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PROSPECTIVE LIFE CYCLE ASSESSMENT OF NONWOVEN MAT MANUFACTURING: COMPARING PRE-CONSUMER WOOD WASTE FIBERS TO POST-CONSUMER RECYCLED APPAREL FIBERS

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ABSTRACT
The apparel industry's substantial contribution to increasing Municipal Solid Waste (MSW) from discarded apparel through fast fashion approaches necessitates exploring sustainable alternatives. Over the past fifty years, throwing away textiles has risen four times as fast as MSW generation rates in the U.S. This study examines the environmental impact of an existing nonwoven mat manufacturer that uses pre-consumer wood waste to make fiber for nonwoven mats with a post-consumer recycled apparel alternative. This alternative, the Fiber Shredder, a lab-scale innovative mechanical textile recycling technology, takes discarded apparel and turns it into valuable fiber. The recycled cotton fiber produced by the Fiber Shredder from discarded apparel is long enough to manufacture new nonwoven textiles. The final products, nonwoven mats, are intended for landscaping purposes and thus use biodegradable fibers. The novel mechanical textile recycling technology to create fibers from discarded apparel, the Fiber Shredder, developed at the University of Minnesota Duluth, is scaled up theoretically to compare its potential impact upon commercialization to an existing industrial process that creates wood fibers from waste wood. A prospective Life Cycle Assessment (LCA) compared the environmental impacts of three options for manufacturing nonwoven mats; (A) pre-consumer waste wood fibers, (B) current lab scale post-consumer recycled cotton fibers from the Fiber Shredder and (C) post-consumer recycled cotton fibers from the scaled up Fiber Shredder. This LCA encompasses emissions, energy usage, and materials from the acquisition of raw materials through the production processes or cradle-to-gate. The results show that although the lab-scale Fiber Shredder has higher environmental impacts than the commercial nonwoven manufacturer, scaling up the Fiber Shredder will lead to reduced impacts. However, the scaled-up Fiber Shredder still needs improvement in electricity consumption and speed of production to be able to match the current commercially available technology. The limitations of this study involve simplifying assumptions such as neglecting packaging during shipping, energy consumption for apparel sorting and notion removal, and potential microplastics generation. In conclusion, transitioning to post-consumer apparel recycling holds promise but requires careful consideration of energy usage for scalability of the Fiber Shredder. This study underscores the importance of prospective LCA to optimize the design of emerging recycling technologies for sustainable production.

Keywords — life cycle assessment (LCA), nonwoven mat production, post-consumer textile recycling, prospective LCA

Terminology

AP	Acidification Potential
EPA	Environmental Protection Agency
GHG	Greenhouse Gas
GWP	Global Warming Potential
LCA	Life Cycle Assessment
MSW	Municipal Solid Waste
ODP	Ozone Depletion Potential
PMFP	Particulate Matter Formation Potential
SmogP	Photochemical Oxidant Formation Potential

INTRODUCTION & BACKGROUND

The textile industry is one the biggest contributors to Municipal Solid Waste (MSW). The US generates over 15 million metric tonnes (17 million US tons) of textile waste each year, while less than 15% of this textile waste is recycled [1]. Each year around the globe apparel production creates:

- 92 million metric tonnes (over 100 million US tons) of textile waste,
- 4-5 billion tonnes (4.4-5.5 US tons) of greenhouse gas (GHG) emissions or 8-10% of worldwide GHG output, and
- 190,000 metric tonnes (>200,000 US tons) or 35% of ocean-bound primary microplastics[2].

As demand for fibers and textiles increases due to growing population and overconsumption, incorporating recycled fibers in place of new fibers is important to reduce environmental impact. Life cycle assessments found varying environmental impact reductions for recycled as compared to new fibers, e.g. 60% environmental impact savings for a specific 100% recycled wool fiber [3] and GHG savings of 2-8% when substituting in 30% mechanically recycled cotton fiber [4]. Substitution of different recycling processes and recycled fibers in textile products result in different environmental impact improvements.

