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The Effect of Denim Fabric as a Feedstock in Large Scale Composting of Manure/Bedding and Food Scraps

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ABSTRACT

This study provides scientific evidence for the process of denim biodegradation and the viability of including denim waste in large scale composting facility feedstock streams. Fourteen samples of denim using different dyes and dye processes provided by Cotton Incorporated as well as worn and unworn whole and scrap denim fabric were incorporated into a manure/bedding and food scrap windrow at the Cornell composting facility and in a bench scale laboratory trial. Grab samples of compost were analyzed for compost parameters, metals and PFAS. Visual observation of decomposition of denim showed polyester blended denim degraded at a slower rate than non-blended denim. However, after four months of hot composting, most of the denim had decomposed into organic matter, leaving only small pieces of the polyester thread, labels, and pockets. Bench scale degradation, tracked by carbon dioxide evolution and mass difference showed significant degradation at the macro and microscopic levels at day 75. Composting denim fabric has no detrimental effect on the composting process, nor on the quality of the resulting compost and thus can be used to grow cotton and other crops, reducing the carbon footprint, and contributing to the circular economy.

Introduction

Pre-consumer textile wastes are associated with all the manufacturing steps for making a finished fabric/garment. In the denim/jeans industry, because cotton is a carbon-rich organic material, composting of pre-consumer denim waste could contribute to the circular economy, i.e., grow the cotton to make the fabric, then use the composted fabric to grow the cotton and other agricultural products. Li, Frey, and Browning (2010) compared the biodegradability of cotton and polyester fabrics in the lab and in a large-scale composting facility. Weight loss and morphological changes of the fabrics were evaluated. This study looked at the degradability of cotton jersey fabrics with three levels of finishing treatments and a polyester jersey fabric. All fabric was laundered 30 times to simulate post-consumer disposal. Their results showed 50–77% weight loss after 90 days of thermophilic composting for the cotton fabrics, versus only a 20% weight loss for the polyester fabric over the same period. Morphological changes, based on SEM imaging, showed damage of cellulose-based fibers in the cotton samples, while the polyester fabric retained fabric and fiber structure. In another trial, Singh et al. (2022) evaluated the use of post-consumer cotton textile as a carbon source for vermicomposting. The cotton was blended, pre-composted to reach thermophilic temperatures and then added to worm bins in four different amounts. The final compost of each trial was similar with fine homogenous particles and no visible individual constituents (leaves, cotton, etc.).

Sarkar (2017) conducted a study at the Fashion Institute of Technology in New York City, NY.

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Fashion design students use 100% cotton muslin fabric for their draping, sewing and patternmaking classes generating over 100 lb of cotton scraps per week. Instead of sending it to the landfill, they collected and shredded it all. It was composted 50/50 with food waste plus additional moisture. They composted in-vessel, spinning every other day, then moving it to a vermicomposting system for final decomposition and maturation. Compost testing showed good total Kjeldahl nitrogen (TKN), organic matter (OM) and carbon to nitrogen (C:N) ratio. The second part of the study used the compost to grow plants for natural dying of the fabric. Germination rate increased when compost was used, and the color strength and colorfastness was better in the plants that were grown using compost. This project demonstrated the potential for transforming fabric waste into compost from any point in the supply chain to create new raw material.

Most denim is yarn-dyed fabric with the warp yarns dyed with indigo dye and the filling yarns left undyed. Denim can be composed of 100% cotton or blended with other fibers such as spandex or stretch polyester to provide elasticity. Typically, denim is sewed with polyester thread. There are several modifications or alternatives in the dyeing process that are routinely used to change the overall look or performance of the fabric (Cotton Incorporated 2004). Compostability of cotton fabric has been shown, but there have been no studies that measure the concentration of possible heavy metals from the dyes or dye processes or per- and polyfluorinated substances (PFAS) that may be used as a finish on denim fabric when composted in a large-scale compost facility. Smith et al. (2021) studied the impact of typical textile dyes or finishes on the biodegradation of cotton fabric in soil and found they did not impede the degradation of the cotton fabric. Also, it should be noted that PFAS finishes are used for water and soil repellency and are not typically applied to denim fabrics or garments (Cousins et al. 2019).

Composting of textile sludge (the effluent from textile chemical processing wastewater) was studied by Guha et al. (2015). They found that the composted sludge had high concentrations of copper, chromium and iron that were detrimental to crop plants. However, their method of composting consisted of mixing textile sludge with soil in a plant tub for one month. This method does not mimic thermophilic composting in a large-scale compost facility, nor did it measure concentration of these metals in finished compost. Additionally, metals concentrations are expected to be high in textile sludge and lower in fabrics.

The objective of this study was to not only observe the degradation of different denim fabric samples in a large-scale composting windrow, but to also assess the effect denim fabric may have on the compost process and to measure the quality of the compost produced. In the United States, there is no comprehensive national standard for compost. However, the United States Environmental Protection Agency (EPA) has nationally applicable standards that affect the use of biosolids-based composts (those made from human manure), regarding heavy metals and pathogens, but these restrictions do not widely apply to other feedstocks (Stehouwer, Cooperband, and Rynk 2022). Although the indigo dye types evaluated in this study were not known to have heavy metals or PFAS contamination and only biosolid composts are regulated for either of these, it was deemed prudent to include both heavy metals and PFAS in the evaluation of the quality of compost produced.

