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Biodegradation of Textile Fabrics Info-sheets

Design for Transformation Initiative

By Libby Sommer, Principal at Libby Sommer LLC and Strategic Advisor to The Biomimicry Institute
Based on a literature review conducted by Olivia Skilbeck and Dr. Richard Blackburn, Leeds University.

Thanks to Dr. Tom Federle for his early guidance and support.

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Infosheet #1: Understanding Biodegradation & Textiles

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Introduction

This is the first of three Infosheets which originated from conversations within the Design for Transformation Initiative.[1] In nature, biodegradation is a critical process for managing waste. In the textile industry, it's considered an important component of circularity.[2] Yet, understanding of biodegradation is often muddled, and claims of biodegradability are often misrepresented. These Infosheets aim to empower individuals across the textile, apparel, and fashion sectors to better understand and to ask informed questions about biodegradability. Additionally, since fragments from all textiles are found throughout the natural environment, there is a call for testing to clarify the impact of these materials as they break down. Where supported by data, solutions focused on redesigning materials to minimize environmental impact upon their release are described.

Highlights

- **Biodegradation is carried out by microorganisms (namely bacteria and fungi).**

- **Biodegradation is the outcome of two equally important factors: 1) the physical form and chemical structure of the textile, material, or product; and 2) the environmental conditions into which the textile, material or product goes.** The

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[1] Also check out *Infosheet #2: Biodegradation and Toxicity of Natural & Manmade Cellulosic Textiles*, and *Infosheet #3: Biodegradation and Toxicity of Synthetic Textiles.*
[2] https://biomimicry.org/thenatureoffashion/

former determines whether a textile has the potential to biodegrade, while the latter determines whether in practice biodegradation occurs.

- **Textiles that have the potential to be biodegradable will not break down in environmental conditions that don't support the microorganisms necessary for biodegradation**, e.g., in cold environments.

- **Some textiles are effectively 'non-biodegradable'[3] in any environment.** It is the physical and chemical structure of textiles that impacts the potential to be biodegradable (not whether the material comes from petroleum or natural sources).

- **Toxicity (to humans and the environment) from the degradation of all textiles is poorly understood including the potential for exposure to hazardous chemistry and to microfibers.**

- **Designing for biodegradability also requires designing for low toxicity.** Hazardous finishes and treatments have the potential to reduce biodegradability and increase toxicity.

Definitions

- ***Biodegradation*** is the conversion of complex substances by microorganisms, such as fungi and bacteria, into smaller, simpler, ideally non-toxic compounds.
    - Something is considered ***ultimately biodegraded*** when it is completely converted by microorganisms to carbon dioxide, water, and biomass.
    - ***Primary biodegradation*** is a step towards ultimate biodegradation. It is the structural change (transformation) of a material by microorganisms resulting in the loss of a specific property (ECETOC, 2014).
- ***Biodegradability*** describes the theoretical capacity of something to be broken down via microorganisms.
- ***Composting*** is a controlled series of physical, mechanical and biological processes that break down materials into decayed organic matter (aka compost). Biodegradation is one of the steps in the composting process.
- ***Compostability*** is the ability of a product to be composted. It is typically measured via standardized test methods.

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[3] *Recalcitrant* or *persistent* are terms often used to describe something that is not biodegradable.

- A ***microfiber*** (sometimes also called a “fiber fragment”) is a fiber in the micro-scale that is characterized by a thin, fibrous shape. (Moody Wood et al., 2022)
- ***Toxicity*** is the ability of a substance to cause harmful effects to an organism.

What is Biodegradation?

"Biodegradation" and "biodegradable" - these are terms with which most people are familiar. Intuitively, fresh fruits and veggies decompose (biodegrade). Leaves and trees also decompose, albeit at varying rates. However, two important aspects of biodegradation are frequently overlooked: the influence of physical form and chemical structure on biodegradability (for instance, leaves degrade more quickly than fallen trees) and the significant impact of the surrounding environment on the rate and completeness of degradation.

Biodegradation - or, *the conversion of complex substances by microorganisms into smaller, simpler, ideally non-toxic compounds* - is fundamentally the outcome of two equally important factors:

1. The physical form and chemical structure of the textile, material, or product, and
2. The environmental conditions into which the textile, material or product goes.

Consider a piece of fruit, perhaps a strawberry, in the fridge compared to another strawberry on the kitchen counter. It's probable that the fruit on the counter will biodegrade more quickly. The warmer ambient temperature increases the likelihood of microbial growth leading to faster spoilage (biodegradation). These environmental conditions influence the rate of biodegradation.

Now compare that piece of fruit to an onion just brought home from the supermarket. Which of these will biodegrade more quickly? Likely the fruit. Among the reasons for this, fruit contains a higher proportion of sugars (small molecules) that are more easily accessible to bacteria, fungi, and other microorganisms. Eventually, both will biodegrade, but at different rates. The chemical structure and physical form of the strawberry and onion affect susceptibility to microorganisms, thereby impacting biodegradability. These same concepts apply to textiles.