Circular economies are being promoted for all types of textile waste from pre-consumer offcuts and mill ends to post-consumer discarded textile products. Closed-loop textile recycling involves diversion and processing of textile waste back into the original fibers and textile products they once comprised. Open-loop recycling involves reclaiming discarded textile products into new products, which may increase the number of product life cycles a fiber undergoes but probably will eventually end up in MSW [5]. Transition to circular textile economies will require open-loop recycling options on the path towards closed-loop recycling.

Discarding of textile waste after use in the US has risen four times faster than MSW growth from 1960-2018 due to increases in consumer wealth, population growth, and fast fashion practices pushing acquisition of new and dissatisfaction with old trends [6]. Thus, there is an urgent need for new recycled textile products and textile recycling technologies. Production of nonwoven textiles using recycled fibers is much easier than creating knit or woven fabrics; yarn spinning needed for creating knit and woven fabrics depends upon sufficient fiber length. However nonwoven textile production is not as dependent on fiber length as yarn spinning processes. Decreased fiber quality of mechanically recycled fibers, in particular shorter fiber lengths, are one of the biggest issues usually encountered preventing the use of recycled fibers or requiring blending with new fiber material for production. Additionally post-consumer textile waste requires the removal of notions (zippers, buttons, trims, etc.) before recycling, which is often done by hand and again is a barrier to textile recycling [5].

Attributional life cycle assessment (LCA) compares environmental impacts between at least two alternatives. This

(a) **(b)**

Figure 1. a) Fiber Shredder [7] b) nonwoven sample made from recycled cotton fibers

study considers two options for producing nonwoven fabric mats, a novel mechanical textile recycling process utilizing post-consumer discarded apparel in the Fiber Shredder and an existing commercial scale process for pre-consumer waste wood at a nonwoven manufacturer. The Fiber Shredder is a mechanical recycling technology developed at the University of Minnesota Duluth, which successfully shreds post-consumer textiles back into fibers [8]. Currently, the Fiber Shredder is at a lab scale (Figure 1a), this analysis involves a theoretical scaling up of this innovative process to a commercial scale. The existing nonwoven fabric mats are made from pre-consumer wood waste chips. This LCA compares the current lab scale process for the Fiber Shredder to make nonwoven mats (Figure 1b) with a theoretical prospective commercial scale Fiber Shredder approach to fiber production from post-consumer discarded apparel with pre-consumer waste wood chips as the material input for the nonwoven fabric mats.

This prospective analysis allows a screening type LCA for a new technology under development at a small scale, e.g. the Fiber Shredder, at a modeled commercial scale of production to anticipate concerning life cycle performance as compared to existing available processes [9]. Prospective LCA can be instructive about potential impacts of and can inform the design process for innovations, such as the Fiber Shredder, before scaling up processes [10].

Prior work has reviewed or analyzed the environmental life cycle impacts of existing [11], [12] and novel textile recycling processes [13], [14] and circular textile products [4], [15]. Prospective LCA comparison of current chemical recycling processes at lab-scale for closed-loop utilization of PET originally recycled from bottles was carried out identifying areas of concern for commercial scaling [16]. However, to the best of the authors' knowledge, a prospective LCA concerning post-consumer apparel recycling fabric-to-fiber has not been considered yet. This analysis contributes a screening level assessment of environmental impact prospectively for emerging post-consumer textile recycling processes as compared to existing commercial scale waste wood recycling and nonwoven textile production.

