt annually but in the 50 years from 1964 to 2014 production increased 200-fold to be more than 300 Mt in 2014 (Figure 1).

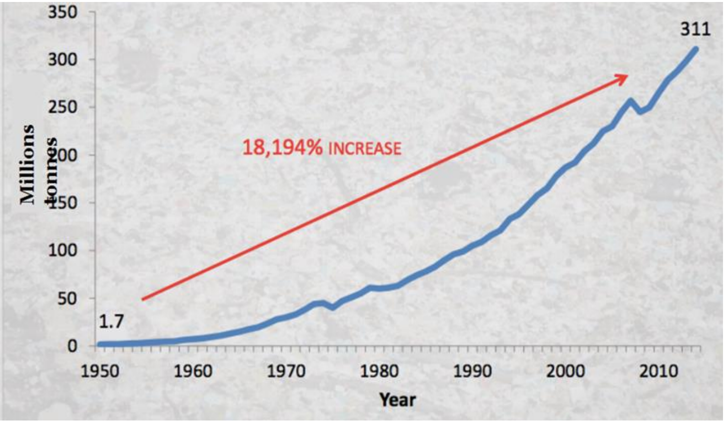


Figure 1. Global growth in plastics production per year 1950-2014 from virgin petroleum-based feedstocks i.e. excluding bio-based and recycled materials. (Figure reproduced from PlasticsEurope Market Research Group, Plastics – The Facts (2015).

High consumption, low cost and resistance to degradation have resulted in rapid growth in plastic waste in parallel with the expansion in production. In the oceans alone, it has been estimated that the mass of plastics by 2025 will equal one third of the mass of all fish (Mather and Ravasio 2016). Most media attention has been given to marine plastics that are floating at or near the ocean surface and, therefore, visible to people but this component represents only about 1% of all marine plastics, i.e., an average global concentration of less than 1kg/km^2. Studies have revealed that gyres, particularly in subtropical regions, are hotspots for microplastic accumulation (Wright et al. 2013b) with concentrations up to 18kg/km^2 recorded in the North Pacific Gyre. Taken as a whole, the sea floor is estimated to contain around 94% of the plastic that enters the ocean with an average of 70kg of plastic in each square kilometre of sea bed (Eunomia 2016).

Over 80% of microplastic waste in marine systems is estimated to come from land-based sources with transfer to the oceans via rivers and other terrestrial flows. However, understanding of sources and transfers of environmental microplastics pollution is still evolving. One of the first studies to examine in detail the dispersion patterns (Browne et al. 2010) reported that plastics accounted for 65% of debris, in terms of abundance, recorded in the Tamar Estuary in the UK. Browne et al. (2011) analysed samples of shorelines across six continents and found that variation in abundance of microplastics was related to human population density in the surrounding area (Figure 2) and that this was linked to sewage disposal. These authors estimated that microfibres, predominantly of polyvinylchloride, polyester, and synthetic polyamide (nylon), make up 85% of all anthropogenic debris on global shorelines. Analysis of spatial patterns indicated that habitats downwind accumulate more plastics and that microplastics tended to be transported by the flow of water and be deposited where movement of water slowed.

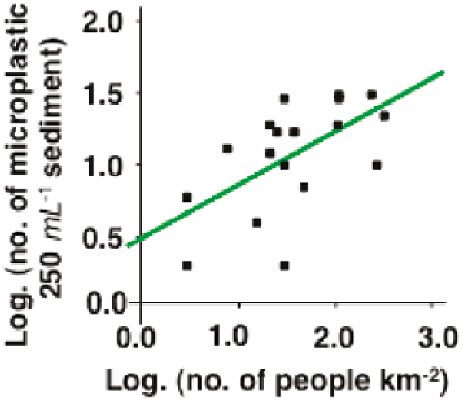


Figure 2. Relationship between population-density and number of microplastic particles in sediment from sandy beaches (Reproduction of Figure 2B from Browne et al. (2011).

Microplastics now appear to be ubiquitous in waterways. Sampling across 29 tributaries over six states of the US showed the presence of microplastics in all 107 samples (http://www.adventurescience.org/microplastics.html). Recent results indicate that studies published to date may have underestimated the extent of microplastic pollution with evidence that commonly used techniques are not capable of detecting plastic nanoparticles (those between 1 and 100 nanometers (10^{-9} meters) in size) in natural environments although they are believed to be present (Lambert & Wagner 2016). Kang et al. (2015) compared floating microplastic samples (which they defined as <2mm in diameter) using two types of mesh, a 330 µm manta trawl net and a 50 µm hand net and found that two orders of magnitude more microplastics were collected using the hand net. They concluded that using a manta trawl as in some earlier research would fail to detect a significant proportion of microplastics including microfibres. Hence, there is an urgent need to develop protocols for quantifying and monitoring microplastic prevalence in habitats in order to more accurately assess prevalence and exposure of organisms and impacts along the food chain including in humans.

Further advances in analytical techniques based on focal plane array-based micro-Fourier-Transform Infrared (FTIR) imaging (Mintenig et al. 2017) provided further evidence of the prevalence of microplastics in 12 waste water treatment effluent in Germany. Samples were firstly purified by a plastic-preserving enzymatic-oxidative procedure and subsequent density separation using a zinc chloride solution. The advanced analytical method allowed the identification of polymers of all microplastics down to a size of 20 nm. For microplastics, polyethylene was the most frequent polymer type across size classes measured and polyester predominated in the synthetic microfibre fraction. The authors estimated that, considering the annual effluxes of the tested WWTPs, total discharges of 9×10^7 to 4×10^9 microplastic particles and fibres per treatment plant could be expected. Interestingly, one tertiary WWTP had an additionally installed post-filtration that reduced the total microplastic discharge by 97%. The sewage sludge of six WWTPs was also examined and the existence of microplastics, predominantly polyethylene, was revealed confirming that these plants could represent both a sink and a source of the microplastic pollution.

2.2 Microplastic fibres (Microfibres) from textiles

2.2.1 Production and consumption

Estimates of the proportion of all primary source microplastics in oceans that originates from textiles vary. Eunomia (2016) suggest that 20% of primary microplastics in the marine environment in 2014, i.e. 0.19 million tonnes per annum, were fibres from synthetic clothing while the estimate of Boucher & Friot (2017) is even higher, 35%. Consumption statistics highlight the contribution of synthetic fibres to the increase in global plastic production and use, particularly over the past two to three decades (Figure 3).

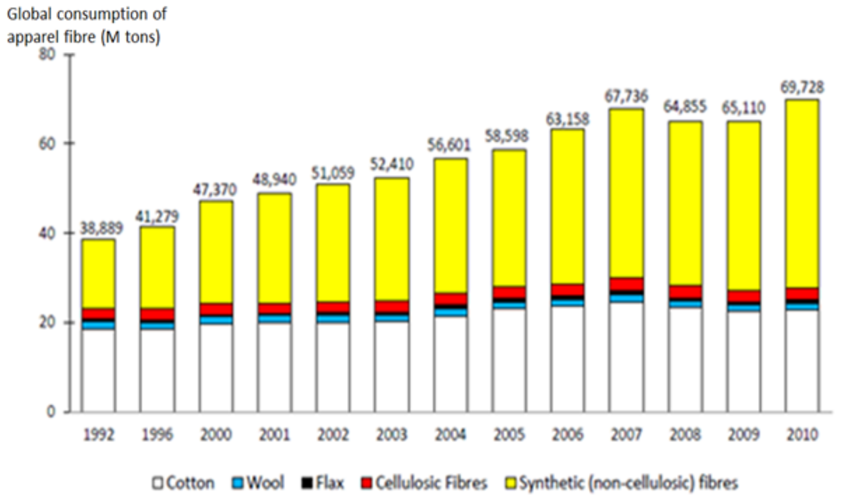


Figure 3. Global consumption of apparel fibre in millions of tons, showing that synthetics dominate consumption growth (Source: FAO/ICAC World Apparel Fibre Consumption Survey (2013).

Over a period of only 14 years, the share of synthetic fibre in clothing increased from about 50% in 2000 to more than two-thirds. The most dramatic increase in production of synthetic fibre for clothing has been in Asia (Figure 4). By 2014, China alone accounted for 69 percent of all polyester fibre production globally, the combined production of China, India and Southeast Asia represent over 80 percent of the global total.

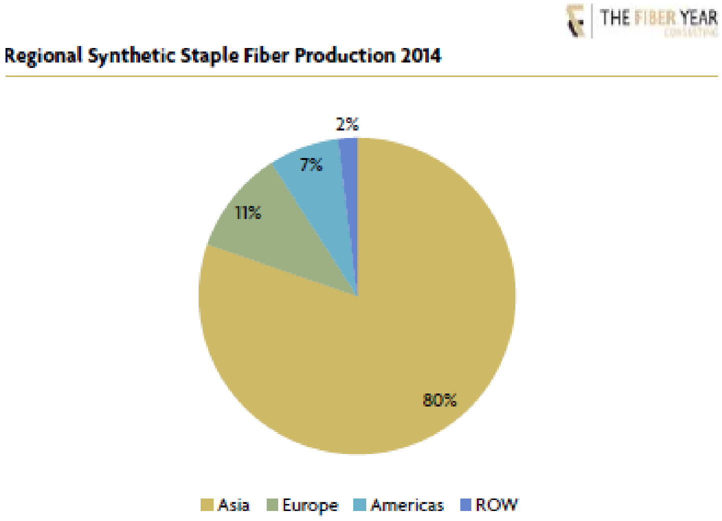


Figure 4. Regional distribution of synthetic fibre production in 2014 showing the dominance of Asia (Source: https://www.textilemedia.com/assets/Uploads/TFY15-sample-pages.pdf Accessed December 2016).