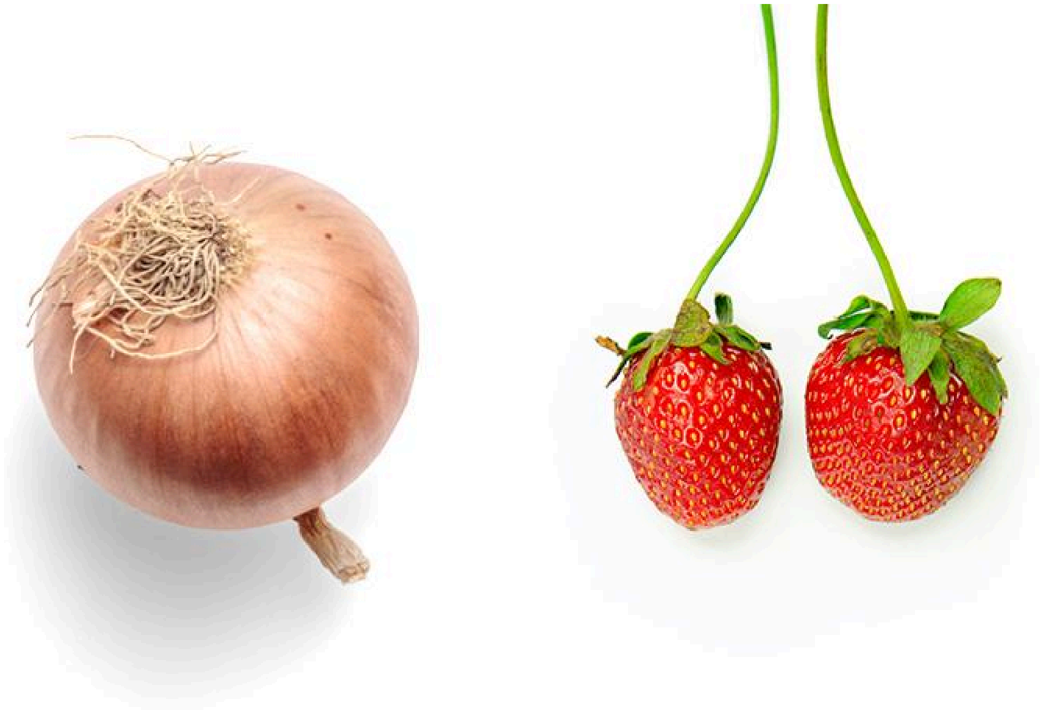

Figure 1: On your kitchen counter, a strawberry likely biodegrades more quickly than an onion due to its inherent chemical and physical structure, which makes it more accessible to microorganisms.

The physical form and chemical structure of the textile dictates whether it has the potential to be biodegradable, while the environmental conditions determine whether in practice a potentially biodegradable textile does in fact biodegrade.

The Role of Environmental Conditions in Biodegradation

Microorganisms, like all life, require basic necessities for survival. However, their ability to thrive depends on specific conditions such as moisture levels, temperature, and oxygen availability. Biodegradation occurs more readily under favorable conditions where these factors are abundant. Conversely, biodegradation may be hindered or delayed under less optimal environmental conditions, such as in arid environments, cooler temperatures, or those with limited oxygen. Table 1 below outlines key environmental factors influencing the likelihood of biodegradation.

Table 1: Environmental conditions affecting biodegradation

Reduces the Likelihood of Biodegradation	Promotes Biodegradation
Cold temperature	Warm temperature
Short time period	Long time period
Low moisture	High moisture
Insufficient nutrients (nitrogen, phosphorous, iron, trace elements)	Sufficient nutrients (nitrogen, phosphorous, iron, trace elements)
Little to no sunlight	Lots of sunlight
Low oxygen	High oxygen

Materials that have the potential to biodegrade might not do so when environmental conditions do not support microbial activity. Take for example cotton denim, a fiber that most might imagine to be biodegradable. Let's compare this material in two environmental extremes - one very cold, and the other quite warm.

In September 1857, the *SS Central America* capsized in the Atlantic Ocean. For more than 100 years, the ship and all its contents lay at the bottom of the ocean where the surrounding environment was cold, dark, and low in available nutrients. After the contents of the shipwreck were recovered in the late 1980s, a pair of denim jeans made prior to September 1857 were found stained, but intact, even "supple." (Kuta, 2022)

Figure 2: Denim pants recovered from the SS Central America, which capsized in 1857. Courtesy of Holabird Western Americana Collections.

In a composting study by Cornell University published in 2024, a variety of denim fabric samples were tested with many of the samples substantially degraded in less than three months (Alwala, 2024). Similar materials, in this case denim, will not biodegrade in the same manner in all environments. This is likely one of the reasons why fragments from natural fibers are commonly detected in oceans around the world. Among the issues, marine environments often lack key nutrients, such as iron, making environmental conditions challenging for microorganisms.