Materials and Methods

The denim samples used in this study were supplied by Cotton Incorporated and used as received (Table 1). Each sample except Brands 2, 4 and 5 were provided in both a raw and washed form. All denim samples received at Cotton Incorporated were loom-state meaning they still contained size applied to facilitate weaving. The "Raw" connotation refers to that loom-state denim and would represent cutting room waste from apparel production. The "Washed" denim has been through two processes. The first process was a desize bath with amylase enzymes and heat to remove starch and any polyvinyl alcohol size applied to protect the yarns through weaving and add stiffness to the fabric for cut and sew. Following the desize step, the fabrics were processed with a neutral cellulase enzyme and tumbled with Tonello's NoStone® plates. This combination emulated a stone wash process to remove some indigo and some cotton fibers from the surface of the fabrics giving them a slightly worn appearance.

Thirteen lingerie bags were filled with compost and cut up scraps of denim supplied by Cotton Incorporated (shown below in Table 1) and 3 pairs of jeans sourced from common denim manufacturers as well as a bag of worn jean scraps with compost. Baling twine and labels were attached to these bags for easy retrieval. On July 8, 2022, these bags were incorporated into the end of a windrow of 53% food scraps and 47% manure and bedding from the school of Veterinary Medicine (by tons, as received) at the Cornell University Compost Facility (CFC), Ithaca, NY. The windrow was approximately 6 feet high by 12 feet wide and the samples were spaced across 30 feet in length. The north side of the windrow had 3 samples, the south, 11 and the west, 3. Initial analysis of the materials in this windrow showed a moisture content of 62.4%, pH of 7.05, 23.2% carbon, 1.1% nitrogen and a carbon to nitrogen ratio (C:N) of 21:1. In addition, 13 samples (replicates of the first 13 in Table 1 below) were buried in a mixture of the same compost and perlite in glass desiccators to track the extent of degradation determined by carbon dioxide evolution, mass differences and visual analysis (Alwala et al. 2024).

Table 1. List of samples put in the compost pile.

Bag #	CI internal ID	Dye process/dye	Denim type
3	22423-B-W	Dry Denim	Washed
4	22423-C-R	Dry Denim	Raw
7	22423-F-W	Standard Pre-reduced	Washed
8	22423-G-R	Standard Pre-reduced	Raw
11	22423-J-W	Natural Indigo	Washed
15	22423-N-W	Brand 1	Washed
16	22423-O-R	Brand 1	Raw
18	22423-R-W	Brand 2	Washed
19	22423-T-W	Brand 2	Washed
21	22423-V-W	Undyed	Washed
22	22423-W-R	Undyed	Raw
24	22423-Y-R	Brand 3	Raw
25	22423-Z-W	Brand 3	Washed
29	RT	Brand 4	Worn – 98.83% cotton, 1.17% elastane
30	Stretch Jeans	Brand 5	1 ½ pair – 74% cotton, 24% polyester, 2% spandex
31	NS	Brand 4	Worn – 100% cotton – ¾ of a pair
32		Brand 4 scrap	Cut up pieces of various cotton jeans

Bags with samples were pulled from the windrow once a month for 4 months beginning in August 2022. At the same time, the temperature of the windrow was taken by inserting a 3 foot compost thermometer (Reotemp Series APF, Reotemp, San Diego, CA) at 4 different locations in the compost pile and taking an average of the readings. A farm services employee used a bucket on a tractor to remove the top of the pile. Bags were then hand dug from the windrow. Grab samples of denim and compost were taken from the lingerie bags and sent to the Cornell Nutrient Analysis Laboratory (CNAL) to be tested for typical compost parameters [moisture, pH, soluble salts, organic matter (OM), total nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), total carbon (TC), carbon to nitrogen ratio (C:N)] and metals analysis. Metals included sodium (Na), iron (Fe), copper (Cu), zinc (Zn), manganese (Mn), aluminum (Al), sulfur (S), arsenic (As), Cadmium (Cd), Chromium (Cr), nickel (Ni), lead (Pb), cobalt (Co), lithium (Li), molybdenum (Mb), and Strontium (Sr). The lingerie bags were then buried back in the same spot and the pile was covered again with the material that was removed earlier. Although this windrow was not truly turned, the disturbance incurred in rebuilding the windrow at each of the four sampling events served to incorporate oxygen allowing the process to mimic a municipally turned windrow.

In the 5th month, two sets of samples were taken in the same manner as the first 4 months. One set was sent to the Frey Laboratory to run Scanning Electron Microscopy (SEM) images and the other was sent to Analytical and Technical Services at the State University of New York, College of Environmental Science and Forestry, Syracuse, NY for PFAS analysis. The remaining contents of the bags were emptied into the windrow. The windrow was mixed and moved to continue composting and curing. In March 2023, after 9 months of composting, one final composite sample was taken by digging to a depth of 8–12" at 8 spots around the pile, mixing and pulling a sample from this mixture. This sample was sent to CNAL for analysis as described above.

Results and Discussion

Visual Observations

August 8, 2022: The temperature of the compost was measured at 140°F. After one month of hot composting, some fabric swatches showed visible degradation, while others showed discoloration only (Figure 1).

September 1, 2022: The temperature of the compost pile was measured at 150°F. After 2 months of hot composting the cotton portions of the material showed much more degradation than the "stretch" or polyester thread used to sew the jeans (Figure 2).

October 3, 2022: The compost pile was still hot, measuring 150°F. Considerable degradation of denim had occurred. Figure 3 below shows what was left of the samples after 3 months of composting. All that was left was spandex from bag 19, and the pockets, thread, and tag from the whole pair of Brand 4 RT jeans.