The highest levels of textile consumption per person occurred in OECD countries (Figure 5), with North America consuming 37 kg per capita in 2014. In comparison, on the African continent each person consumed on average less than 5 kg. Australians were the second highest consumers at 27 kg per capita but were the highest per person consumers of wool, on average. As for production, man-made fibres made up more than half of all consumption. In this analysis, man-made fibres include both cellulosic and non-cellulosic fibres but data from FAO/ICAC (2013) showed that oil-based fibres dominate this category representing more than 95% of all apparel textiles in 2010.

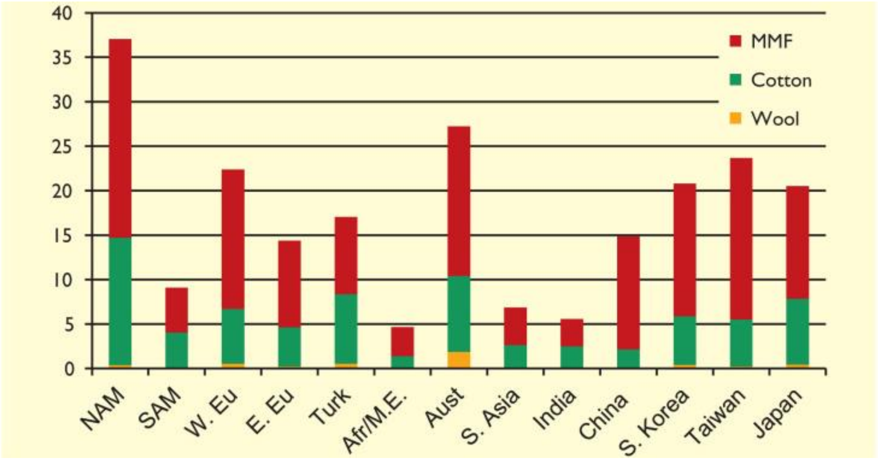
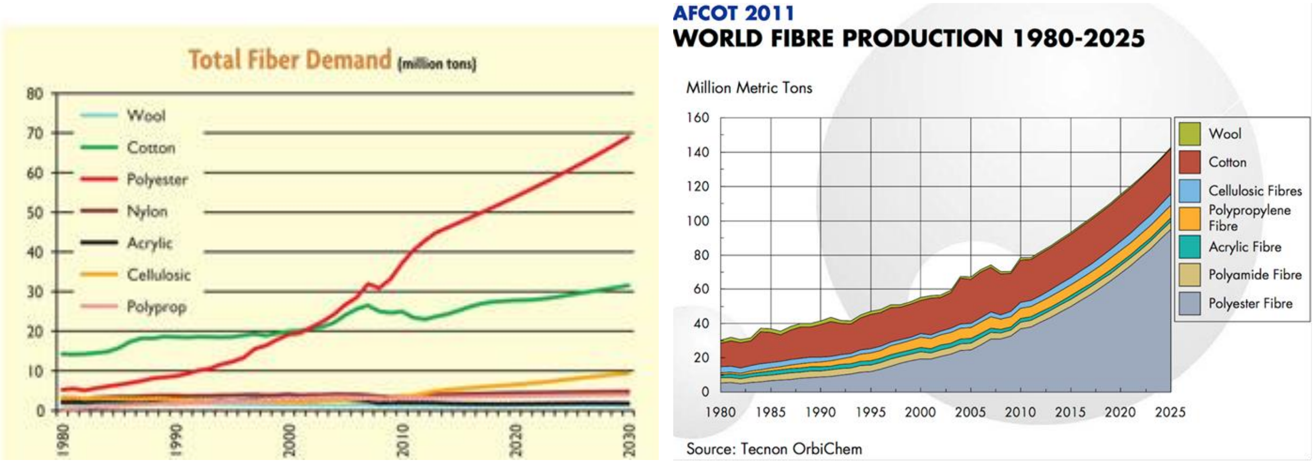


Figure 5. Global consumer demand in textiles expressed as kg per capita In North and South America (NAM, SAM); Western and Eastern Europe (W. Eu, E. Eu), Turkey (Turk), Africa and the Middle East (Afr/M.E.), Australia (Aus), South Asia (S. Asia), India, China, Republic of South Korea (S. Korea), Taiwan, and Japan. (Source: Textile World http://www.textileworld.com/textile-world/fiber-world/2015/02/man-made-fibers-continue-to-grow/)

It is forecast that production of synthetic textiles will continue to increase as global population rises to over 9 billion by 2050 with the contribution of synthetic textiles expected to grow in a society that has rapidly adopted cheaper 'fast fashion' options (Figure 6). Technon OrbiChem (2014) has predicted that by 2025, production of polyester fibre alone will reach 84 Mt (Figure 6B).



A. **B.**

Figure 6. Global fibre demand and production, broken down by fibre type. The analysis and forecasts in Figure 6A were published in Textile World (http://www.textileworld.com/textile-world/fiber-world/2015/02/man-made-fibers-continue-to-grow/) based on forecasts from PCI. The production data and forecasts to 2030 in Figure 6B were sourced from Tecnon OrbiChem.

2.2.2 Microfibre pollution

During their production, service life and after disposal, synthetic textiles may represent both primary and secondary sources of microplastic pollution. Synthetic fibre production and consumption contributes significantly to the volume of total plastic waste in landfills and incinerators. Although accurate statistics are not compiled globally, the mass of discarded clothing is estimated to be in the order of millions of tonnes (Cobbing and Vicaire 2016). In landfill and other waste sites, synthetic textiles degrade only slowly over periods of decades to smaller particles without breakdown to constituent elements. They are a potential source of secondary microplastic pollution following fragmentation. Synthetic clothing also represents a primary source of pollution during the consumer use phase as shedding during washing releases microfibres to the environment (Browne et al. 2011, Dris et al. 2015, Napper and Thompson 2016). Waste water discharged from washing machines may flow via sewage systems to coastal habitats carrying with it microfibres which may also pass through the filters of WWTPs to enter the environment.

Quantities of microfibres in the influent of WWTPs at four locations in Europe were reported to range from 550 million to 440 billion fibres per day (Bruce et al. 2016). Globally, the proportions of different plastic fibres found in shoreline habitats that received sewage were found to resemble those used in clothing, i.e. about 67% polyester, and Browne et al. (2011) found that waste water treatment sludge contained mostly fibres of polyester (78%) and acrylic (22%). The authors did not propose a reason for the proportion of acrylic fibres being greater in these samples than that in apparel consumption (approximately 5%) but the relative shedding of fibres from different fabrics during wash is now beginning to be studied with a view to standardising assessment as well as understanding fibre loss.

Accumulation of microplastics has been shown to be linked to population density at shoreline sites around the world (e.g. Figure 2, Browne et al. 2011), with 85% of this man-made debris being microfibres. A more recent paper by Mason et al. (2016) reported that averaging tests from 17 waste water treatment facilities indicated that wastewater treatment facilities are releasing over 4 million microparticles per facility per day, related to influent from regional populations. Statistical analysis suggested facilities serving larger populations discharged more particles and the largest plant surveyed released 15 million microplastic particles per day. Fibres (predominantly from plastics) and fragments were found to be the most common type of particle within the effluent but Mason and co-authors estimated that in total 3 to 23 billion (with an average of 13 billion) microbeads were also being released into US waterways every day via municipal wastewater.

Bruce et al. (2016) averaged the ratio of concentration of microfibres in the effluent and influent of WWTPs as reported for four locations in Europe to estimate a removal rate of 65 – 99.9%. Nevertheless, the concentrations of microfibres in effluent were as high as 160,000 fibres per cubic metre and there is room for improvement in the less efficient plants. Based on a linear density (mass/m) of microfibres of 0.15 mg/fibre, each cubic metre of effluent contained from 0.6 mg (Swedish site) to 24,000 mg (Russian site). Even for a relatively efficient removal rate with only 13,800 fibres/m^3 in effluent, a plant with a discharge rate of 270,000 m^3/day would each day discharge 3.73 billion fibres or 81 kg microfibres into the nearby environment.

In contrast, analyses by the Global Microplastics Initiative (http://www.adventurescience.org/microplastics.html) found that while microfibres made up about 90% of plastic debris in 2,000 aquatic samples, their prevalence and distribution were not related to urban dependent watershed attributes, wastewater effluent contribution, or hydrologic condition (Baldwin et al. 2016). The authors concluded that the lack of correlation between fibre concentrations and hydrologic conditions and between fibre concentrations and watershed attributes highlights the need for further work to better understand the sources of fibres in streams. The samples included both marine and freshwater which may have complicated the analysis of distribution.