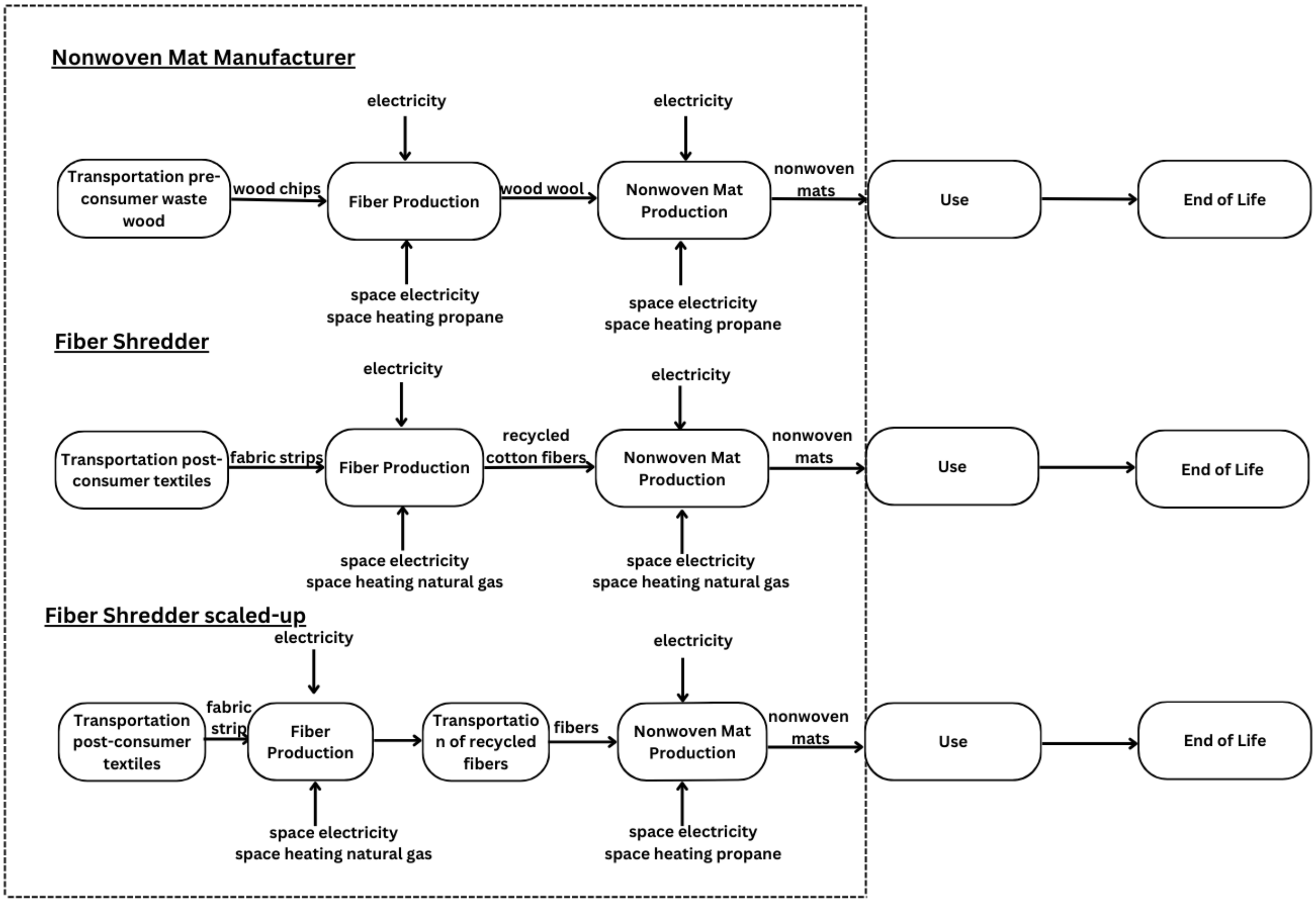

Figure 2. System Boundary for the three nonwoven mat production options

METHODS

The goal of this prospective LCA was to assess environmental impact of manufacturing one square meter of nonwoven mat for landscaping applications via three options (Figure 2):

- Option A: Pre-consumer wood waste fiber produced at the nonwoven manufacturing facility.
- Option B: Post-consumer recycled cotton fiber produced from the Fiber Shredder and nonwoven textiles at lab-scale at UMD.
- Option C: Post-consumer recycled cotton fiber at a scaled up volume from the Fiber Shredder at UMD transported to the nonwoven manufacturing facility.