November 7, 2022: After 4 months of hot composting, most of the material had decomposed and had been digested into the organic matter portion of the compost. There was no visible material left in bags 8, 16, 22 and 24. Some visible material (crumbles in fingers) in bags 7, 18 and 25 and a lot of material visible, with some strength, in bags 3 and 11. Bag 32 (brand 4 scrap) just had polyester thread in it. Figure 4 shows what was left of the Brand 5 (30) and the Brand 4 RT (29) on November 21, 2022, after 4.5 months of hot composting. The cotton warp from sample 30 had decomposed and left only the framework of the spandex weft yarn. The skeleton of the jeans was clearly visible. In contrast, both the warp and weft from sample 29 had decomposed, leaving only the pockets and some of the thread from seams on the outside of the legs and the bottom hem. Cotton denim decomposed quickly in hot compost. However, polyester thread, spandex and other non-cotton material remained and did not compost. This remaining material could cause problems with machinery in a compost facility, such as thread wrapping around beaters (rotating bars with teeth) on compost turners and metal zippers/snaps chipping blades/teeth. Realistically whole pairs of jeans or other garments would not be directly placed in the compost waste stream. Rather, some pre-processing should be applied to overcome some of these logistical challenges.

Figure 1. Degradation and discoloration after 1 month of hot composting.

Figure 2. Further degradation of organic material after 2 months of hot composting.

Figure 3. Swatch 19 (left) and Brand 4 RT jeans (right) after 3 months of hot composting.

Weight Analysis

The brand 4 RT jeans (29) weighed approximately 621,421.5 mg (1.37 lb) when put in the pile. One and a half pair of brand 5 stretch jeans (30) were buried and weighed 652,039 mg (1 lb 7 oz) per pair for a total of approximately 978,058.5 mg (2.2 lb). Sample 31 (brand 4) was missing most of one of the legs and weighed approximately 530,703.1 mg (1.2 lb). The final weight for sample 29 was 57.9 mg, the final weight for sample 30 was 376.7 mg and the final weight for sample 31 was 61.8 mg. Using equation (1) below, the decomposition values for samples 29, 30 and 31, respectively are 99.99%, 99.96% and 99.99%. According to Esmaeilzadeh and Rashidi (2018), the European standard for disintegration of packaging materials (BS EN 14806:2005) says if the weight loss percentage between the initial solid mixture and resulting compost at the end of the test is greater than or equal to 30%, the test is valid, and the fabric is biodegradable under composting conditions. Decomposition of all three of these samples was greater than 30% indicating compostability.

$$D = \frac{Mi - Mr}{Mi} \times 100 \tag{1}$$

where, D = disintegration value, in percent. M_i = initial dry weight of the test sample. M_r = dry weight of the residual particles less than 2 mm.

Bench Scale Degradation (Alwala et al. 2024)

The bench scale trials were conducted following ASTM-D5338 for materials in compost. The trials

Figure 4. Brand 5 jeans (left) and Brand 4 RT (right) after 4.5 months of hot composting.

proceeded for 77 days, during and after which various tests were run to gauge the level of degradation. Both carbon dioxide evolution [min:18%, max:33% avg:26%] and mass loss [min:27%, max:62%, avg:49%] results pointed to degradation of the samples at day 77. These results were supported by photos and SEM that confirmed breakage and fibrillation at the fiber level. Further, fabric characteristics including dye process, fabric weight and denim type were assessed for a correlation with the degree of mineralization observed. Dye process and fabric weight had no observable effect on the level of degradation whereas denim type i.e., whether it was washed or raw had varied effects on the level of degradation. Finally, since thermophilic temperatures were not reached, the lab study recorded lower levels of degradation compared to the large-scale composting study.

Based on carbon dioxide evolution, the raw samples degraded faster than the washed ones on average. However, all samples showed significant degradation at the macroscopic and microscopic level at day 75. Fabric weight loss average across all samples and batches was 49% indicating compostability.

Compost Process

Composting is the aerobic decomposition of organic materials by microorganisms under controlled conditions. The process of composting is affected by the materials that are mixed and sized appropriately to provide the nutrients needed for microbial activity, and growth, including a balanced supply of carbon and nitrogen and enough moisture to permit biological activity without hindering aeration (Table 2). A compost pile/windrow that is working properly will heat up in a matter of days and hold that heat for several weeks to months, show a loss of moisture and mass and a decrease in the ratio or carbon to nitrogen due to the loss of carbon as CO_2.

The denim compost pile started within the reasonable ranges in the table above for thermophilic composting (62.4% moisture, C:N 21:1 and pH 7.05). The temperature was 140°F after 1 month of composting and increased to 150°F by month 2, remaining there through 5 months. Tables 3–5 show the average moisture, C:N and pH over time for the samples taken in and around each fabric bag over 4 months of active composting, respectively. The change in moisture over time (as shown by the slope of linear regression) ranged from decreasing by 0.08% per month to increasing by 0.33% per month over the 4-month period when samples were taken. Only one set of samples showed a statistically significant decrease (Pre-Reduced washed, $p = 0.003$). As none of the rest of the samples showed a significant difference

Table 2. Key initial parameters for thermophilic composting.