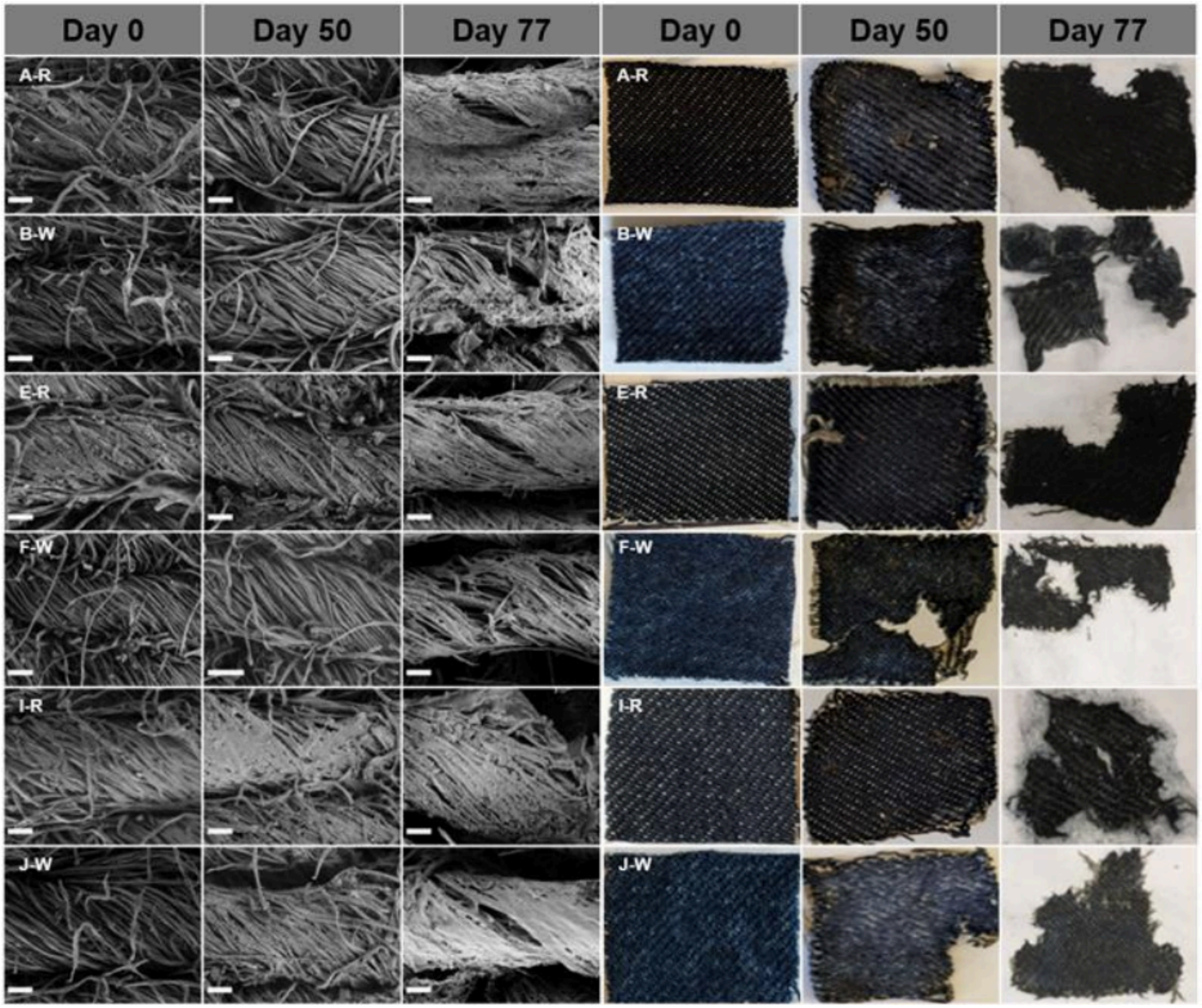

Figure 3: Denim fabric samples from Cornell University composting study. Source: Alwala et al., 2024.

The Role of Physical Form and Chemical Structure on Biodegradation

The strawberry and onion from our earlier example biodegrade at dramatically different rates in the same environment. Their physical and chemical properties explain these differences. Onions are about 90% polysaccharides, which are large molecules (Kumari et al., 2022). Strawberries by contrast are about 90% water and 5% sugars, the latter being a small molecule (Bjarnadottir, 2019; Cotton, 2024). As shown in Table 2, affinity for water (and relatedly, water content) is a positive for biodegradability. An onion's chemical structure, which includes a high proportion of large molecules, decreases the rate of biodegradability relative to the small molecules in strawberries.