Further evidence for the deposition of clothing microfibre pollution in deep ocean sediments comes from analyses reported by Woodall et al. (2014). Microplastic fibres were up to four orders of magnitude more abundant per unit volume in deep-sea sediments from the Atlantic Ocean, Mediterranean Sea and Indian Ocean than in contaminated sea-surface waters. Fibres of polyester, acrylic and polyamides were the most abundant microplastics in sediment samples (Figure 7). These plastic polymers are used in a range of domestic and industrial applications, particularly in textiles but also in packaging and electronics. Rayon fibres which were also detected in relatively large numbers may come from clothing, cigarette filters, and personal hygiene products. Since impact on marine organisms is likely related to frequency of encounter (in turn dependant on abundance), the high concentrations of microfibres detected in sediments are of particular environmental concern. Woodall et al. (2014) concluded that further data are needed to properly establish the impact of microfibres on deep sea communities and related ecosystem services.

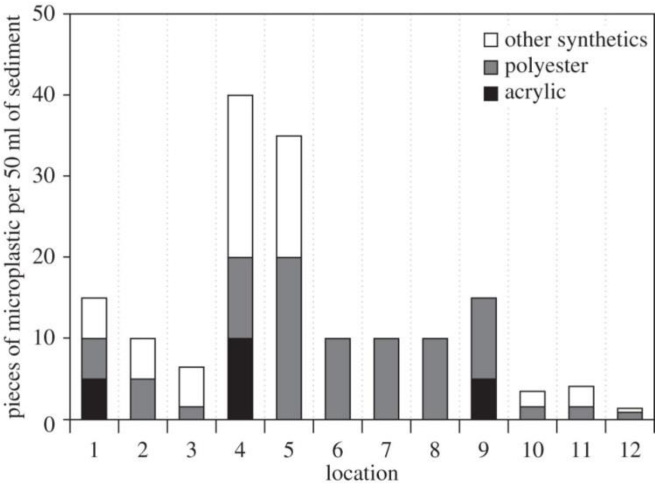


Figure 7. Quantity and type of plastic fibres found in 50 ml of sediment sampled from twelve sites in the North Atlantic Ocean, Mediterranean Sea and SW Indian Ocean. (Reproduced from Woodall et al. 2014, Figure 2)

Where there is an absence of direct links between WWTP effluent and concentrations in the environment this may relate to the contribution of sewage sludge. Sludge may be disposed of on shorelines or used as a nutrient-rich soil amendment in agricultural lands. Microfibres contained within applied sludge material persist for more than 15 years in the soil (Zubris and Richards 2005), and more than a decade after application, disposal sites still contained more than 250 percent more microplastics than reference sites. Analyses of sewage treatment plant effluent showed microplastic particles were dominated on average by fibres of polyester (67%) and acrylic (17%), with proportions roughly similar to fibre proportions in synthetic textiles (78% polyester, 9% polyamide, 7% polypropylene, 5% acrylic). From these results, Browne et al. (2011) concluded that the source of microplastic fibres in sludge and effluent samples was most likely to be fibres shed from synthetic clothing during washing.

3. Environmental impacts of microplastic pollution

3.1 Impacts on ecosystems

Initial studies on potential impacts of microplastic pollution focussed on marine and freshwater habitats. With an accumulated average level of 70kg plastics per square kilometre of sea floor and as much as 2,000kg/km^2 on average on beaches globally (Eunomia 2016), impacts on marine and shoreline organisms is a serious environmental concern. Figures for debris on beaches include plastics larger than 5 mm but these larger pieces have the potential to become secondary sources of microplastics through disintegration over time. Browne et al. (2011) highlighted potential ecosystem impacts of primary sources of microplastics, particularly microfibres on beaches.

Ecosystem impacts of microplastics have the potential to occur through physical, chemical and biological pathways. In a detailed examination of the effects of accumulation of polystyrene microplastic waste on the development, behaviour and survival of Eurasian perch Lonnstedt and Eklov (2016) concluded that microplastic particles operate both chemically and physically on larval fish performance and development. This study clearly demonstrated the ecological significance of microplastics in the vulnerable early life stages of fish. Exposure to microplastic particles inhibited hatching, decreased growth rates and altered feeding preferences and innate behaviours of the perch larvae. Observed changes in response of larvae to olfactory threat cues under experimental conditions would likely translate to increased mortality rates from predator attacks in the wild. This study demonstrates the complexity of ecosystem vulnerability to microplastic pollution. Preliminary research on microplastics in the digestive tracts of terrestrial birds found the presence of < 5 mm size particles and fibres was ubiquitous but, possibly due to a very small sample size, found no relationship between presence and body condition (Zhao et al 2016). In summary, recent work highlights the need for further research on impacts due to exposure to various forms of microplastics, including textile microfibres. Other evidence for impacts at the organism level is reviewed below.

3.1.1 Physical impacts of microplastics

Microplastic particles in aquatic environments have been found to be readily, and even preferentially, ingested by aquatic species. If organisms substitute microplastics for feed, adverse effects can occur through physical gastrointestinal blockages. Because of the potential for entanglement, microfibres are less likely to be excreted than microbeads or more discrete plastic particles, potentially exacerbating physical impacts leading eventually to starvation.

Early work focussed on passive intake by filter feeders such as mussels and oysters (Wright et al. 2013b) but ingestion has now been shown to occur across organism types from zooplankton to vertebrates. Three recent studies from diverse regions, North-east Pacific Ocean (Desforges et al. 2015), a freshwater site in Slovenia (Jemec et al. 2016) and the seas off the northern coast of Australia (Commonwealth of Australia 2016), have reported ingestion of microplastics or microfibres by zooplankton. These papers discuss not only effects including lower growth rates and higher mortality in these organisms but also the potential for adverse impacts at higher trophic levels, e.g. in salmon or other fish valued for human food. Wright et al. (2013b) reviewed the expanding body of literature on the ingestion of microplastics in vertebrates (e.g. Denuncio et al. 2011, Yamashita et al. 2011) and this work is now supported by more recent studies (Mathalon and Hill 2014). Synthetic fibres appear to have a higher potential than other microplastics to enter the food chain because their size and form allow them to be readily consumed by aquatic organisms and to bioaccumulate. A detailed analysis and comparison of methods and results in papers reporting microplastics in marine organisms by Vandermeersch et al. (2015) concluded that there is a critical need for further research to develop a standardised operating protocol for microplastic quantification and monitoring. Effects across marine trophic levels are currently difficult to quantify and to reconcile between sites.

3.1.2 Chemical and biological impacts of microplastics

The toxicology of plastic and additives associated with plastic waste and the ways they affect organisms is complex in both aquatic and land-based ecosystems. Toxic compounds are commonly added during plastics manufacture potentially causing additional direct chemical impacts. Indirect chemical effects due to sorption from surrounding water have also been shown to occur (e.g. Mato et al. 2001).

The majority of studies examining aquatic ecosystem impacts of chemicals associated with microplastics focus on the importance of sorption onto the surface of microplastics as a mechanism of enrichment of toxins, particularly organic compounds, and their introduction into the food chain. However, the situation is not clear, and distinguishing direct and indirect sources is difficult. For example, flame retardant additives such as polybrominated diphenyl ethers (PBDEs) are frequently used in plastics. These compounds are now also common in coastal seawater and have been detected in the abdominal adipose of oceanic seabirds that had ingested microplastics. Teuten et al. (2009) discussed evidence for their direct derivation from plastics in which PBDEs are additives or indirectly from sorption onto microplastics from surrounding seawater and concluded that both appear to occur. The ubiquitous presence of chemicals associated with the use of fire retardants in textiles highlights the need for more research on their impacts, particularly since PBDEs are suspected thyroid disruptors in both wildlife and humans (WHO/IPCS 1994).

Entry of a range of organic compounds into food chains is a major concern due to their toxicity (Batt 2006). In humans, they lead to deterioration of the immune function and endocrine disruption. In addition to PBDEs, organic contaminants such as polychlorinated biphenyls (PCBs), polycyclic aromatic hydrocarbons, petroleum hydrocarbons, organochlorine pesticides, alkylphenols and bisphenol A are frequently found in plastic debris (Teuten et al. 2009). Model calculations and experimental observations have consistently shown that polyethylene accumulates more organic contaminants than other plastics such as polypropylene and polyvinyl chloride (Teuten et al. 2009). Mato et al. (2001) found that sorption of hydrophobic chemicals is the primary source of PCBs in polypropylene waste in the marine environment along the Japanese coast.

Biological pathways for impacts can occur when microplastics host bacteria not normally found in the ecosystem. Exposure to these microorganisms through surface contact or ingestion has disease implications since an associated immune response may be lacking. Bacteria of concern include some linked with human gastrointestinal infections (McCormick et al. 2014).

In summary, in wastewater and aquatic systems, microplastic particles can sorb chemicals such as polychlorinated biphenyls (PCBs) and triclosan, due to their affinity for the hydrophobic surface of plastic. There are relatively few studies on the bioaccumulation of plastics and chemical effects associated with sorbed substances such as carcinogenic Persistent Organic Pollutants (PoPs), but ingestion by organisms has been demonstrated to have potential to introduce these toxic compounds to higher trophic level species causing adverse effects, including damage to internal organs and decline in reproductive success. The importance of plastic debris, and specifically textile microfibres, as a vector for the transport of harmful chemicals relative to alternative pathways remains uncertain (Napper and Thompson 2016, Besseling et al. 2013) and cannot yet be quantified and attributed to a source. Further research is needed to understand the full impacts on ecosystem health and the potential harm to human health as discussed below.