Parameter	Reasonable range	Preferred range
Moisture	40–65	50–60
C:N	20:1–60:1	25:1–40:1
pH	5.5–9.0	6.5–8.0
Temperature (°F)	113–160	120–150

($p>0.05$), this indicates moisture content remained the same throughout the 4 months of sampling in the rest of the pile. Final moisture content of the pile after mixing and composting for 9 months was 64.3%. The average moisture content for all samples over the 9-month period showed a regression line of Y=0.05x–2177.1, $p=0.03$, r-square = 0.83. In general, the composting process should release moisture, causing moisture to decrease over time. A final moisture content of between 40–50% is desirable for most compost uses, however, manure/food waste composts, range from 40–60% (Table 6). Although this pile

Table 3. Average moisture (%), linear regression slope, p-value and r-square value from each fabric bag over 4 months of active composting.

Date/Dye process	Dry denim		Pre reduced		Nat indigo	Brand 1		Brand 2		Undyed		Brand 3		Brand 4 worn			
Denim type*	W	R	W	R	W	W	R	W	W	W	R	R	W	–	–	Brand 5	Brand 4 scrap
Bag #	3	4	7	8	11	15	16	18	19	21	22	24	25	29	31	30	32
8/6/22		55.0	54.2		54.6	63.2			48.4		52.4	55.1		59.7		54.5	
9/1/22	53.5	58.2	52.0	50.7	45.7	53.3	44.7	36.9	53.7	58.5	51.2	48.3	46.7	53.8	50.8	53.8	50.8
10/3/22	47.2	61.3	49.5	55.5	45.3	68.4	54.3	58.1	37.4	53.7	57.3	58.5	38.6	63.2	60.6	46.4	61.6
11/7/22	48.3	50.8	45.8	58.0	53.6	64.7	58.4	59.6	54.8	59.9	55.3	57.0	49.9	65.6	55.1	60.4	61.1
Slope	−0.08	−0.04	−0.08	0.11	−0.003	0.06	0.20	0.33	0.01	0.02	0.05	0.05	0.05	0.07	0.06	0.04	0.02
p-value	0.45	0.67	0.003†	0.13	0.98	0.58	0.16	0.31	0.93	0.85	0.31	0.51	0.81	0.37	0.72	0.72	0.51
r-square	0.56	0.11	0.99	0.96	0.001	0.41	0.97	0.78	0.004	0.06	0.48	0.24	0.09	0.39	0.18	0.08	0.48

*W = washed, R = raw.
†*p*-values <= 0.05 are significant.

Table 4. Average C:N, Linear regression, *p*-value and r-square value from each fabric bag over 4 months of active composting.

Date/dye process	Dry denim		Pre reduced		Nat indigo	Brand 1		Brand 2		Undyed		Brand 3					
Denim type*	W	R	W	R	W	W	R	W	W	W	R	R	W	Brand	4 worn	Brand 5	Brand 4 scrap
Bag #	3	4	7	8	11	15	16	18	19	21	22	24	25	29	31	30	32
8/6/22		28.1	26.1		25.1	31.4			22.4		22.9	25.4		23.7		28.8	
9/1/22	25.0	27.2	22.5	22.6	25.9	22.6	24.6	23.6	26.2	27.8	26.2	24.2	23.8	26.7	24.0	24.0	30.1
10/3/22	17.9	24.9	14.0	19.8	19.4	14.7	16.6	16.1	18.2	26.3	17.5	20.4	18.0	27.9	18.9	19.0	22.6
11/7/22	17.0	17.1	14.5	17.0	17.1	15.2	14.1	16.1	19.6	23.3	17.2	17.5	15.6	23.9	18.8	18.1	20.2
Slope	−0.11	−0.11	−0.14	−0.08	−0.09	−0.17	−0.15	−0.11	−0.05	−0.07	−0.08	−0.09	−0.12	0.001	−0.08	−0.11	−0.15
p-value	0.28	0.06	0.08	0.02†	0.07	0.09	0.21	0.35	0.38	0.11	0.21	0.009†	0.16	0.98	0.33	0.05†	0.20
r-square	0.81	0.87	0.85	0.99	0.87	0.83	0.90	0.73	0.38	0.97	0.61	0.98	0.94	0.001	0.75	0.90	0.90

*W = washed, R = raw.
†*p*-values <= 0.05 are significant.

Table 5. Average pH, linear regression, *p*-value and r-square value from each fabric bag over 4 months of active composting.

Date/dye process	Dry denim		Pre reduced		Nat indigo	Brand 1		Brand 2		Undyed		Brand 3					
Denim type*	W	R	W	R	W	W	R	W	W	W	R	R	W	Brand	4 worn	Brand 5	Brand 4 scrap
Bag #	3	4	7	8	11	15	16	18	19	21	22	24	25	29	31	30	32
8/6/22		8.0	8.2		7.1	8.7			8.9		9.2	9.0		9.0		9.0	
9/1/22	8.5	8.9	8.8	8.9	8.9	9.1	9.0	8.5	9.1	9.0	9.1	9.1	9.0	9.0	8.9	8.9	8.6
10/3/22	8.7	8.7	8.2	8.2	8.7	7.7	7.5	8.6	7.8	8.8	8.4	8.3	7.8	8.6	8.8	8.6	8.7
11/7/22	8.6	7.3	7.2	6.8	8.7	7.4	7.4	6.4	6.9	8.7	7.9	7.2	7.5	8.7	7.9	7.0	7.9
Slope	0.00	−0.01	0.06	−0.03	0.01	−0.01	−0.02	−0.03	−0.02	−0.00	−0.01	−0.02	−0.02	−0.00	−0.01	−0.02	−0.01
p-value	0.60	0.50	0.07	0.11	0.33	0.13	0.31	0.34	0.06	0.04†	001†	0.07	0.21	0.27	0.25	0.10	0.37
r-square	0.33	0.25	0.87	0.97	0.44	0.75	0.78	0.74	0.89	0.99	0.98	0.87	0.89	0.53	0.85	0.80	0.69

*W = washed, R = raw.
†*p*-values <= 0.05 are significant

Table 6. Compost guidelines and specifications.