Table 2: Physical and chemical characteristics affecting the potential for biodegradability

Decreases Biodegradability (Increases Persistence)	Increases Biodegradability (Decreases Persistence)
Crystallinity (a measure of how highly structured a molecule is)	Amorphous regions (random molecular shape)
Insolubility in water	Solubility in water
Hydrophobicity (repels water)	Hydrophilicity (affinity to water)
Large molecule[4], such as polymers	Small molecule (non-polymeric)
Molecular arrangement is dissimilar to naturally occurring materials[5]	Molecular arrangement similar to naturally occurring materials
Less surface area	More surface area

In the textile world, the effect of physical form and chemical structure is apparent in the biodegradability of textiles. Ignoring for a moment the impact to biodegradability from chemical finishes and treatments common to all textiles, cotton has a high affinity to water (hydrophilicity), and is made primarily of cellulose, a common naturally occurring polymer. Polyester is hydrophobic, composed of a polymer that is dissimilar to naturally occurring materials, and is semi-crystalline. Therefore it’s not surprising that in environments where biodegradation can occur, untreated cotton tends to biodegrade whereas polyester shows minimal evidence of decomposition.

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[4] The size of a molecule is typically characterized by the molecular weight which is measured in Daltons. A common criterion for large molecules is a molecular weight >500 Daltons.

[5] Biodegradation usually begins with the release of enzymes from microorganisms. The process is analogous to a lock and key. Only certain keys will open a given lock. When materials are dissimilar enough from naturally occurring substances, the enzymes are not able to function or “unlock” the biodegradation process.

Misconceptions about Biodegradability: Laboratory testing confirms whether or not something is biodegradable.
Laboratory studies (i.e., those carried out in artificial environments) show whether something can biodegrade in a specific set of conditions, but often lack transferability to real world conditions. Field studies and other such experiments done in environmentally relevant testing conditions are necessary to show whether, in practice, something does biodegrade in the conditions it is most likely to be found. Even then, due to the shedding and dispersal of all textiles, it is impossible to test for all conditions into which they are released.

Toxicity of Textiles During Degradation

All textiles have the potential to “degrade” into smaller particles (such as microfibers) through physical processes like abrasion and UV exposure. Finishes and treatments can affect the degree to which biodegradable textiles actually do biodegrade. Both synthetic and natural materials have the potential to sorb (or take up) pollutants. When they are ingested or inhaled, fish, birds, humans and many other organisms can be exposed to these substances. At present, the impacts here are poorly understood. Further testing is required to support the redesign of textiles for a safer end-of-life. As Ladewig et al., 2015 states, “Researching both synthetic and natural fibers together to understand the specifics of their roles in the…environment will help to fill gaps in knowledge and also link key points in the transport and fate of chemical pollutants in the…environment.”

Putting Biodegradation into Context in the Circular Economy

Biodegradation is a critical waste management process, and an important part of creating a circular economy. Designing textiles to be biodegradable increases the likelihood of them breaking down once released into the environment. Since nearly all textiles are modified with mechanical & chemical finishes and treatments, better understanding of how these affect toxicity is important. At a minimum, removing hazardous substances from the textile production process is a good first step.

While biodegradability is necessary for the circular economy, it is not sufficient to bring this industry in alignment with planetary boundaries.[6] First and foremost, efforts to create a circular economy should:

- Address overproduction, overconsumption, and underutilization of textiles. Already textile fiber production has nearly doubled from 7.6 kg of fibers per person in 1995 to approximately 14 kg in 2018. (Weis et al., 2022)
- Products, once made, should be kept in circulation as long as possible.
- Products should be able to be disassembled for reuse, recovery and recycling.
- When materials and components of products are no longer able to be used, they should be able to be broken down through biological mechanisms (aka biorecycling).
- Where biodegradation is the desired end-of-life of textiles, infrastructure should be designed with conditions that promote biodegradability.
- Finally, as there is leakage in any system including textiles, materials should be designed for biodegradability and low toxicity.

Misconceptions about Biodegradability: If something is “biodegradable” that means it will degrade anywhere it is disposed of.

Unless you’ve skipped the sections above, you already know that biodegradability is the outcome of both the properties of a material as well as the environment into which it is disposed. For materials that in theory have the potential to biodegrade, their practical biodegradability out in the world is largely dependent on environmental conditions. It’s possible that the same material may biodegrade completely in one environment, and not at all in another.

When making a biodegradability claim on any product, the timeframe and environment where biodegradation will occur should be clearly stated.

For more about the biodegradation of natural and manmade cellulosic materials, check out *Infosheet #2: Biodegradation and Toxicity of Natural & Manmade Cellulosic Textiles*. For more about the biodegradation and toxicity of synthetic materials see *Infosheet #3: Biodegradation and Toxicity of Synthetic Textiles*.

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[6] https://www.stockholmresilience.org/research/research-news/2021-04-12-six-targets-for-a-sustainable-textile-industry.html#:~:text=The%20fashion%20and%20textiles%20industry%20is%20putting%20increasing%20pressure%20on,current%20trends%20intensify%20the%20risks.