Option A

An existing commercial nonwoven manufacturing facility produces approximately 700 rolls of 1.5 by 30 meter (5 by 100 foot) per 10 hour workday from wood waste. The wood waste starts as chips and then through a proprietary fiber opening process is turned into wood fibers. These wood fibers are then blended with a very small percentage of copolymer and sent on a nonwoven manufacturing line that uses thermal bonding and compression of the fibers to create a thick, high-quality, long-lasting biodegradable landscaping fabric mat.

Option B

Strips of 100% woven cotton denim apparel fabric of 76.4 x 254 20 millimeters (3 x 10 inches) were fed into the Fiber Shredder, a novel mechanical recycling technology, where the fabric was mechanically recycled to obtain fibers. Up to fifty grams of fabric were fed into the machine at one time which produced usable fibers and yarns in 90 seconds. Next, the fibers were put through an electric drum-based carding machine to obtain a carded web of recycled cotton fibers. This carded web was precisely cut into squares matching the dimensions of an aluminum mold. The aluminum mold with interior dimensions of 203.2 by 203.2 millimeters (8 by 8 inches) built at UMD compresses thin and thick aluminum plates together with screws to apply pressure on the carded web, also called a batt, of fibers. Then a sheet of polylactic acid (PLA) was taken and cut to fit the fiber bat and interior mold size. Assembling the final product involved layering two squares of the carded cotton fiber web, with the PLA sheet nestled between them. This assembly was then enclosed within the aluminum mold, the screws securely fastened, and transferred to a preheated oven at 300°C. After one hour, the mold assembly was taken out and left to cool. After cooling at room temperature, the mold screws were loosened, and a firm sheet of cotton nonwoven textile infused with PLA was taken out (Figure 1b).

Option C

The current lab-scale Fiber Shredder process was estimated to scale-up to six times the output without twice the electricity use. This scale-up efficiency was projected due to the relative size of electric motors calculated for a larger designed Fiber Shredder and a presumed shorter time to produce fibers of only 30 seconds instead of 90 seconds. Transportation of these recycled fibers to the nonwoven manufacturing facility in standard cotton fiber bales via a standard size 36-tonne (80,000 lb.) semi-trailer truck with interior dimensions 16 m long by 2.5 m wide by 2.8 m high (53 feet long by 100 in. wide by 110 in. high) was assumed. A cotton fiber bale was presumed to weigh 217 kg (480 lb.) and 1.40 x 0.51 x 0.84 m (54 x 20 x 33 inches) and be stacked full in the truck without pallets. The recycled cotton fibers were assumed to work as a one-to-one substitution for wood fibers by weight in the nonwoven manufacturing line. This assumption was confirmed by the manufacturing line manager in an on-site evaluation of the recycled cotton fibers at the manufacturing facility in 2023.

The impact of a product's life cycle, from manufacturing to disposal, can be reasonably estimated using the Life Cycle Assessment (LCA) methodology framework. The product's emissions to air, water, and soil are evaluated at every stage of its production, usage, and disposal. The LCA scope establishes the boundaries and limits of the life cycle assessment. The scope of this study is cradle-to-gate. The nonwoven mats produced with Fiber Shredder recycled cotton fibers have not undergone the use and end-of-life stages yet. Further testing of fibers and nonwoven mat samples produced at lab-scale with the Fiber Shredder is ongoing. Figure 2 depicts the life cycle stage diagram and the system boundary for this study. A functional unit is a quantifiable measure of the function a product serves including quality, quantity, and time period. The chosen functional unit for this study is the production of a one square meter area of nonwoven mat for landscaping applications. All emissions, materials, and energy consumption are compared relative to this functional unit.

The software openLCA version 2.0.3 and ecoinvent database v3.10 were used to model the product system life cycles. The potential impacts of manufacturing a square meter of nonwoven mat were assessed with the environmental impact assessment method TRACI version 2.1 developed by the US Environmental Protection Agency (EPA). TRACI inventories emissions to assess midpoint impact categories related to GHG emissions, ozone depletion, acidification, eutrophication, human and ecosystem health among others [17]. The emission rates for electricity were calculated from the US EPA's eGRID [18]; electricity emission rates specific to the generation capacity and power plant fuel types specific to the MROW NERC region representing upper Midwest US geography were utilized. The impacts from propane [19] and natural gas combustion [20] were calculated using emission factors provided by the US EPA. The semi-trailer truck emissions were calculated using transportation emission factors provided by the US Bureau of Transportation Statistics [21].