3.2 Impacts on human health

The potential for exposure of the human population to physical, chemical or biological impacts resulting from the accumulation of microplastics in the environment was introduced above with reference to aquatic ecosystems and marine food sources. In this context, there are three mechanisms identified as raising risks to human health:

(1) Microplastics retained in organisms used as human food sources can enter the human body where their fate is not known. This is particularly relevant to textile microfibres due to their greater retention in small organisms where entanglement reduces natural passage through the body;
(2) The high relative surface area and its hydrophobic nature, particularly for fibre forms of microplastics, facilitates adsorption of chemicals from surrounding water, raising the risks of introduction of sorbed organic carcinogenic and non-carcinogenic compounds;
(3) Biological risks whereby microplastics host bacteria not normally found in the ecosystem (and therefore without associated immune response), including some bacteria linked with human gastrointestinal infections (McCormick et al. 2014).

Over the past decade, several studies providing evidence of the presence of marine microplastics in seafood species consumed by humans have speculated on the potential threat to food safety and human health. For example, Li et al. (2015) found microplastics in all samples of commercial bivalves sampled from a fishery market in China with microfibres making up more than half the total microplastics in each of the eight species sampled. This points to potential contribution of textiles to contamination of these species.

Van Cauwenberghe and Janssen (2014) assessed the annual dietary exposure for shellfish consumers in Europe and found it may be as much as 11,000 microplastic particles per year. Assessing physical and chemical impacts of microplastic in humans is complex due to variability across geographical regions and across demographics and the absence of a clear baseline reference. Recent research led by Professor Janssen from University of Ghent has confirmed that despite more than 99% of microplastic particles readily passing through the human body, the retained microplastic particles are likely able to enter the blood stream and accumulate in the body over time. The level of retention by tissues, though small, is therefore of concern. The rapid rise in the prevalence and exposure to microplastics means that longer-term studies have not been conducted and, hence, any implications of extended consumption of food species containing microplastics have not yet been evaluated. Professor Janssen stressed the need to investigate the fate of retained plastics and to conduct research on the rising exposure by marine organisms and subsequently humans. In the longer-term, it is conceivable that microplastic pollution may affect the availability of seafood due to concerns about the safety in human diets. This may lead to enhanced food and nutrition insecurity, especially for communities with low economic outlooks and limited access to sources of protein other than seafood.

4. Assessing and managing microfibre loss from clothing

Understanding the impacts of microfibre loss from synthetic clothing during laundry (primary source) or after disposal of garments (secondary source) has emerged as a major priority for the apparel and textile industries (e.g. Patagonia 2017). A first step in improving management strategies is to quantify microfibre loss and analyse factors that influence the rate of shedding. The value of experimental studies to date seeking to characterise synthetic fabric fibre loss during washing is constrained by variations in laundry practices and techniques for fibre capture and analysis. However, early results show that shedding is substantial, with Browne et al. (2011) finding that more than 1900 microscopic sized fibres could be released into the environment during one wash of a single synthetic garment. Most studies on microfibres have examined shedding through analysis of washing machine effluent.

Recent tests, such as those by Hartline et al. (2016), have confirmed high levels of fibre shedding from synthetic garments during washing. This research has started to demonstrate how factors such as filter mesh size, garment age and garment condition affect the rate of loss. Together with improved methods, such as spectroscopy techniques that enhance the sensitivity of detection, this research has the potential to underpin the development of effective mitigation strategies.

A recently identified source of uncertainty in microfibre pollution is the possibility of a significant contribution by sources such as airborne fibres that have previously been overlooked. For example, Sundt et al. (2014) identified airborne textile microfibres as a source of deposition in dust wet-cleaned from household surfaces in Norwegian homes. Household surfaces were estimated to yield over 400 tonnes per year (or 0.08 kg per capita per year) compared with laundry effluent emissions of around 600 tonnes per year (equivalent to 1.2 kg per capita per year) derived from a review of geographically relevant studies. In humans, inhaled microplastic fibres may deposit in lung tissue due to their size and shape, and have been associated with tumours (Pauly et al. 1998). The degree of cancer risk is largely unknown and research is urgently needed to establish the risk to some sectors of the population as the prevalence of synthetic textiles grows, increasing exposure during production or use of fibres or apparel. More research is needed to confirm the findings of Sundt et al. (2014) and the potential underestimation of risk in not accounting for airborne textile and clothing microfibre release in past studies.

In summary, studies indicate that synthetic textile microfibres are likely to be more pervasive than early estimates. Due to their shape and dimensions, their abundance increases concern for potential impacts of microfibres on ecosystems and human health. Despite the fact that the science is still evolving, the need to take action to mitigate microplastic pollution is now widely accepted, making development of assessment and monitoring protocols and mitigation options for textile microfibres a priority. Maximising use of textiles made from natural biodegradable fibres is commonly proposed as contributing to mitigation measures but research is also needed to quantify the benefits.

4.1 Examples of studies on microfibre loss from clothing

The number of peer-reviewed studies on microfibre loss from clothing remains small. Detection and analysis techniques continue to improve so at this time understanding of the dynamics and fate of fibre loss from textiles under different washing practices, and hence the quantified mitigation benefits are still evolving. In this section, we review three published studies that have quantified microfibre shedding during washing as a basis for discussing the additional research required to enable development of monitoring protocols and development of environmental indicators of microfibre pollution from textiles that could support actions to mitigate impacts. These examples highlight the knowledge gaps that must be addressed for effective management of microfibre pollution. Characteristics such as how loose fibres are, fabric composition, garment construction, presence of insulation in garments such as jackets are all likely to influence fibre shedding during washing to some extent.

4.1.1 Study 1: Polyester blanket, fleece jacket and shirt (Browne et al. 2011)

Browne et al. (2011) reported results of experiments quantifying fibres lost in wastewater from washing blankets, fleeces and shirts made from polyester. Polyester was targeted because it is the dominant synthetic textile, making up about 78% of the total. The authors did not report on the age of the blanket and garments evaluated. The trials used three brands of front-loading domestic washing machine. During washing no detergent or conditioner was added and a temperature of 40C was used. All articles released more than 100 fibres per litre of effluent with over 180% more from fleece fabric. The authors concluded that a single polyester fleece garment can produce more than 1900 fibres per wash.

Later studies suggest that under these experimental conditions the rate of release was likely lower than under common washing practices since Hartline et al (2016) found that top-loading machines produced five times more shedding than front-loaders and Napper and Thompson (2016) measured lower fibre loss with no detergent or conditioner than when these products were added during the washing. In contrast, Pirc et al. (2016) found no significant influence of detergent and conditioner use on shedding of fibres for polyester fleece washing.

4.1.2 Study 2: Polyester, acrylic and poly-cotton blend (Napper & Thompson 2016)

Napper and Thompson (2016) tested standardised area samples of popular jumpers sold in the UK (Plymouth) of the three most commonly used fabrics, 100% polyester, 65%/35% polyester-cotton blend and 100% acrylic. To investigate the impact of washing practices on fibre release, a factorial design was used for each fibre-type with two wash temperatures (30C and 40C), three detergent treatments (No detergent, Bio detergent, Non-bio detergent) and two conditioner treatments (No conditioner, Conditioner).

Fibres from washing machine waste effluent had an average size ranging from 11.9 to 17.7 µm in diameter and 5.0 to 7.8 mm in length. The number and mass of fibres retrieved varied with wash treatment but no clear recommendations were possible on best practice to consistently reduce loss across fibre types. While garment age was not a specific variable in these experiments, each fabric was washed four times before collecting the data used for comparison of fabrics to eliminate the influence of any initial spike in fibre loss from new clothes. Tests showed little change in fibre release between the 4th and 5th wash. Data from the 5th wash was, therefore, used for analysis to enable valid comparisons across variables studied. However, the recorded results for the first four washes are also informative, with a marked decline occurring from the 1st to 4th wash for polyester and acrylic fabrics but not for polyester-cotton blend.

Measurements of fibre loss for polyester and acrylic fabrics decreased from 2.79 mg and 2.63 mg, respectively, in the 1st wash to 1.63 mg and 0.99 mg, respectively, for the 4th/5th wash. The polyester-cotton blend had the least variation, with loss in the 1st wash of 0.45 mg and 0.30 mg in the 4th wash. Future research on change in fibre loss during aging of garments would assist in modelling total impact during the garment service life.

There was a clear relationship between fabric type and fibre release, as shown in Table 1, with the polyester-cotton blend having lower loss of fibres than the 100% synthetic fibres tested. Only microplastic fibres were reported with the nature of fibres confirmed using FTIR spectroscopy. The study did not report on whether loss of cotton fibres from the blend was detected. The authors evaluated the process of fibre loss through pilling in relation to factors such as tensile strength and resilience and possible role of detergent and softener. They explore options for synthetic garment manufacturers to reduce environmental pollution starting with consideration at the design stage, including producing clothing with: (1) longer service life; (2) minimal release of non-degradable synthetic fibres; and (3) compatibility to end-of-life recycling.

Table 1. Mean characteristics of fibres captured from washing machine effluent for fabric samples of jumpers made from commonly used fibre types in the UK (Data from Napper and Thompson, 2016).