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Infosheet #2: Biodegradation and Toxicity of Natural & Manmade Cellulosic Textiles

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Highlights

- **When environmental conditions are suitable to sustain biodegradation, unmodified natural and manmade cellulosic textiles (such as cotton, viscose and lyocell) are likely to break down over time.** The speed and completeness of biodegradation depends upon finishes and treatments that may be present as well as the ambient conditions where the material is disposed.

- **The vast majority of natural and manmade cellulosic fibers undergo physical and chemical processing that can impact biodegradability (positively or negatively).** In this infosheet, the term “unmodified” refers to fibers that have not undergone such processing.

- **Some finishes and treatments on these fibers delay or impede biodegradation despite the presence of suitable environmental conditions for biodegradation.** Antimicrobials and easy care finishes are notable examples.

- **There is no meaningful difference in the rate of biodegradability of unmodified cotton vs. unmodified manmade cellulosics.**

- **While unmodified natural fiber and manmade cellulosic textiles can biodegrade completely, they do not always biodegrade quickly in the natural environment.** ‘Biodegradable’ textiles may take weeks to months to completely break down. Fibers from all types of textiles including natural and manmade cellulosic are found around the world.

- **It is unknown the extent to which finishes and treatments on natural and manmade cellulosic textiles are released during biodegradation, and whether such chemistry is toxic to people or the environment.** There are mixed results about impact. Further study is warranted given the bioavailability of these textiles.

Definitions

- **Manmade cellulosic fibers** (MMCFs) are regenerated fibers usually made from the dissolved wood pulp or "cellulose" of plants. Viscose, lyocell, and modal are examples of manmade cellulosics. MMCFs are also known as *regenerated cellulosics* or *semi-synthetics*. In this Infosheet, the term manmade cellulosics is used in alignment with terminology from the Textile Exchange.

- **Mercerization** is a textile finishing process involving sodium hydroxide applied to cotton yarns or fabrics to increase luster and dyeability. Those processes also changes the structure of the cellulose in the cotton from Cellulose I (more crystalline) to Cellulose II (less crystalline).

What Affects the Biodegradability of Natural and Manmade Fibers?

If you haven't already, please read the introductory *Infosheet #1: Understanding Biodegradation & Textiles.* As described there, biodegradability is the outcome of both the physical and chemical structure of the textile as well as the environmental conditions where the textile is disposed of.

Where environmental conditions are suitable to sustain biodegradation, undyed and unfinished materials based on naturally occurring polymers such as cotton, linen, rayon, lyocell, and wool are likely to biodegrade eventually. However, many environments do not always provide such suitable conditions. Further, how quickly and completely these materials biodegrade depends upon the finishes and treatments that may be present.

In our review of the literature, we found that finishes that are designed to impact microorganisms, specifically antimicrobial treatments, reduce and sometimes stall the biodegradation of natural fibers. Additionally, there is evidence that finishes and treatments that bond to fabric via cross-linking, such as easy care finishes, also impede biodegradability. Dyes and water repellent treatments delayed the initial start of biodegradation, increasing the overall time it takes for the textile to biodegrade. Softeners appeared to speed up the start of biodegradation reducing the overall time frame for biodegradation. Zambrano et al., 2021 states that softeners are “composed mainly of surfactants that can promote the attachment of different microorganisms to the surface of the fabric, thus, improving the biodegradation rate in soil.” Lastly, some data were available to evaluate the impact of converting from Cellulose I (more crystalline) to Cellulose II (less crystalline), which occurs during mercerization and in the creation of manmade cellulosics. Overall, there was little meaningful difference in the biodegradability of those two forms of cellulose.

Table 1: Common Finishes and Treatments and the Impact to Biodegradability

Finish or Treatment	**Impact to Biodegradability**	
Antimicrobial treatments	⇣	Reduces and may even stall biodegradability of textiles. Antimicrobial treatments target microorganisms, which are necessary for biodegradation (Lykaki et al., 2021 and Smith et al., 2021.)
Easy care and durable press finishes	⇣	Easy-care finishes reduce the total biodegradation of textiles and time taken for textiles to biodegrade in simulated laboratory soil and water environments. (Li et al., 2010; Smith et al., 2021; Zambrano et al., 2021). When the rate of biodegradation of a textile finished with easy-care was measured, it was significantly lower than other textile finishes (Zambrano et al., 2021).
Dyes	🕒	The total level of biodegradation is not changed in textiles due to the addition of dyes; however, dyes are shown to increase the time it takes a textile to biodegrade (Kim et al., 2022; Lykaki et al., 2021; Zambrano et al., 2021).
Water repellents	🕒	Rate of biodegradation is reduced. Textiles finished with water repellents take longer to biodegrade and longer for biodegradation to begin (Kim et al., 2022; Smith et al., 2021; Zambrano et al., 2021).
Softeners	⏱	Impact of softeners showed no significant difference to total biodegradation in an environment (Lykaki et al., 2021; Zambrano

Finish or Treatment	Impact to Biodegradability	
		et al., 2021). However, these textiles take a shorter time to biodegrade due to a smaller lag time from when biodegradation can start (2.3 ± 1.5 days) (Li et al., 2010; Zambrano et al., 2021).
Mercerized and Manmade Cellulosic Fibers	=	No significant difference was observed between the biodegradability of mercerized and manmade cellulosics vs. unmodified natural fibers (Nagamine et al., 2022; Zambrano et al., 2020; Zambrano et al., 2019; Lykaki et al., 2021).