Moist (%)	pH	Soluble salts (mmhos /cm)	OM (%)	TKN (%) (mg/kg)	C:N	Plant macronutrients K, Ca, Mg, P (%) and S (ppm)	Plant micronutrients/metals Fe, B, Mn, Zn, Cu, Mo, Ni (ppm)
40–50	5–8.5	≤6	50–60	1–2 5000–25,000	10–20	0.1–1.5% or 1000–15,000 ppm depending on the plant and soil.	0.1–100 ppm depending on the plant and soil

showed a significant increase in moisture content over time, it cannot be attributed to the addition of denim fabric and is most likely due to the feedstocks taking in moisture as the pile cooled down.

The change in C:N over time (Table 4) ranged from decreasing by 0.15 per month to increasing by 0.001 per month over the 4-month period when samples were taken. Three sets of samples showed a statistically significant decrease and only one, showed a very slight increase. The rest of the samples all showed decreasing C:N ratios, indicating that composting is occurring. Average C:N for all samples over the 9-month composting period showed a statistically significant regression line of Y= −0.04x + 1740, $p=0.015$, r-square = 0.67 (Figure 5). This indicate that carbon was lost, and composting has occurred with no negative effects from the fabric samples. A final C:N ratio of 16.97 is within the preferred range of 10–20 for finished compost.

Most finished composts have neutral to slightly alkaline pH. Compost pH above 8 is often associated with high sodium

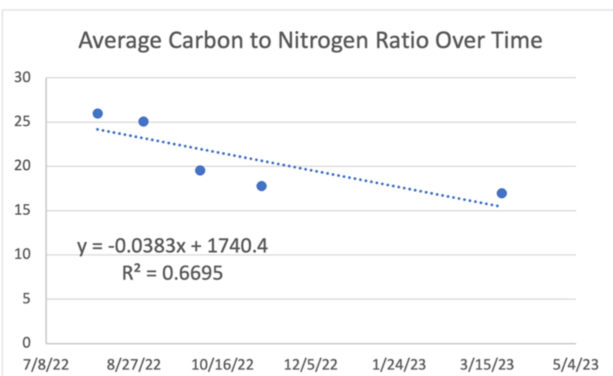

Figure 5. Average C:N Ratio in the compost pile over time.

concentrations found in manure and food waste composts. All samples but one started above pH 8, but then decreased to between 6.4 and 8.7 by 4 months of composting (Table 5). The pH changed from between an increase of 0.06 per month to a decrease of 0.03 per month. Although only the samples from the undyed (both washed and raw) bags showed a significant decrease, it may be possible that the addition of denim to a manure/food waste compost pile could help with final pH. At the very least the addition of denim is not impeding the compost process. The final pH of 7.7 for the composite sample is well within the range of 5–8.5 for most compost uses.

Compost Quality

Nutrients

Compost is a soil amendment that improves the physical, chemical, and biological properties of soils. It can improve soil quality, control erosion, supply nutrients for plant growth, sequester carbon, conserve water and nutrients, suppress diseases and suppress weeds. Depending on the intended use, compost quality parameters of likely interest include organic matter content, nutrient content, nutrient availability, C:N ratio, pH, soluble salts, maturity, and physical and chemical contaminants (Ozores-Hampton et al. 2022). The use of compost to create circularity in the cotton/denim fabric/clothing industry would most likely entail incorporation of the compost in the soil in which the cotton is grown. Table 6 gives compost guidelines and specifications for most uses and Table 7 shows

Table 7. Characteristics of a sampling of NYS composts made from manure and food scraps (https://hdl.handle.net/1813/48204).

	Moisture (%)	pH	Salts (mmhos/ cm)	OM (%)	P (%)	K (%)	Ca (%)	Mg (%)	C:N
# samples	24	24	25	24	24	24	11	11	24
Mean	50.4	7.3	4.1	28.8	0.41	0.51	3.5	3.5	13.2
St Dev	5.9	0.5	3.5	6.7	0.37	0.34	3.9	3.9	1.9
Minimum	38.8	6.2	0.9	22.3	0.14	0.21	1.0	1.0	10.8
Maximum	60.3	8.0	17.1	41.7	1.36	1.29	12.0	12.0	17.1

	Na (ppm)	Fe (ppm)	Cu (ppm)	Zn (ppm)	Mn (ppm)	Al (ppm)	S (ppm)	As (ppm)	Pb (ppm)	Cd (ppm)
# samples	3	24	24	24	16	3	3	8	3	7
Mean	693	11,807	38.9	116.0	605.9	9375	0.46	6.6	21.6	1.6
St Dev	181	3028	31.3	18.0	194.8	227	0.00	4.2	0.5	0.5
Minimum	587	7728	24.0	97.4	373.0	9196	0.46	0.0	0.8	1.0
Maximum	903	19,007	166.5	178.6	936.0	9630	0.46	10.0	21.9	2.0

typical values for a sampling of New York State dairy manure and food waste composts.

Table 8 shows the average moisture, pH, salt content, OM, TKN and C:N over the 4 months of composting for each of the separate denim types and dye processes as well as the final compost sample at 9 months. Anova of all the samples in the first 4 months showed significant differences in salts and OM. However, the range of values for both (5.9–13.3 mmhos/cm and 30–43%) is within the range of what is typically seen in composts made from manure and food scraps in New York (Table 7).