RESULTS AND DISCUSSION

As an impact assessment method built into openLCA, TRACI serves as a framework to assess environmental impacts across different impact categories (Figure 3). The TRACI methodology includes a set of impact categories, or midpoint indicators that represent various environmental concerns. As seen in Figure 3, the current lab-scale Fiber Shredder has higher environmental impacts across most categories except for acidification potential and photochemical oxidant formation (smog), where the nonwoven manufacturer using wood waste performs worse. This finding makes sense due to improvements in environmental impact simply due to increased production scale.

The prospective LCA performed for the scaled-up Fiber Shredder reveals a mix of both improved and worsened environmental impacts (Figure 4). More efficient use of energy, specifically electricity, in the scaled-up version of the Fiber Shredder, where production increases by six times and electricity use by only two times, is responsible for the improvements across all environmental impacts over the lab-scale version. Acidification and smog formation are worse for the nonwoven manufacturer's current commercial scale processes than the Fiber Shredder operations at either scale. The scaled-up Fiber Shredder has significant environmental improvements in particulate matter release and eutrophication in comparison to the current lab-scale process.

The largest difference between the lab- and commercial-scale Fiber Shredder processes and the nonwoven manufacturer's existing processes is the relative decline in electricity usage per meter squared of nonwoven textile produced (i.e., per functional unit). Additionally, due to the

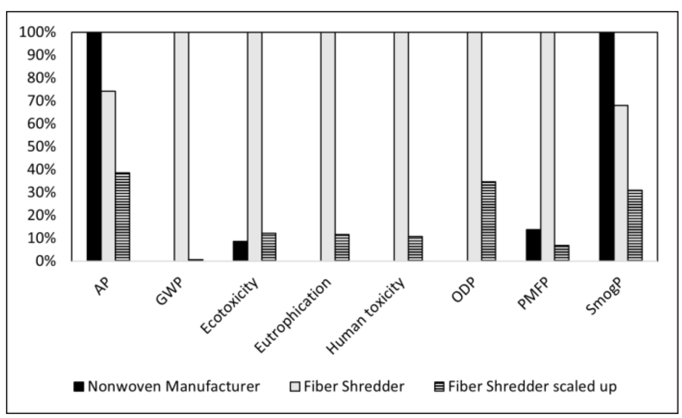

Figure 3: Comparison of impacts across impact categories for options A, B, and C

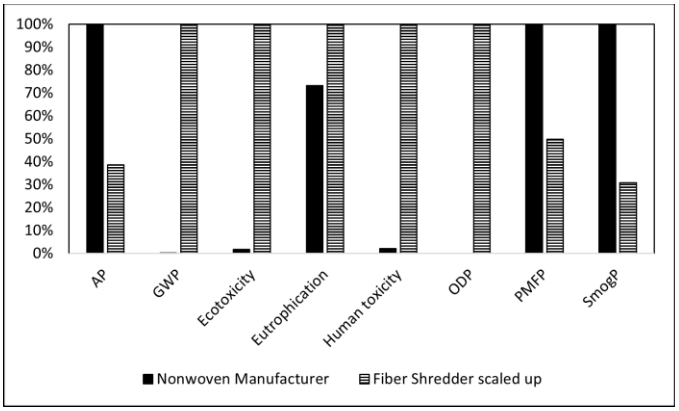

Figure 4. Comparison of impacts across impact categories for options A and C

transition to commercial-scale manufacturing at the nonwoven manufacturer's facility means an increase in propane consumption as compared to the lab-scale process site where natural gas is used for space heating. This change in space heating energy fuel also has implications for environmental impact.

The scaled-up Fiber Shredder uses the majority of the energy in the life cycle for manufacturing fibers as seen in Figure 5. The scale of the production at the nonwoven mat manufacturer is much larger than the scaled-up Fiber Shredder. Every hour the nonwoven mat manufacturer produces nearly 700 sq m of nonwoven mats, whereas the scaled-up Fiber Shredder produces only eight sq m of nonwoven mats.