Can Natural and Manmade Cellulosic Textiles Become Toxic During Biodegradation?

It's important to recognize that natural and manmade cellulosic fibers are almost always significantly altered via chemical and physical processes during textile production. The treatments and finishes mentioned above represent a small portion of the estimated 8,000 chemical compounds used across the entire textile production chain (Weis et al., 2022). In our search for information about the toxicity of treated and untreated textiles as they biodegrade, we found a severe lack of data. Further, the fragmentation of natural and manmade cellulosics into microfibers is understudied, and needs more attention due to the unique properties of these textiles which make them more bioavailable - a good thing for biodegradability, but possibly a downside if there are toxicity concerns.

Just a few studies have assessed the toxicity of chemistry applied to textiles. For example, a handful of studies evaluated the impacts of reactive dyes after application to the textile and during biodegradation. These studies found that toxicity is often reduced when dyes are bound to textiles and this continues to be the case as the textiles degrade (Leme et al., 2014; Barathi et al., 2020; Gottlieb et al., 2003; Klemola et al., 2007).

While the data above suggest lowered concern for reactive dyes as textiles biodegrade, the many remaining chemicals used in finishes and treatments are unstudied. This becomes an important question to address because the physical properties of natural fibers mean these are more likely to take up and hold ("sorb" in the parlance of chemists) chemicals, and their more rapid break down relative to synthetics "may increase the rate of delivery of toxicants into the environment and to organisms, relative to more slowly degrading synthetic fibers (Weis et al., 2022)."

Conclusions

Textiles from natural sources can provide a number of sustainability benefits depending on the production system. During the production of all textiles, significant physical and chemical processes are carried out. Some of these processes appear to affect biodegradability (either increasing or decreasing it). Finally, as there is leakage in any system including textiles, materials should be designed for biodegradability and low toxicity. In regards to the last point, what can be said, and strongly recommended, is that designing out hazardous chemicals from production systems will pay dividends. Industry Restricted Substances Lists (RSLs) are an important step, but greater supply chain communication and action to remove persistent, toxic, and bioaccumulative chemistry is needed.

Summary of Biodegradation Testing

When interpreting biodegradation studies, a useful rule of thumb is >60-70% degradation indicates that ultimate (complete) biodegradation has likely taken place in that study.[7] Weight and tensile strength loss can indicate some form of degradation, though they do not strictly imply biodegradation.

Material	**Form**	**Time (days)**	**Conditions**	**Results**	**Method**	**Reference**
Unmodified Cotton	Yarn	33	Seawater	48.5%	ASTM D6691	Zambrano et al., 2020
	Yarn	35	Lake water	77.22%	ISO 14851	
	Yarn	38	Activated sludge	89.12%	ISO 14851	
	Fabric	42	Seawater	25-57% depending on yarn count & weave density	Non-standard method	Kim et al., 2022
	Fabric	42	Soil	100% tensile strength loss		
	Fiber	60	Activated sludge	70%	ISO 14851	Lykaki et al., 2021
	Fabric	90	Soil / Composting	23%	ASTM D 5988	Li et al., 2010
	Fabric	77	Soil	95% weight loss	Non-standard method	Warnock et al., 2009
	Fabric	102	Activated sludge	72.2%	ISO 14851	Zambrano et al., 2021
	Yarn	250	Seawater	77%	ISO 14851	Zambrano et

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[7] This rule of thumb is shared with a note of caution. The details of the biodegradation study such as test conditions and rate of biodegradation should always be considered before applying this criterion.