Table 8. Average compost quality parameters by dye process and denim type and final composite.

Denim type and dye process	Bag #	Moisture (%)	pH	Salts (mmhos/cm)	OM (%)	TKN (%)	C:N
Dry denim washed	3	49.7	8.6	12.1	39.3	1.4	20.0
Dry denim raw	4	56.3	8.2	6.5	37.6	1.2	24.3
Std pre reduced washed	7	50.4	8.1	11.0	37.2	1.4	19.3
Std pre reduced raw	8	54.8	8.0	9.9	30.2	1.1	19.8
Natural indigo washed	11	49.8	8.3	8.4	42.4	1.6	21.9
Brand 1 washed	15	62.4	8.2	9.9	42.6	1.5	21.0
Brand 1 raw	16	52.5	8.0	10.8	30.3	1.1	18.4
Brand 2 washed	18	51.5	7.8	13.3	36.9	1.1	18.6
Brand 2 washed	19	48.6	8.2	8.6	28.5	0.9	21.6
Undyed washed	21	57.4	8.8	7.4	37.2	1.1	25.8
Undyed raw	22	54.0	8.6	8.5	31.6	1.0	21.0
Brand 3 raw	24	54.7	8.4	9.3	32.0	1.0	21.9
Brand 3 washed	25	45.1	8.1	10.5	29.7	1.2	19.1
Brand 4 RT	29	60.1	8.8	5.9	42.5	1.3	25.6
Brand 5	30	53.7	8.4	8.2	35.9	1.2	22.5
Brand 4NS	31	55.5	8.5	8.6	39.7	1.5	20.6
Brand 4 scrap	32	60.8	8.4	7.5	44.0	1.3	24.3
Final composite (finished compost)		64.3	7.7	1.1	33.9	1.0	17.0

Therefore, any differences seen during the compost process are more likely due to the major feedstocks rather than the denim. In addition, the final value for salts (1.1 mmhos/cm) is within guidelines for most uses. None of the other properties showed any significant difference and all are within what is typical for this type of compost and within guidelines for most uses.

There were no significant differences in macro- or micro-nutrients between any of the samples taken over the 4-month period. The average of all samples taken (combined denim type and dye process) as well as the finished compost sample, show that K, Mg, P, and S (Table 9) are all within the specifications for most uses. Ca, Fe and Mn are higher than what is recommended, but fall within the range of typical manure/food scrap compost (Table 7) and thus are more likely a factor of those feedstocks, rather than the denim.

Metals

All compost products contain heavy metals (chemical elements with a relatively high molecular weight), just as all soils and food products do. It is the concentration and the relative availability for plant uptake that is important in compost use. At low concentrations, some heavy metals such as molybdenum (Mo), copper (Cu) and zinc (Zn) are essential nutrients to plants.

Table 9. Average macro- and micronutrients by dye process and denim type and final composite.

		Macronutrients (%)					Micronutrients (ppm)	
Denim type and dye process	Bag #	K	Ca	Mg	P	S (ppm)	Fe	Mn
Dry denim washed	3	1.4	6.5	0.6	0.6	2649	4535	224
Dry denim raw	4	0.8	8.8	0.8	0.7	1724	6450	226
Std pre reduced washed	7	1.3	7.3	0.7	0.8	2327	5862	234
Std pre reduced raw	8	1.5	8.3	0.9	0.8	2780	6641	248
Natural indigo washed	11	1.3	5.2	0.6	0.8	2588	4771	202
Brand 1 washed	15	1.4	5.4	0.7	0.7	2558	5500	198
Brand 1 raw	16	1.0	12.0	0.9	0.5	1807	6808	284
Brand 2 washed	18	1.2	9.7	1.0	0.6	2281	6960	294
Brand 2 washed	19	1.1	11.5	0.8	0.6	2082	6252	289
Undyed washed	21	1.1	6.9	0.6	0.8	2361	4975	237
Undyed raw	22	1.0	8.6	0.8	0.6	1927	7399	276
Brand 3 raw	24	0.8	8.6	0.9	0.6	1835	6500	278
Brand 3 washed	25	1.2	8.8	0.9	0.8	2333	7279	327
Brand 4 RT	29	0.9	4.7	0.6	0.9	2263	4835	233
Brand 5	30	1.0	6.4	0.7	0.8	2262	6861	238
Brand 4NS	31	1.1	6.3	0.7	0.7	2201	6727	228
Brand 4 scrap	32	1.0	5.9	0.6	0.8	2091	6688	236
Average of all above		1.1	7.7	0.7	0.7	2239	6179	250
Final composite (finished compost)		0.5	5.2	0.7	0.5	2761	10,984	319

High concentrations of some, such as iron (Fe), Zn, Cu, lead (Pb) and cadmium (Cd) represent health risks and are regulated. These regulations are in place for composted biosolids (compost made from human sewage at wastewater treatment plants) but are reasonable guidelines for using any compost. The current United States Environmental Protection Agency (USEPA) and New York State Department of Environmental Conservation (NYSDEC) standards are shown in Table 10. Regulatory limits have been set by EPA for nine heavy metals based on a risk assessment analysis. These include standards to be met for a sludge to qualify as "exceptional quality" (EQ). Class A EQ sludges and sludge products should be applied at agronomic rates.