Microplastic fibre Characteristics	**Fabric type** **Acrylic**	**Polyester**	**Polyester-Cotton Blend**
Mean Fibre diameter (µm)	14.05	11.91	17.74
Mean Fibre length (mm)	5.44	7.79	4.99
Estimated fibres released per 6kg wash	728,789	496,030	137,951
Estimated number of fibres per mg of dry fibres collected from effluent	763,110	475,998	334,800

4.1.3 Study 3: Five Jackets; impact of quality, age and wash practices (Hartline et al. 2016)

This study by the University of California was commissioned by Patagonia Inc. to assess the quantity of microfibres shed by their jackets during washing with the aim of improving understanding of the potential ecological impacts and informing strategies for mitigating impacts (Table 2). Four Patagonia jackets and one comparable budget jacket were used to quantify microfibre shedding and test differences with: (1) washing machine type (front (horizontal axis drum) or top-loading (agitator action)); and (2) garment age (new or artificially aged using an established experimental ‘killer wash’ procedure). The Patagonia test ‘killer wash’ is a 24-hour wash cycle that simulates a lifetime of wear. At the end of this period shedding during a normal wash cycle was compared to the initial new garment wash. During each trial, the output water from the washing machine was collected and samples passed through 333 µm and 20 µm sized mesh filters to collect fibres.

Table 2. Garments tested by Hartline et al. (2016)

Jacket	**Description**
Patagonia A	Technical non-fleece nylon (polyester insulation) jacket
Patagonia B	Polyester blend fleece pullover
Patagonia C	Polyester blend mid-layer jacket
Patagonia D	Polyester blend sweater fleece jacket
Budget	Polyester sweater fleece jacket

The median mass of microfibres recovered during washing in a top-loading machine was significantly greater (1906 mg per garment) compared to a front-loading wash (220 mg). Hartline et al. (2016) suggest that the significantly higher shedding may be due to the central agitator of the top-load washing machine being more abrasive on garments than the rotating drum of the front-load machine.

The results of these trials showed that:

- during washing of the synthetic jackets in a top-loading machine, overall approximately seven times more fibres were recovered than from a front-loader ; andthe mass of recovered fibres increased significantly after aging ($p < 0.001$) with, on average, aging resulting in 25% more fibres recovered;Results for the interaction between jacket type and recovered fibres were not conclusive but it appeared that jacket brand, perhaps related to manufacturing processes or variations in materials of construction, can influence the characteristics of fibres (size) recovered.

- Fibre mass captured onto 333 µm was significantly greater (almost 3-fold) than onto 20 µm filters in top loading washing machine, noting that part of the mass on the larger mesh may have consisted of clumped pills of smaller fibres. For the top-loading machine wash the difference in fibre recovery for filter types was not significant but tended to be slightly higher for 330 µm filter

A model of microfibres in WWTPs was developed to estimate the environmental implications of microfibres leaving the washing machine. Assuming a WWTP microplastic removal rate of 98.4%, 0.35 m^3 of sewage per person per day as influent to the WWTP, the fibre release rates found by Hartline et al. (2016) indicated that a city of 100,000 people would produce approximately 1.02 kg of microfibres per day. Based on this, and once per month to twice per year washing with all released microfibers transporting to the WWTP, laundering of synthetic jackets would account for approximately 71 to 428% of the fibers observed in WWTP influent. While there is a degree of uncertainty in this modelling, it can be concluded that common jacket washing could account for a substantial proportion of synthetic microfibre load into WWTPs in a typical city.

4.2 Microfibres in textile LCA: possibility for indicator development

4.2.1 Background and limitations to textile LCA

Life cycle assessment (LCA) is currently the most commonly used tool for evaluating environmental impacts of a product system through all stages of its life cycle. If properly implemented across the full life cycle, it provides a valuable resource for quantifying the environmental sustainability of comparable product choices at a given point in time and for identifying hotspots for targeted action to reduce impacts. Partial LCA, sometimes called cradle-to-gate or gate-to-gate assessment, should not be used in comparative assertions (ISO 14044:2006) but is a useful tool for internal business evaluation of the stage(s) of the life cycle over which the business has control. It is well-recognised (e.g. ISO TS 14067:2014) that focussing an LCA on a single impact, such as climate change (greenhouse gas emissions), fails to account for the total impacts of a product and risks decisions being made with unintended perverse outcomes. Importantly it also increases the risks of leakage into the natural environment. All material impacts should, therefore, be included in an environmental assessments but a limitation of LCA studies is that only impacts for which there are agreed methods of assessment can be included. To date there has not been an agreed indicator and quantification method for the impacts of microplastic release on ecosystems or on human health.

To enable the textile and clothing sector to move towards more sustainable production and consumption choices, indicators are needed to show the link between practices or interventions and environmental or health impacts.

4.2.2 Introduction to LCA impact categories relevant to microplastic pollution

Over the past decade, recognition of the widespread pollution by microplastic fibres from textiles has raised questions of whether impacts of this source of pollution can be quantified in LCA studies. Their inclusion in LCA would enable indicators to be added to tools such as the Sustainable Apparel Coalition's (SAC) Higg Index. The SAC has invested a large amount of expertise in development of the Higg Index suite of tools that aim to guide the apparel, home textile and footwear sectors to become more sustainable and to develop tools specifically for assessment of and promoting greater sustainability of textiles and apparel. The component of the Higg Index focussed on environmental assessment of apparel, footwear and textile materials, the Material Sustainability Index, provides an approach based on life cycle thinking for assessing a limited number (currently five) of impact categories.

The summary below provides an overview of eco-toxicity and human-toxicity assessment in LCA in relationship to possible accounting for a chemical-based contribution of microfibres. It is critical to note that research on microplastic impacts is a new field of science and substantial research and monitoring would be required to confirm preliminary impact findings and to collect representative data before assessment could be made with confidence. This research will assist in defining what indicator would be best for assessing potential impacts. Currently it isn't clear whether impacts are correlated more with mass of microfibres, number and size of fibres, surface properties or a combination of characteristics. Affinity of the surface to harmful organic compounds is an example of additional information needed to help define a meaningful indicator. In the absence of sufficient understanding to include microplastic pollution in LCA studies by extending existing impact categories or developing new methods, we provide a preliminary discussion of the issues to be considered in moving forward. Development of international consensus on methods for quantifying and monitoring microplastic pollution from a product life cycle is dependent on ongoing research and monitoring to improve data and methods, but it is important to take actions now to address the known risk.

4.2.3 Toxicity impacts in LCA and microplastic effects

In LCA studies, available methods for life cycle impact assessment (LCIA) of eco-toxicity and human toxicity aim to account for the fate, route of exposure and toxicity impact of toxic substances when released to air, water or land.

The human toxicity impact category, which includes both carcinogenic and non-carcinogenic impacts on human health, varies with the impact pathway, fate and exposure (Hauschild et al., 2011). These variables are often poorly understood for toxic chemicals and there are few if any data to support modelling of chemicals such as organic compounds associated with microplastics and specifically with textile microfibres.

Eco-toxicity accounts for the effects of emissions on the environment in particular on individual species. Assessment uses the same fate modelling framework as human toxicity and this, along with the exposure pathways, is subject to a similar high degree of uncertainty. The fate-exposure models for eco-toxicity seek to estimate effects on freshwater, marine and terrestrial environments, although many studies are limited to freshwater species, due to lack of data. The ILCD Handbook with the UNEP-SETAC Life Cycle Initiative recommends the USEtox model (Hjubregts et al, 2010) as the default LCIA method for characterisation of human and eco-toxicity impacts but ReCiPe is used by other practitioners. In addition to attempting to quantify the end-point for toxicity impacts, the USEtox model enables estimation of a midpoint indicator in Comparative Toxic Unit for humans (CTUh). Similarly, the mid-point indicator for eco-toxicity Comparative Toxic Unit equivalents (CTUe) per is an estimate of the potentially affected fraction (PAF) of species integrated over time and volume per unit mass of a chemical emitted (PAF m^3.day/kg) (Henderson et al., 2011).

Factors contributing to the high uncertainty in LCA toxicity impact assessment modelling include: (1) poor data quality and assumptions in fate-exposure modelling, (2) variability amongst response to different chemicals, and (3) variability across geographical and demographic ranges. These sources of uncertainty are likely higher for microplastics than for other toxicity agents such as pesticides. In addition, the rapid rise in microplastic prevalence means that the dynamics of exposure to microplastic pollution cannot be related to past experience. A third point is that the wide dispersion of microplastics, particularly in marine environments, and complex food chains make modelling of exposure extremely complex. Regionalised fate models accounting for both local emission exposures and transportation of pollutants between different regions are now being developed and regional USEtox factors have been developed (Kounina et al., 2014). Recent measurements of microfibre loss from garments during washing provide some potential for use as an inventory value for monitoring improvement in 'emissions' over time in the apparel and textile industries. However, with the current level of data and process understanding it is difficult to easily translate the ILCD Handbook calculations of mid-point indicators and end-point impacts for microplastics.

Table 3 summarises the development required to account for the known impacts in LCA studies. Refer to sections on Ecosystem and Human health impacts for further detail on possible impacts.

Table 3. Potential for inclusion of microplastic chemical and physical impacts in LCA using existing impact categories.

Impact identified in microplastic studies	**Relevant LCA impact category (if any)**	**Development needed for microplastics**	**Specific issues for textile microfibres**
Physical impacts on organisms via ingestion	None Possible *Biodiversity* effect	New emissions impact method for Eco-physical harm; inventory for increased exposure possible with loss data	Microfibre loss may provide mid-point accounting
Direct chemical toxicity	Eco- toxicity; Human-toxicity	New characterisation factors	Very little data on leaching of chemical additives (e.g. dyes) from textile microfibres
Indirect chemical toxicity	Eco- toxicity; Human-toxicity	New characterisation factors for exposure or inventory	Data on enhanced levels of compounds such as PoPs with ingested textile microfibres may enable proportional inclusion in toxicity inventories in future

4.2.4 Possible mid-point indicator development

Research quantifying the number of fibres shed from textiles during washing and studies linking impact in terms of ingestion by aquatic organisms to microplastic encounter and, therefore abundance, provide a first opportunity to develop a meaningful (though preliminary) mid-point indicator for environmental impact of microfibres in life cycle analysis. Figure 8 gives a summary of factors affecting fibre shedding and emissions from textiles based on available data (Cesa et al. 2017) and this review.