Material	Form	Time (days)	Conditions	Results	Method	Reference
						al., 2019
Modified Cotton	Fabric + Water Repellent	42	Seawater	2.6%	Non-standard method	Kim et al., 2022
	Fabric + Softener	90	Soil / Composting	27%	ASTM D 5988	Li et al., 2010
	Fabric w/Resin + Softener	90	Soil / Composting	16%		
	Fabric + Reactive Dye	102	Activated sludge	66.22%	ISO 14851	Zambrano et al., 2021
	Fabric + Durable Press Finish			63%		
	Fabric + Softener			89.6%		
	Fabric + C6 DWR			74.9%		
	Fabric + Water Repellent	154	Soil / Composting	Decreased biodegradation relative to untreated fabric	ASTM D 5988	Smith et al., 2021
Rayon / Viscose	Yarn	33	Seawater	45.87%	ASTM D6691	Zambrano et al., 2020
	Yarn	35	Lake water	72.71%	ISO 14851	
	Yarn	38	Activated sludge	87.01%	ISO 14851	
	Fabric	42	Field soil burial	95% weight loss	Non-standard method	Warnock et al., 2009

Material	**Form**	**Time (days)**	**Conditions**	**Results**	**Method**	**Reference**
	Fiber	60	Activated sludge	85%	ISO 14851	Lykaki et al., 2021
	Yarn	250	Seawater	61%	ISO 14851	Zambrano et al., 2019
Modified Rayon/ Viscose	Fiber + Reactive Dye	60	Activated sludge	72–75%	ISO 14851	Lykaki et al., 2021
	Fiber + Antimicrobial			~10%		
Lyocell	Tencel™	112	Field soil burial	~60% weight loss	Non-standard method	Warnock et al., 2009
Unmodified Ramie	Fiber	30	Seawater	10-14%	Non-standard method	Nagamine et al., 2022
			River water	40-50%		
Modified Ramie	Mercerized Fiber	30	Seawater	4-10%	Non-standard method	Nagamine et al., 2022
			River water	34%		
Manmade Cellulosic	Fiber	30	Seawater	2-6%	Non-standard method	Nagamine et al., 2022
			River water	34-38%		

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Infosheet #3: Biodegradation and Toxicity of Synthetic Textiles

Design for Transformation Initiative

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Based on a literature review conducted by Olivia Skilbeck and Dr. Richard Blackburn, Leeds University

Highlights

- **Synthetic materials such as polyester (PET) and nylon show no appreciable level of biodegradation in any environmental compartment.**

- **Though biodegradation data for common synthetics such as acrylic, elastane and polyurethane were not found, these synthetics are also unlikely to be biodegradable in any environmental compartment.**

- **Whether the feedstock for a material is bio-based or fossil-based has no bearing on biodegradability or toxicity.** It is the chemical and physical structure of synthetic materials that make them resistant to biodegradation. Similarly, toxicity is related to structure rather than origin of feedstock.

- **While synthetic materials are generally resistant to biodegradation, they can undergo physical changes such as deterioration and disintegration** due to abrasion, UV degradation and other non-biological processes.

- **It is unknown the extent to which chemistry used in finishes and treatments is released during degradation, and whether such chemistry is toxic to people or the environment.**

Definitions

- A **microfiber** (sometimes also called a "fiber fragment") is a fiber in the micro-scale that is characterized by a thin, fibrous shape. (Moody Wood et al., 2022)

Biodegradability of Synthetic Textiles

It's often stated that synthetics such as polyester are not biodegradable. But what does this mean? Indeed there is no consistent time frame for claims of biodegradability. In industrial composting studies, the maximum time allowed to demonstrate complete breakdown is typically 180 days (SPI: The Plastics Industry Trade Association, 2016). In other studies, especially in freshwater environments, biodegradation is often measured over a period of 30 days. The US Federal Trade Commission advises that claims of biodegradability must be based on evidence that the item "will completely break down and return to nature (i.e., decompose into elements found in nature) within a reasonably short period of time after customary disposal (FTC, 2012)."

In *Infosheet #1: Understanding Biodegradation and Textiles*, it was explained how biodegradation is a combination of both the properties of the material and the environmental conditions into which it is disposed. Synthetic materials including polyester, nylon, acrylic, and elastane generally have physical and chemical properties that make them resistant to biodegradation once released into the natural environment. Crystallinity, hydrophobicity, and molecular arrangements that are dissimilar to naturally occurring materials[8] are some of the reasons why these materials generally do not biodegrade in a reasonably short period of time in any environment.

Misconceptions about Biodegradability: "Any material made from a natural source will be biodegradable. Conversely, any material made from a fossil fuel feedstock will not be biodegradable."
Petroleum-based materials often lack biodegradability, whereas many bio-based materials can biodegrade. However, biodegradability isn't solely determined by the material's origin. Bio-based materials derive their carbon from recently living plant or animal sources like corn, sugarcane, or cotton, while fossil- or petroleum-based materials originate from natural gas, oil, or coal. In nature, microorganisms do not distinguish between these carbon sources. Synthetic materials (which often happen to be fossil-based) have a molecular and physical structure that does not resemble molecules found in nature, and therefore are difficult for microorganisms to biodegrade.

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[8] See *Infosheet #1: Understanding Biodegradation and Textiles* for further explanation of these concepts.

This structural complexity can hinder biodegradation in bio-based synthetic materials, such as bio-based nylon, which degrades at a similar rate to petroleum-based nylon. While marketing claims may tout the bio-based content of a material or product, this cannot and does not imply anything about biodegradability.