Table 11 shows the average metals content over the 4 months of composting for each of the separate denim types and dye processes as well as the final compost sample at 9 months. There were no significant differences in any of the metals for denim types or dye processes and all values fall well below the standards for land application of sewage sludge (Table 10, Columns 2, 3 and 5) and to qualify as "exceptional quality" (Table 10, Columns 3 and 5). The addition of denim as a feedstock does not have an effect on the content of metals in the finished compost. In addition, from Table 6, the compost meets the requirements of between 0.1 and 100 ppm Zn, Cu, Mo and Ni for most uses.

PFAS

PFAS are a group of chemicals used to make fluoropolymer coatings that resist heat, oil, stains, grease, and water (CDC Centers for Disease Control and Prevention 2022). Fluoropolymer coatings can be in a variety of products, including clothing. PFAS are a concern because they do not break down in the environment, can move through soils and contaminate drinking water sources, and bioaccumulate in fish and wildlife. Unlike other persistent contaminants, they do not sorb as much to organic matter or other soil constituents (Beecher and Brown 2018). Because PFOA (perfluorooctanoic acid) and PFOS (perfluorooctane sulfonate) have been ubiquitous in daily use for decades, biosolids and composts made from recycled paper mills, food waste or animal manures, typically contain single digit to tens of μg/kg (ppb) concentrations of each. Testing at Purdue University showed composted biosolids had concentrations of PFAS ranging from 20 to 85 ppb while composts made from various combinations of food scraps, compostable service ware and yard trimmings had PFAS concentrations between 22 and 52 ppb. Pure yard trimmings compost registered concentrations of 2 to 5 ppb (Coker 2020). According to NYSDEC (New York State Department of Environmental Conservation 2023), the USEPA will be completing a risk assessment for PFOA and PFOS in biosolids by December 2024. In the interim period before EPA issues standards for PFAS in recycled biosolids, NYSDEC will reduce the risk associated with biosolids recycling by setting criteria that will identify biosolids that are impacted by industrial PFAS sources and requiring those sources be identified and addressed if recycling is to occur (Table 12).

Table 10. Current EPA and DEC standards for land application of sewage sludges.

Contaminant	NYSDEC sludge and sludge product, monthly average (ppm)	NYSDEC sludge and sludge product max (ppm)	EPA 503 EQ limit (ppm)	NYSDEC cumulative limit (kg/ha)	EPA 503 Cumulative limit (kg/ha)
Arsenic (As)	41	75	41	None	41
Cadmium (Cd)	21	75	39	4	39
Chromium (Cr)	1000	1000	None	446	None
Copper (Cu)	1500	4300	1500	112	1500
Lead (Pb)	300	840	300	267	300
Mercury (Hg)	10	57	17	None	17
Molybdenum (Mo)	40	75	None	None	None
Nickel (Ni)	200	420	420	45	420
Selenium (Se)	100	100	100	None	100
Zinc (Zn)	2500	7500	2800	223	2800

Cox, B., Thomas-Murphy, J., eds. 2015 Cornell Guide for Integrated Field Crop Management, Cornell University Cooperative Extension, Ithaca, NY

All samples sent to Analytical and Technical Services were analyzed through extraction for the following 40 PFAS: 11Cl-PF3OUdS, 3,6-OPFHpA, 4:2FTS, 6:2FTS, 8:2FTS, 9CI-PF3ONS, FHpPA, FOSA, FPePA, FPrPA, HFPO-DA, NaDONA, N-EtFOSA, N-EtFOSAA, N-EtFOSE, N-MeFOSA, N-MeFOSAA, N-MeFOSE, PF4OPeA, PF5OHxA, PFBA, PFBS, PFDA, PFDoA, PFDoS, PFDS, PFEESA, PFHpA, PFHpS, PFHxA, PFHxS, PFNA, PFNS, PFOA, PFOS, PFPeA, PFPeS, PFTeDA,

Table 11. Average metals content (ppm) by dye process and denim type and final composite.

Denim type and dye process	Bag #	As	Cd	Cr	Cu	Pb	Mo	Ni	Zn
Dry denim washed		0.3	0.3	2.9	53.5	1.5	0.2	2.7	61.7
Dry denim raw	3	0.5	0.5	2.4	27.2	2.0	0.0	3.9	55.7
std pre reduced washed	4	0.5	0.5	1.7	39.4	1.6	0.1	3.5	60.7
Std pre reduced raw	7	0.5	0.5	2.2	45.8	1.2	0.2	4.3	68.7
Natural indigo washed	8	0.4	0.4	0.9	37.1	1.3	0.1	2.9	60.2
Brand 1 washed	11	0.5	0.5	1.4	57.0	1.3	0.1	3.2	60.3
Brand 1 raw	15	0.5	0.5	4.1	33.1	1.1	0.1	3.7	52.9
Brand 2 washed	16	0.3	0.3	2.4	34.5	1.1	0.1	6.6	56.9
Brand 2 washed	18	0.5	0.5	2.1	37.2	1.4	0.1	3.8	55.2
Undyed washed	19	0.3	0.3	0.7	43.6	0.9	0.1	2.8	57.4
Undyed raw	21	0.7	0.7	2.7	33.0	1.7	0.1	4.6	57.2
Brand 3 raw	22	0.5	0.5	3.4	38.4	1.6	0.1	4.0	53.0
Brand 3 washed	24	0.3	0.3	2.3	48.0	1.2	0.1	4.0	66.5
Brand 4 RT	25	0.8	0.8	1.1	47.7	1.6	0.1	3.2	64.0
Brand 5	29	0.7	0.7	2.7	35.8	1.9	0.1	4.6	64.9
Brand 4NS	30	0.2	0.2	2.2	58.6	0.8	0.1	3.2	64.4
Brand 4 scrap	31	0.2	0.2	0.5	36.3	0.8	0.1	2.9	60.9
Average of all above		0.5	0.4	2.1	41.5	1.4	0.1	3.8	60.0
Final composite (finished compost)		2.3	0.4	bdl*	60.7	bdl*	bdl*	5.6	20.3

*bdl = below detection limit

Table 12. NYSDEC interim guidelines for PFOA and PFOS in biosolids recycled.