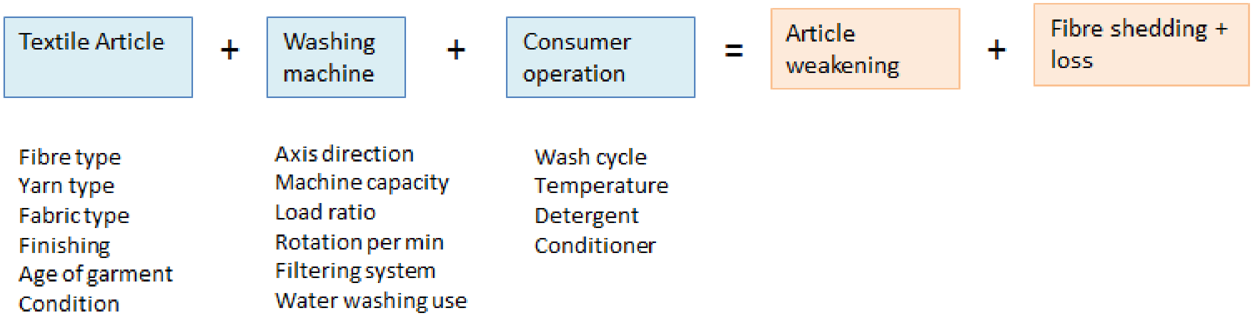


Figure 8. Stages and factors affecting the rate of shedding and emissions of microfibres from washing of textiles.

The following preliminary data are derived from the results of fibre shedding from jackets as reported by Hartline et al. (2016) for polyester with indicative modifying factors for washing machine type and age of garment. Bruce et al. (2016) found in this study that when the mass of fibre shed from jackets was normalised by the original mass of the garment, Kruskal-Wallis tests indicated that different jackets were not significantly different and the values shown in Table 4 are the average of the five polyester jackets tested. Future work may find that quality is significant for some garments. Factors for acrylic and polyester-cotton garments are derived from the trials by Napper and Thompson (2016), and it is proposed that the factor for natural, biodegradable fibres such as wool and cotton is assumed to be zero.

A recent study by Zhao et al. (2016) using a small sample size provided preliminary data that showed natural fibres (136 items) accounted for 37.4% of the total microscopic litter in the digestive tract of terrestrial birds. A decline in the proportion of natural fibres from the oesophagus to stomach to intestine suggested that, unlike synthetic fibres, they may be digestible. Research for a Masters of Science project at University of Canterbury (Brown 1994) using both laboratory and *in-situ* experiments concluded that wool is biodegradable in marine environments. Confirming this research is essential to support the assumption of a zero factor for natural fibres.

Further research is also needed on how to account for cellulosic polymers which biodegrade more slowly than natural fibres since rayon was detected in samples by Woodall et al. (2014), noting that rayon fibres from textiles could not be distinguished from those from alternative products such as cigarette filters. Napper and Thompson (2016) investigated the impact of wash temperature, detergents and conditioner products on fibre shedding during washing but results were too inconclusive to develop factors. This is an area also requiring further evaluation.

Identifying opportunities for mitigation could encourage best practice from design to consumer use and end-of-life disposal if accounting included factors reflecting differences in impact. Gaps in knowledge include:

- Evidence for differences in potential impact on ecosystems of different fibre sizes was considered insufficient at this time but incorporation should be considered when sufficient data are available.
- Regional differences in impacts would derive from differences in efficiency of waste water treatment and where evidence exists that sewage treatment retains a higher percentage of fibres in sludge and this is not released to the environment. Bruce et al. (2016) estimated that effluent from a low-polluting treatment releases only 8.2% the mass of microfibres as a high-polluting treatment.

Possible indicative factors are given in Table 4, noting that the intent in presenting these values is to provide a preliminary indication of potential inclusion in textile LCA studies only.

Table 4. Preliminary indicative factors for microfibre shedding from garments during washing, showing relativity with fabric type, wash treatment and garment aging.

Study and Treatment	**Multiplier factor (No. of persistent/plastic fibres shed)**	**Multiplier factor (Mass of persistent/plastic fibres shed)**	**% mass shed per wash**
Napper & Thompson (2016)			
Reference: Polyester garment in front-loading washer (# Fibres or mass fibres per 6kg wash)	1 (496,030)	1 (1.04 mg)	0.02%
Acrylic garment	1.5	0.92	0.02%
Polyester-cotton (65%:35%) garment	0.3	0.39	0.01%
Natural fibres (inclu. wool, cotton)	0	0	0%
Cellulosic polymer (e.g. rayon)	No data	No data	No data
Hartline et al. (2016)			
Reference: New polyester jacket in top-loading washer (mass fibres/ jacket/wash)		1 (1.8 g)	0.37%
New garment in front-loading washer		0.15	0.03%
Aged garment in top-loading washer		1.09	0.34%
Aged garment in front-loading washer		0.2	0.08%

As an initial check and data comparison, the approach is not dissimilar to a recent global modelling study undertaken on behalf of IUCN (Boucher and Friot 2017) based on activities and loss factors. Boucher and Friot (2017) assumed an average annual number of laundry cycles per capita of 55 and load per standard wash of 4 kg based on Pakula and Stamminger (2010). Global activity used regional population data from UNDP (2015) and regional synthetic shares derived from FAO/ICAC (2011). Global loss of synthetic textile microfibres was estimated for pessimistic and optimistic scenarios of 300 and 1500mg, respectively, per kg of synthetic textiles per wash, as reported in Lassen et al. (2015). The central value was taken as 900 mg/kg. Losses to wastewater streams were assumed to average 15% globally, i.e. a global treatment efficiency of 85%. This value was based on a 3 -6% release of microplastic fibres in wastewater treatments systems (Lassen et al. 2015) and 10% for overflows in Europe (Phillips et al. 2012). The high uncertainty in these numbers, especially for developing economies where data are scarce, is acknowledged. More research is needed to understand the impacts in these countries where there is greater use of hand-washing which may reduce mechanical friction but this may be countered by direct emission without filtration of fibres to waterways.

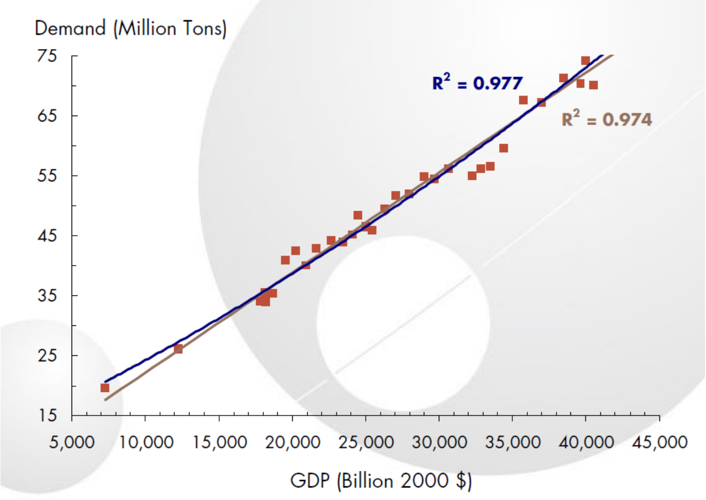
Further research is critical to credible quantification of microfibre mid-point indicators, mitigation practices and impacts but within the bounds of high uncertainty and limited data availability, there is a basis for evaluating initial possibilities to quantify a baseline and mitigation scenarios such as use of filters to reduce microfibre pollution from synthetic textiles.

5. Discussion

Microplastics, including the sub-category known as microsynthetic fibres or microfibres, are now ubiquitous in aquatic and terrestrial ecosystems globally. Their abundance is set to increase as consumption of plastics and use of synthetic fibres in clothing continues to expand with population growth and economic development particularly in Asia.

Secondary sources of microplastics include fragmentation of larger plastic items that have entered the environment in use or as waste. Primary sources i.e. direct input of micro-sized (<5 mm diameter) particles and fibres occurs through the use of microbeads in cosmetics and other personal products, abrasion of tyres on road surfaces and shedding of fibres from synthetic apparel products during washing (Eunomia 2016). Banning of microbeads in personal products across several jurisdictions including the United Kingdom and United States of America in recent years is an indication of the level of concern relating to microplastics. However, reducing microfibre pollution from tyres and textiles is seen as more difficult due to their use being less discretionary.

Demand for synthetic textiles is linked to both population growth and Gross Domestic Product (GDP) (Figure 9). As a result, total fibre consumption is expected to increase, with Tecnon OrbiChem forecasting 3.7% growth per annum to 2025. Even allowing for strong forecast growth in cellulosic fibres of around 5% annually, limited expansion in cotton and wool production means that the current trends will continue resulting in synthetic fibre making up more than 98% of the growth in total global production to 2025 as shown in Figure 6.



