Mechanical upcycling of cotton waste using additive manufacturing- A forward step to a circular economy and a sustainable future.

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Problem statement

Post-consumer textile waste (PCTW) is an pressing environmental issue that must be addressed by the academic researchers and textile industry (Mehta, 2023). An estimated 15 million mattresses are discarded in the US alone each year, which either end up in landfills or are collected by mattress recycling facilities (Mattress Recycling Council, n.d.). International sleep products association established the mattress recycling council (MRC)- a non-profit organization to develop and implement statewide recycling programs for discarded mattresses. Unfortunately, these recycling facilities are not present in every state, however, their presence is expanding. Currently, MRC collects, sorts, separates, and recycles about 75% of the components of a mattress, while the remaining 25% are landfilled (Mattress Recycling Council, n.d.). Textiles such as cotton, shoddy felt pad, box spring covers, and other fibers are a big portion of the waste that goes into landfills due to a lack of viable options. With this project, we collected mote cotton from the mattress recycling facilities and upcycled the cotton waste into consumer products to replace single-use plastics using additive manufacturing technology. Cotton-based 3D printing filaments provide a unique set of properties that makes them of interest in 3D printing. For example, cotton is a good conductor of heat that would allow uniform heating of the filament during 3D printing.

The manufacturing of fiber reinforced composites (FRP) composites has progressed swiftly in recent years because of their high performance compared to traditional plastics (Narajo-lozada et al., 2019). There is an increasing demand in the market for FRPs due to their high strength-to-weight ratio, resulting in a highly strong yet lightweight material (Block et al., 2018). They have exceptional properties such as high durability, flexural rigidity, stiffness, abrasion, and corrosion resistance. FRPs have a huge potential for applications in industries such as automotive, aerospace, petrochemical, and sporting goods industries (Agarwal and Broutman, 1990; Mallick, 2008). The overarching goal of this project is to upcycle post-consumer textile waste using additive manufacturing and develop a diverse portfolio of sustainable consumer products to replace single-use plastics.

Methods

The cotton fibers were collected from a mattress recycling facility in Connecticut, USA and the poly(lactic acid) PLA polymer for composite formation was purchased from Natureworks™. The fibers were scoured and sanitized using a 5% peroxyacetic acid solution prior to mixing with PLA. They were mixed with PLA polymer in a Haake PolyDrive internal mixer at 150 ^{0}C and

100 rpm for 5 minutes. Once mixing is done, the sample was collected using a brass spatula and was allowed to cool at room temperature. In the next stage, the sample was broken into sizes suitable for additional processing by cutting into snips and granulating in a Dynisco Mini bench-top granulator. As a next step, the 3D printing filaments were extruded using the Rosand RH2000 capillary rheometer. The heated barrel of the rheometer melted the snips of PLA-cotton matrix into a viscous solution that was extruded into a filament form. Upon extrusion, the filament can either be cooled with air or it can be extruded into the water which will result in cooling and solidification at a faster rate. Once the 3D filament with optimum configuration was ready it was used to 3D print the prototypes of consumer products.

Results

The results of this study showcase a proof-of-concept for successful mechanical upcycling of cotton textile waste. Figure 1 depicts the initial sample of the PLA-cotton mixture resulting

Fig. 1 PLA-cotton sample extracted from the internal mixer.

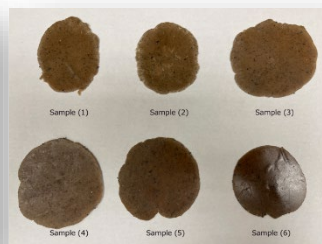

Fig. 2 PLA-cotton samples mixed at different conditions.

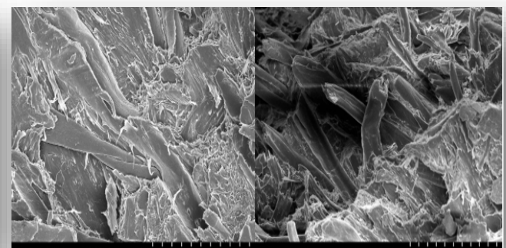

Fig. 3 SEM micrographs of PLA-cotton mixture.

from the internal mixture that was further milled and fed into the rheometer for extruding into a 3D printing filament. The mixing speed, temperature, and time variables were manipulated during the experiment to optimize the mixture properties. Table 1 illustrates the variable conditions, and the resulting samples are shown in figure 2 in the middle above. It is clear from figure 2 that the cotton fibers in sample 6 mixed at 200 ^{0}C were charred. Additionally, there was no significant difference between the properties of sample 1 and the rest of the samples.

Table 1. Variable conditions for mixing PLA-cotton samples.

Sample	Temp.	Mix time	RPM
Sample (1)	150ºC	5 min	100 rpm
Sample (2)	150ºC	8 min	100 rpm
Sample (3)	150ºC	10 min	100 rpm
Sample (4)	200ºC	5 min	100 rpm
Sample (5)	200ºC	8 min	100 rpm
Sample (6)	200ºC	10 min	100 rpm

Fig. 4 3D printed consumer products with PLA-cotton composite.

Therefore, it was determined that the mixing conditions of sample 1 were the most energy-and-process efficient. For further characterization, the scanning electron microscopy (SEM) analysis of the mixture sample was conducted and illustrated in figure 3 (a and b) above on the right. In phase 2, different 3D printed using the filament derived from FRP composite developed in phase 1 of the project. Some of the 3D print prototypes developed in this project such as a dental floss pick, toothbrush handle, and a coat button are illustrated in figure 4.

Conclusion

Given the pressing issue of the environmental impact of textile waste, strategies are needed to address textile waste management. It is crucial to find pathways that transform our linear production and consumption of textiles into a circular economy. This paper provides a proof-of-concept for the successful mechanical recycling of cotton waste into 3D-printed consumer product prototypes that can provide new job opportunities for mattress/textile recyclers. Due to the nature of this lab-scale study, 3D printing was used as a manufacturing technique for producing consumer product prototypes, however, this concept can be easily scaled up for industrial-scale production methods such as injection molding, thermoforming, etc.

In future studies, other fiber types will be explored as this project was limited to developing cotton-reinforced composites for 3D printing.

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