Table 1 below summarizes the biodegradability results for synthetic textiles in various environments. When interpreting biodegradation studies, a useful rule of thumb is >60-70% degradation indicates that complete biodegradation has likely taken place.[9] Yet, most studies reported poor to negligible degradation. Weight loss measurements can indicate some form of degradation (physical or biological), and were included in the table for completeness.

Overall very little data were available to characterize the biodegradability of these materials. This makes sense because they are anticipated not to be biodegradable, and therefore testing is usually deemed not useful. In most cases, the available biodegradation data on synthetics comes from comparative studies involving natural or regenerated cellulose textiles. For some common synthetics such as acrylic, elastane and polyurethane, no biodegradation studies were identified. Yet based on the material properties of these polymers, likewise no significant biodegradation in any environmental compartment is anticipated.

Table 1: Biodegradation Results for Synthetic Materials

Material	**Form**	**Time (days)**	**Conditions**	**Results**	**Method**	**Reference**
Polyester (PET)	Yarn	33	Seawater	4.24%	ASTM D6691	Zambrano et al., 2020
	Yarn	35	Lake water	Negligible	ISO 14851	
	Yarn	38	Activated sludge	5%	ISO 14851	
	Fiber	60	Activated sludge	1.6%	ISO 14851	Lykaki et al., 2021
	Shirt	90	Soil /	13%	ASTM D	Li et al., 2010

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[9] This rule of thumb is shared with a note of caution. The details of the biodegradation study such as test conditions and rate of biodegradation should always be considered before applying this criterion.

Material	Form	Time (days)	Conditions	Results	Method	Reference
			Composting		5988	
	Yarn	250	Seawater	4%	ISO 14851	Zambrano et al., 2019
Nylon	Nylon 66 pellets	90	Marine	7% weight loss	Custom method	Sudhakar et al., 2007
	Nylon 6 fibers	90	Marine	2% weight loss	Custom method	Sudhakar et al., 2007
	Fiber	270 days	Soil	Negligible	Unknown	Stuart et al., 2017

Can Recalcitrant (aka Non-Biodegradable) Polymers be Made Biodegradable?

This is a question researchers have attempted to answer for a long time. The field of bioremediation, in which microorganisms or enzymes are engineered to intentionally break down environmental pollutants, has made some progress in developing biological mechanisms to degrade recalcitrant substances like polyester (PET). Enzymes engineered to degrade PET have shown high activity on many types of PET. However, for polyester fibers, this is severely reduced by the crystallinity of the fiber. Significant pre-treatment (usually using heat) is required to allow these enzymes to function, and requires a closed system making it not suitable for environmental release, such as with microfibers.

Another area of inquiry is applying additives into the fiber matrix to aid with breakdown. Some additives claim to break the polymer into smaller pieces thereby increasing the surface area, which is a positive for biodegradation. These so-called 'oxo-degradable' additives have been banned in Europe (Packaging Europe, 2024), because they appear to contribute to microplastic pollution, rather than promoting true biodegradation.

Other types of additives to promote the biodegradability of synthetic materials are also being discussed in this industry, such as those that could increase the microbial population on the surface of the textile. Our literature review turned up no independent, peer-reviewed studies evaluating these additives. Further, in lab testing with robust populations of microorganisms present, polyester showed “negligible” biodegradation (Zambrano et al., 2020). As interest in these additives has increased across industries, numerous groups have publicly stated their concerns (National Association for PET Container Resources, 2017; Sustainable Packaging Coalition, 2022). Until openly accessible, peer-reviewed and independent data are available, “such technology so far seems irrelevant or even dangerous when claims are false (Weis et al., 2022).”

Toxicity of Synthetic Textiles During Degradation

The term "degradation" is used here instead of "biodegradation" due to the focus on synthetic textiles. Though these materials are generally resistant to biodegradation, synthetics can degrade into smaller particles (including microfibers) through physical processes like abrasion and UV exposure. As synthetics degrade, two main concerns arise: physical toxicity from microfiber formation and chemical toxicity from substances present on the textile.

Recent publications have delved into the data available on the toxicity of synthetic microfibers. Moody Wood et al., 2022 and Weis et al., 2022 discuss examples of impacts to aquatic life such as fish and coral, and terrestrial species including birds and humans. While synthetic microfibers are often the focus of testing, their toxicity is highly variable, depending on fiber type, shape and size.

Synthetic fibers are considered effective vectors of harmful chemicals including substances added during textile production, and pollutants already in the environment (Ladewig et al., 2015; Roblin et al., 2020). When these fibers are ingested, inhaled or otherwise enter an organism, there is potential for release and exposure to those compounds. Overall, there are reasons to be precautionary about the impacts of microfibers from synthetics. Potential solutions include changing production processes to reduce fiber shedding[10] and reducing the discharge of microfibers by adding filters to washing machines.[11]

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[10] https://www.microfibreconsortium.com

[11] https://www.5gyres.org/plastic-fashion

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