Source: Tecnon OrbiChem

Figure 9. Correlation of world fibre demand and global GDP. Source: http://www.orbichem.com/userfiles/APIC%202014/APIC2014_Yang_Qin.pdf , accessed March 2017).

In the absence of feasible substitutes, a ban on production and use of synthetic clothing does not appear to be politically, economically or practically possible. Consequently, policies and technologies to substantially reduce release of textile microfibres are urgently needed, in combination with consumer education programs to move away from overconsumption and arrest the current growth in 'fast fashion'. However, even if little new plastic debris contamination were added to the environment, the legacy of plastic items, including textiles discarded to landfill sites, would ensure quantities of microplastic pollution continued to increase into the future. Hence, managing microfibre pollution is both a current and future challenge for the apparel and textile industries.

The consequences of microplastic pollution of the environment are not well understood. There is evidence of ingestion of microplastic particles and fibres by marine and freshwater organisms and concern that physical, chemical and biological impacts occur through direct intake and transfer along the food chain. There is also evidence of microfibre intake in human diets through consumption of seafood, particularly shellfish. Microscopic plastic fibres appear to be of greater environmental consequence than more regular shaped microplastic particles. This is due to larger surface area for potential sorption of harmful chemicals such as PoPs and the tendency for entanglement in the digestive tract which can lead to blockages and lower likelihood of their being passed easily from the organism. The outcome can then be gradual leaching of toxic chemical additives or surface contaminants into the host organism and/or eventual starvation.

The severity of impact of microplastics is likely to be related to abundance and exposure of organisms. Experimental testing and hydrological models are beginning to provide some information on levels and fate of microfibre and other microplastic emissions in marine and freshwater systems. However, sufficiently sensitive detection and measurement techniques are still emerging and reliable monitoring periods are currently too short to provide consistent evidence for mitigation strategies.

In the case of textile microfibres, experimental results are starting to quantify shedding during washing of synthetic clothing and the factors affecting the abundance of fibres in washing machine effluent (Browne et al. 2011, Hartline et al. 2016, Napper and Thompson 2016). Some work has also looked at filter and sewage WWTP effectiveness. A study by Bren University for Patagonia stressed the need for “further research on shedding characteristics of apparel and the development of mitigation measures by producers, consumers, waste managers, and policy makers towards addressing the issue of microfibre pollution.” Another fundamental need is the development of agreed statistically relevant protocols for quantifying and monitoring microplastic prevalence in habitats and impacts on ecosystem and human health. The growing evidence of the prevalence and risk of the microfibre component of microplastics highlights the importance of developing an agreed method of including an indicator for the environmental impact of microplastic pollution in life cycle assessment studies of textile and footwear products. Potential methods and indicators are explored in this paper.

Strategies are needed to meet demand for textiles without overconsumption and without unnecessary harm to the environment or risk to human health. Napper and Thompson (2016) describe a set of criteria that synthetic garment manufacturers should consider during design and manufacture stages: (1) performance in service, giving a long-lasting product; (2) minimal release of non-degradable synthetic fibres; and (3) a product that is compatible with end of life recycling. Beginning in 2017, the US outdoor brand, Patagonia, will provide all customers who purchase a Patagonia synthetic item with information about how to care for any synthetic garment to limit the shedding of microfibres in the wash and keeping what does shed out of the ocean. Practices include less frequent washing over the life of a garment, gentler, lower chemical use washing and extending the life of the garment.

The greatest contribution to mitigating the impacts of microfibre contamination of the environment should come from arresting the extreme levels of demand and waste of synthetic textiles that has characterised the fast fashion movement over recent years. A significant contribution would come from promoting long-lasting garments (‘slow fashion’) based on increasing the proportion of natural, biodegradable fibre in the wardrobe. Fibres of plant or animal origin biodegrade naturally to harmless compounds which return essential nutrients back to soil or water for organism growth. They also have lower chemical (detergent) and energy requirements during the consumer use phase. For example, surveys (NZ Merino pers.com.) confirm that compared to equivalent apparel from other fibres, consumers wear wool more times between washing. Wool has natural odour resistance and stain repellent qualities which multiply the environmental benefits that would occur through choosing natural rather than synthetic fibre.

6. Conclusions and Recommendations

Microplastics have been found throughout aquatic and terrestrial ecosystems globally. Without intervention the growing production, consumption and waste generation of plastics together with their resistance to breakdown means that their abundance is set to increase. Much of the microplastics in aquatic environments is from secondary sources, i.e. the fragmentation of larger pieces of plastic, but a major primary source is shedding of fibres from synthetic textiles. Pathways for microplastic fibres (microfibres) entering marine, freshwater and terrestrial habitats is discharge of effluent from washing machines carrying many thousands of fibres shed from synthetic garments.

The impacts of microplastic pollution in the environment are not well understood. There is evidence that ecosystems are potentially affected through physical, chemical and possibly biological pathways. Chemical pathways may be either being direct through leaching of harmful compounds from plastic compounds or indirect via adsorption of chemicals in solution onto the hydrophobic surface of microplastics and then uptake and subsequent release after ingestion. Microfibres appear to be of greater environmental consequence than more regular shaped microplastic particles and transfer in the food chain has potential to impact human health. Consumption by humans of seafood, particularly shellfish, has potential health consequences particularly where microfibres act as a vector for introduction of harmful organic compounds such as polychlorinated biphenyls (PCBs) that adsorb onto the hydrophobic surface of plastics in aquatic environments. More research is needed but microfibre loss from washing of synthetic clothing appears to be affected by textile type the quality and age of a garment and by laundry practices, including, type of washing machine, use of detergents, wash temperature, filter and sewage waste-water treatment plant effectiveness.

Another requirement is for robust protocols for quantifying and monitoring microfibre losses and their prevalence and impacts on ecosystem and human health to provide robust data for impact assessment. Life cycle assessment (LCA) is the tool most widely applied to monitoring environmental performance of products at this time but, to the authors' knowledge, no LCA studies have so far included impacts of microplastic pollution. We discuss the research and data requirements to enable LCA methods to be developed and conclude that current LCA methods for estimating eco-toxicity and human toxicity categories provide a possible avenue for including chemical impacts when data are available, but that physical impacts would require a new approach. At this time, development of methods or mid-point indicators for microfibres in LCA is hampered by the knowledge gaps in mechanisms of action, e.g. whether it is more aligned to mass or number of microfibres to which a system is exposed.

In summary, more research is needed to better understand the contributions to microplastic pollution from textiles, and effective options for management and mitigation. However, review of research to date provides important insights, including:

- Manufacturers and consumers of synthetic textiles should invest in higher quality garments which appear to shed less in the wash than low-quality products, and which are constructed to be more durable so are used longer and kept out of landfill hence reducing secondary sources of microplastics.
- Use of front-loading washing machines and gentler cycles are preferred as they result in lower fibre shedding than alternative laundry practices.
- Shedding of microfibres will likely be lower if garments are washed less often with milder detergents.
- Use of technology such as improved filters in washing machines together with education of consumers and businesses on their management will reduce the amount of microfibres entering laundry effluent.

- Wastewater treatment plants filter much of the microfibre load from effluent but the range of effectiveness varies from 65–92 % offering significant scope for reduction in amounts released into the environment through improvements in lower-end facilities.
- A key action to reduce microsynthetic fibre pollution must be maximising the proportion of natural fibre in global textile products since there is evidence that these biodegrade relatively rapidly and do not accumulate in the environment in the same way as synthetics such as polyester and nylon.
- In addition to fibre biodegradability, the natural properties of wool apparel and textiles such as odour resistance and stain repellent surface characteristics favour less shedding to the environment due to less frequent, lower impact washing, greater durability, and established pathways for recycling.

It is recommended that:

1. Targeted research is undertaken to provide data and process understanding to model the production and fate of microplastic pollution and to develop indicators for inclusion of the impacts on ecosystems and human health in LCA studies.
2. Current understanding of the magnitude of microplastics in the environment and ecological and human health risks form the basis of mitigation programs while ongoing research addresses knowledge gaps. Examples of evidence-based options include::
    - Investment by manufacturers and consumers of synthetic textiles in higher quality garments because (1) they shed less in the wash than low-quality products, and (2) they are constructed to be more durable so are used longer and kept out of landfill.
    - Selection of front-loading washing machines which result in lower fibre shedding than a top-loader.
    - Washing less often on a gentler wash cycle with milder detergents will also generally reduce shedding.
    - Reducing microfibre release to the environment from wastewater treatment plants to increase the effectiveness of filtering of effluent above current levels reported to be 65–92 %.
    - Development, testing and use of technology such as improved filters in washing machines that may reduce the amount of microfibres entering wastewater effluent and education of consumers and businesses is an important step.
    - Maximising the proportion of natural non-synthetic materials in global textile markets since these fibres, particularly wool, biodegrade in marine (Brown 1994) as well as terrestrial environments, require less frequent, lower impact washing, have greater durability, and established pathways for recycling.

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Appendix A

Summary and characteristics of microplastics in the environment where textile microfibres were dominant (Cesa et al. 2017).