PFOA or PFOS in biosolids, dry weight μg/kg (ppb)	Action required for biosolids that are recycled
20 or less	No action required
> 20 but < 50	Additional sampling required. DEC will take appropriate steps to restrict recycling after one year if the PFOS or PFOA levels are not reduced to below 20 ppb or less
50 or greater	DEC will take action to prohibit recycling until PFOS or PFOA concentration is below 20 ppb

Table 13. PFAS concentration (ng/g or ppb, dry weight) by dye process and denim type and final composite.

Denim type and dye process	Bag #	PFBA	PFBS	PFDA	PFHxA	PFPeA	PFNA	PFOA	PFOS	PFOS + PFOA	Total PFAS
Method detection limit (mdl)		0.800	0.200	0.200	0.200	0.400	0.200	0.200	0.200		
Dry denim washed	3	0.000	0.000	0.215	6.202	0.533	0.195	0.294	0.126	0.420	7.552
Dry denim raw	4	0.000	0.000	0.211	2.329	0.289	0.177	0.278	0.156	0.434	3.572
Std pre reduced washed	7	1.207	0.000	0.245	4.979	0.493	0.190	0.328	0.156	0.484	7.906
Std pre reduced raw	8	0.000	0.000	0.264	2.530	0.000	0.190	0.369	0.154	0.523	3.692
Natural indigo washed	11	0.921	0.000	0.203	2.719	0.301	0.000	0.208	0.122	0.330	4.605
Brand 1 washed	15	0.000	0.196	0.223	2.874	0.000	0.000	0.291	0.262	0.553	3.987
Brand 1 raw	16	0.000	0.000	0.224	2.144	0.297	0.000	0.279	0.130	0.409	3.530
Brand 2 washed	18	0.520	0.000	0.200	3.333	0.860	0.000	0.235	0.158	0.393	5.680
Brand 2 washed	19	0.000	0.000	0.246	2.160	0.325	0.188	0.372	0.163	0.535	3.517
Undyed washed	21	0.000	0.000	0.000	1.892	0.330	0.000	0.180	0.000	0.180	2.402
Undyed raw	22	0.000	0.123	0.248	2.329	0.000	0.192	0.330	0.146	0.476	3.581
Brand 3 raw	24	0.000	0.000	0.215	3.184	0.362	0.000	0.251	0.136	0.387	4.288
Brand 3 washed	25	0.000	0.000	0.268	2.969	0.403	0.204	0.384	0.150	0.534	4.585
Brand 4 RT	29	0.000	0.000	0.193	1.358	0.365	0.000	0.283	0.000	0.283	2.207
Brand 5	30	0.000	0.000	0.209	0.867	0.227	0.000	0.256	0.152	0.408	1.711
Brand 4NS	31	0.000	0.000	0.219	2.237	0.308	0.000	0.249	0.158	0.407	3.303
Brand 4 scrap	32	0.000	0.338	0.219	2.207	0.516	0.000	0.324	0.218	0.542	4.134
Average of all above		0.156	0.039	0.212	2.724	0.330	0.079	0.289	0.140	0.429	4.132

PFTrDA, PFUdA. All were non-detect (0.000) or below the method detection limit for that compound (> 0.000 but < mdl) except for the eight shown in Table 13 (EWG [Environmental Working Group] 2023; Water World 2023). Total PFAS concentration in the compost at the individual locations where denim was composted ranged from 1.711 ppb where the brand 5 whole jeans were to 7.906 where the Standard Pre-Reduced washed samples were. The average for all the sites was 4.132 ppb. For only PFOA and PFOS, the totals ranged from 0.180 ppb for Undyed Washed to 0.542 for Brand 4 scrap, with an average of 0.429 ppb. All values are below the proposed 20 or less ppb for "no action required" if this compost were biosolids. ANOVA showed no significant difference between any of the denim samples for PFAS ($p = 0.99$). Because there were no differences, the source of PFAS in the compost most likely comes from the other feedstocks (food waste and manure) than from the denim fabric.

Conclusions

Denim fabric, regardless of dye process or denim type (raw vs. washed) is compostable in large-scale thermophilic composting windrows. Mixed content (i.e., cotton blends) compost more slowly than 100% cotton and can leave contaminants in the final product from the synthetic components. Neither the composting process nor the resulting compost was adversely affected by the addition of denim as a feedstock. Salts and pH were both high during the process but were most likely a factor of the major feedstocks of manure and food scraps rather than the denim. PFAS contamination was minimal and not significantly different between samples of different dye process or denim type. Calcium, iron, and manganese content were higher than what is recommended for most compost uses but were also more likely a factor of the manure and food scraps rather than the denim. If the concentration of those nutrients is essential to growing cotton, other major feedstocks may need to be used when building the windrows. Composting denim fabric has no detrimental effect on the composting process, nor on the quality of the resulting compost and thus can be used to grow cotton, reducing the carbon footprint, and contributing to the circular economy.

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