The limiting factor of production is how fast recycled fibers are produced by the Fiber Shredder. The speed of recycling fibers in the Fiber Shredder process needs to be scaled-up more to match existing commercial levels of nonwoven mat production; the prospective LCA results clarify this critical design improvement needed for scaling up the Fiber Shredder. In summary, these results allow machine and process designers to focus efforts on energy efficiency per unit production output for fibers.

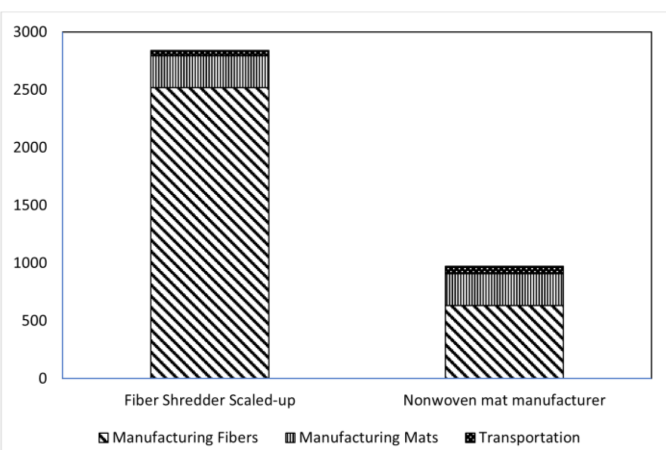

Figure 5. Comparison of life cycle stages or types of energy used for options A and C in kilojoules

Limitations & Future Work

This study is a first attempt to quantify the prospective impacts of a new technology in the process of being scaled-up to existing commercial scale production for nonwoven mats. Some simplifications of the product life cycles considered were made to ease data collection and analysis. Specifically, the packaging operations and requirements of fibers were ignored for the discarded apparel transport and recycled fiber transport. The energy consumption associated with sorting discarded apparel and removing notions (e.g., buttons and zippers) was not considered for this study. Additionally, the Fiber Shredder scale-up assumptions are based on preliminary estimates. In the future, actual energy use will be measured.

Certain environmental impacts of concern were neglected. For example, a lot of cotton clothing also contains elastane for stretchiness. The Fiber Shredder has no difficulty shredding the small amounts of elastane included in these garments; however, whether microplastics, in excess of existing background levels, are created during fiber production using the Fiber Shredder is under investigation currently. Also, the inclusion of elastane may impact the thermal bonding process during nonwoven mat production and needs to be tested to ensure a quality mat is created. Future research is planned to measure microplastics creation during Fiber Shredder fabric-to-fiber textile recycling.

Additionally, the use life cycle stage was ignored in this LCA. Reusing recycled fibers in soil involves putting plants, soil microorganisms, and water runoff from landscaping fabric in contact with dyes and possibly other clothing finishing chemicals. Azo dyes, often used in clothing, but regulated by California Proposition 65 which bans certain toxic compounds, are particularly concerning. Azo dyes persist over time in the environment. In the future, methods to identify azo dyes in discarded apparel and recycled fibers and to determine their potential impacts will need to be pursued.

CONCLUSIONS

Transitioning nonwoven production from pre-consumer wood fibers to recycled post-consumer textile waste may increase emissions, primarily due to higher electricity consumption during fiber production. This concern primarily stems from the efficiency of scale for the emerging technology, the Fiber Shredder. The scaled-up Fiber Shredder technology has a significant improvement in impact over the existing lab-scale technology; this result is unsurprising since scaling efficiencies increase output without increasing all energy inputs linearly. Therefore, while designing a larger-scale Fiber Shredder careful consideration should be given to minimizing electricity usage to be environmentally and economically competitive as compared with the current pre-consumer waste wood process. In the future, conducting a more comprehensive life cycle assessment when the Fiber Shredder is at a larger scale of production will be pursued.

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