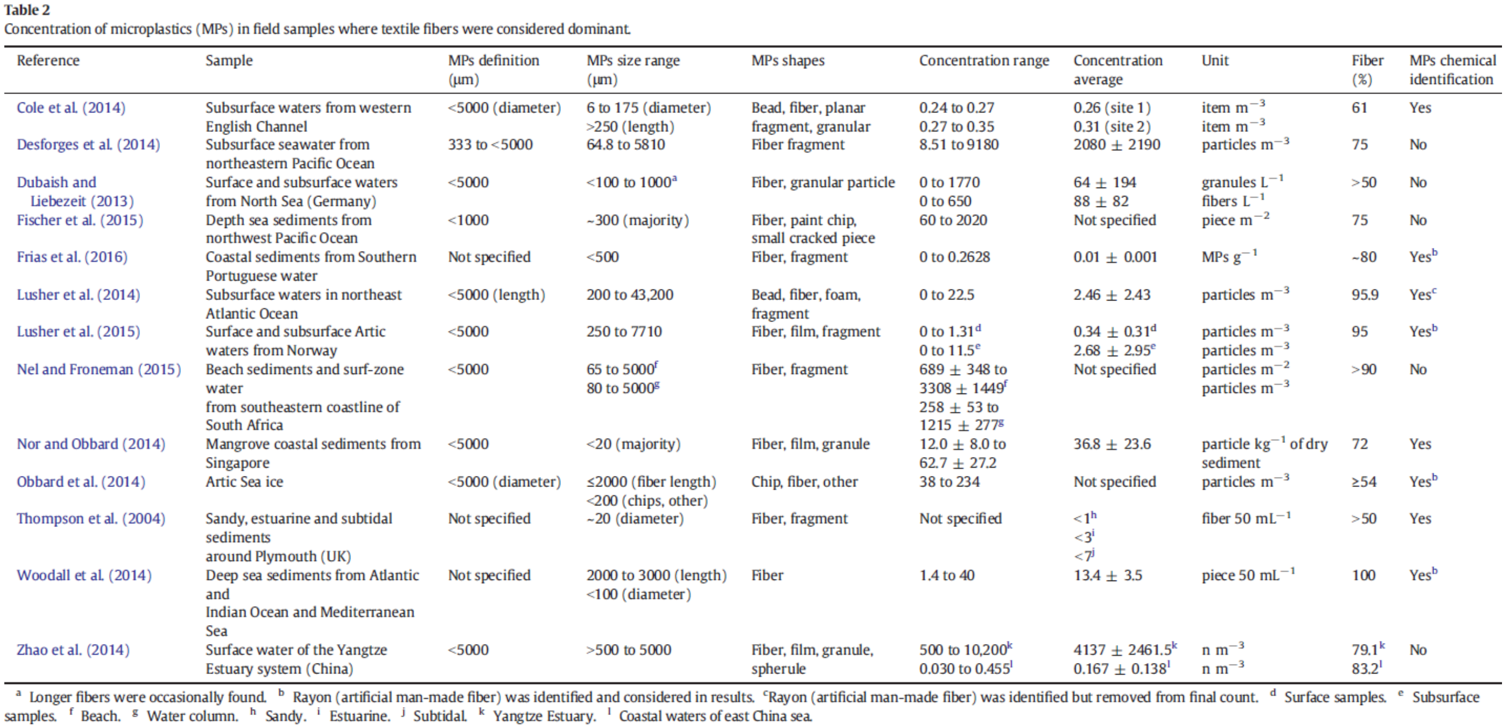


Table 2
Concentration of microplastics (MPs) in field samples where textile fibers were considered dominant.

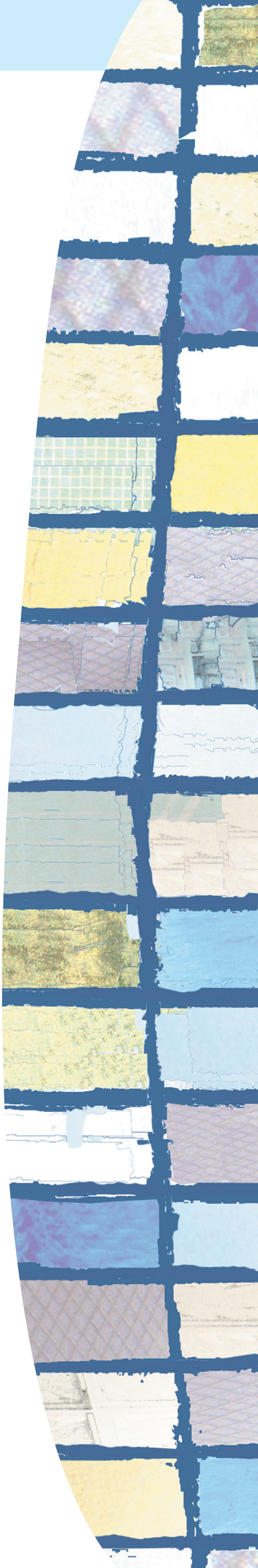
Reference	Sample	MPs definition (μm)	MPs size range (μm)	MPs shapes	Concentration range	Concentration average	Unit	Fiber (%)	MPs chemical identification
Cole et al. (2014)	Subsurface waters from western English Channel	<5000 (diameter)	6 to 175 (diameter) >250 (length)	Bead, fiber, planar fragment, granular	0.24 to 0.27 0.27 to 0.35	0.26 (site 1) 0.31 (site 2)	item m^{-3} item m^{-3}	61	Yes
Desforges et al. (2014)	Subsurface seawater from northeastern Pacific Ocean	333 to <5000	64.8 to 5810	Fiber fragment	8.51 to 9180	2080 ± 2190	particles m^{-3}	75	No
Dubaish and Liebezeit (2013)	Surface and subsurface waters from North Sea (Germany)	<5000	<100 to 1000^{a}	Fiber, granular particle	0 to 1770 0 to 650	64 ± 194 88 ± 82	granules L^{-1} fibers L^{-1}	>50	No
Fischer et al. (2015)	Depth sea sediments from northwest Pacific Ocean	<1000	~300 (majority)	Fiber, paint chip, small cracked piece	60 to 2020	Not specified	piece m^{-2}	75	No
Frias et al. (2016)	Coastal sediments from Southern Portuguese water	Not specified	<500	Fiber, fragment	0 to 0.2628	0.01 ± 0.001	MPs g^{-1}	~80	Yes^{b}
Lusher et al. (2014)	Subsurface waters in northeast Atlantic Ocean	<5000 (length)	200 to 43,200	Bead, fiber, foam, fragment	0 to 22.5	2.46 ± 2.43	particles m^{-3}	95.9	Yes^{c}
Lusher et al. (2015)	Surface and subsurface Artic waters from Norway	<5000	250 to 7710	Fiber, film, fragment	0 to 1.31^{d} 0 to 11.5^{e}	0.34 ± 0.31^{d} 2.68 ± 2.95^{e}	particles m^{-3} particles m^{-3}	95	Yes^{b}
Nel and Froneman (2015)	Beach sediments and surf-zone water from southeastern coastline of South Africa	<5000	65 to 5000^{f} 80 to 5000^{g}	Fiber, fragment	689 ± 348 to 3308 ± 1449^{f} 258 ± 53 to 1215 ± 277^{g}	Not specified	particles m^{-2} particles m^{-3}	>90	No
Nor and Obbard (2014)	Mangrove coastal sediments from Singapore	<5000	<20 (majority)	Fiber, film, granule	12.0 ± 8.0 to 62.7 ± 27.2	36.8 ± 23.6	particle kg^{-1} of dry sediment	72	Yes
Obbard et al. (2014)	Artic Sea ice	<5000 (diameter)	≤2000 (fiber length) <200 (chips, other)	Chip, fiber, other	38 to 234	Not specified	particles m^{-3}	≥54	Yes^{b}
Thompson et al. (2004)	Sandy, estuarine and subtidal sediments around Plymouth (UK)	Not specified	~20 (diameter)	Fiber, fragment	Not specified	<1^{h} <3^{i} <7^{j}	fiber 50 mL^{-1}	>50	Yes
Woodall et al. (2014)	Deep sea sediments from Atlantic and Indian Ocean and Mediterranean Sea	Not specified	2000 to 3000 (length) <100 (diameter)	Fiber	1.4 to 40	13.4 ± 3.5	piece 50 mL^{-1}	100	Yes^{b}
Zhao et al. (2014)	Surface water of the Yangtze Estuary system (China)	<5000	>500 to 5000	Fiber, film, granule, spherule	500 to 10,200^{k} 0.030 to 0.455^{l}	4137 ± 2461.5^{k} 0.167 ± 0.138^{l}	n m^{-3} n m^{-3}	79.1^{k} 83.2^{l}	No

[a] Longer fibers were occasionally found. [b] Rayon (artificial man-made fiber) was identified and considered in results. [c] Rayon (artificial man-made fiber) was identified but removed from final count. [d] Surface samples. [e] Subsurface samples. [f] Beach. [g] Water column. [h] Sandy. [i] Estuarine. [j] Subtidal. [k] Yangtze Estuary. [l] Coastal waters of east China sea.

Consumption Research Norway SIFO at Oslo and Akershus University College of Applied Sciences (HiOA) has a special responsibility to contribute to the knowledge base for consumer policy in Norway and will develop new knowledge about consumption, consumer policy and consumer position and role in society.

Key research topics are:

- consumers in the market and consumer choice
- household resource allocations
- consumer economy - debt development and poverty
- technological development and consumers' every day life
- digital daily life and coping
- environmental effects of different types of consumption
- food and eating habits
- textiles - value chains - consequences for everyday life and environment
- consumption significance for social inclusion
- consumer policy



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