

TEX2MAT – NEXT LEVEL TEXTILE RECYCLING WITH BIOCATALYSTS

Benjamin Piribauer ^{1,*}, Uta Jenull-Halver ², Felice Quartinello ³, Wolfgang Ipsmiller ¹,
Thomas Laminger ¹, Daniel Koch ¹ and Andreas Bartl ¹

¹ Department of Particle Technology, Recycling Technology and Life Cycle Analysis, TU Wien, Getreidemarkt 9, 1060 Wien, Austria

² Chair of Polymer Processing, Montanuniversität Leoben, Otto Glöckel-Straße 2/III, 8700 Leoben

³ Department of Agrobiotechnology IFA-Tulln, University of Natural Resources and Life Sciences Vienna, Konrad Lorenz Straße 20, 3430 Tulln an der Donau

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ABSTRACT

Achieving a circular economy for end-of-life textiles is one of the large challenges in the textile industry. Currently, after disposal, textiles often end up in landfills or incineration plants. In recent years, the textile industry has exhibited high growth rates, with the annual global fibre production reaching 100 million t. It also has to be considered that textile products are increasingly becoming more complex to fulfil special functions, resulting in the use of multi-material textiles. However, these textiles are hard to recycle. The TEX2MAT project is a FFG (Austrian Research Promotion Agency)-promoted project conducted by a consortium of 13 research institutions and private businesses that offers a solution for material recycling. The goal of TEX2MAT is to develop an innovative process for the material recycling of selected multi-material textile streams. In multiple case studies, pre- and post-consumer cotton/polyester textiles from the Austrian SME sector were investigated to close the material cycle from raw material back to raw material. The case studies used a new approach involving the enzymatic hydrolysis of cellulose. Using this approach, cotton can be converted into glucose and polyester remains as the only polymer and is thus accessible for a rather easy recycling process. The obtained glucose can be used as a raw material for different platform chemicals. The project team successfully demonstrated the functionality of the entire processing chain by the complete removal of cotton from the textile and the weaving of new towels with the recycled polyester.

1. INTRODUCTION

The textile industry is growing worldwide, and soon, the world's fibre production will pass the 100 million ton per year mark (Cirfs, 2016). However, this growth is accompanied by a reduction in the average lifetime of textiles before disposal (Korolkow, 2015), which is probably the result of today's fast changes in fashion trends. Both of these factors contribute to the ever-growing amount of textile waste. Aggravating this issue is that many textiles consist of more than one material, which makes them impossible to recycle without significantly reducing the quality of the new product produced from recycled material (Piribauer & Bartl, 2019). These textiles are also a significant source of microplastic emission into the environment through the washing of clothing, etc. (Piribauer, Laminger, Ipsmiller, Koch, & Bartl, 2019).

An easy solution to the problem in regards to using mul-

tle fibre types in one product would be for the producers to stop doing these types of fibre. However, this is often not a viable solution since the different materials are used for a reason. For example the use of spandex fibres is needed to fulfil product requirements regarding elasticity. Carbon fibres are blended into textiles to combat static electricity, which is often needed in medical applications. Cotton/polyester blends are broadly used since they are cheaper than pure cotton fabrics and have high durability while also retaining the moisture absorbing properties of pure cotton textiles. While the reduction in the use of these blended fabrics should be a goal, it is very unlikely that they will vanish from the market anytime soon.

To recycle these blended fabrics, the fibre materials would have to be separated or at least all but one type of material has to be removed from the fabric. There are chemical reactions that can remove certain fibre materials; however, there is always the potential for unwanted side re-

actions, and many of the needed chemicals are potentially harmful to the environment. A possible solution can be the use of enzymes.

Enzymes are biocatalysts; they are very specific in their function and therefore only catalyse specific reactions (Palmer, 2001). While some enzymes can catalyse a biological degradation reaction for many different kinds of fibre materials, only enzymes that use polymers, which occur in nature, as a substrate reach an appropriate reaction speed for a recycling process. One of the most popular fibre material blends (Kunal & Amit, 2017), which contains both a natural polymer material and a thermoplastic synthetic polymer material, is the blend of cotton with polyethylene terephthalate (PET). The natural polymer in cotton is cellulose, and therefore, a group of enzymes, cellulases, exist that degrade cellulose into its monomeric component. On the other hand, PET is a synthetic thermoplastic material, and thus, if cotton is removed from the blend, PET remains and can be melted and re-spun into new fibres of high quality.

This idea of a circular way of removing cotton from blends and recreating new fibres and subsequently new textiles is what led to the start of the TEX2MAT project. The goal of this project is to create a practical circular economy solution that can handle the recycling of cotton/PET mixed textiles from both pre- and post-consumer sources. The recycled product has to be of high enough quality to be able to truly "close the loop", which means the creation of new textiles has to occur at the end of the process. To achieve this goal, three universities and multiple companies along the textile processing chain have collaborated.

Two distinct case studies were defined. One case study handles pre-consumer textiles from cutting rests of towel production. The other case study handles post-consumer bed sheets from a textile rental company. Both of these case studies are challenging in their own way. Pre-consumer textiles can still have waxes and esters on the fibres, which are needed for the weaving process. On the other hand, post-consumer textiles have been washed many times, which may damage the fibre materials. In the case of PET, damage to the fibre materials would be suboptimal, but for cotton, it could be beneficial for hydrolysis, resulting in easier removal.

As already mentioned, to remove cotton, cellulase enzymes are used. These enzymes are commercially available and have been optimized for maximum efficiency by the bio-refinery sector, where these enzymes are extensively used, making them ideal for use for this project. This enzyme class consists of different enzymes with three main functions. Endoglucanase breaks cellulose chains randomly along the chain, exoglucanase removes cellobiose units from the chain ends of the cellulose polymer, and finally, β -glucosidase splits the generated cellobiose molecules into glucose. These enzymes work synergistically, and high reaction speeds can be achieved (Singhania, Adsul, Pandey, & Patel, 2017).

After the removal of cotton with the cellulase treatment, only pure PET should remain. This PET can then be regranulated and, depending on the quality, can either be directly reused or recondensed to reach a spinnable viscosity. Then, fibres can be spun and yarns can be produced. These

yarns can then be used for the production of new towels, and the cycle starts again.

This work consist of two parts. First, the core part of the tex2mat recycling process, the evolution of the enzymatic hydrolysis process with a pre-treatment step, is described in detail, and the experimental data are shown. The second part of this work describes the workflows of the case studies in the tex2mat process and highlights the quality of the recycling product by comparing it with the virgin material product.

2. PART ONE: FEASIBILITY STUDY

The most crucial part of the project was the development of the technology needed for the full degradation of cotton in PET/cotton blends. Early experiments showed that just using cellulase enzymes without further treatment did not result in acceptable degradation speeds and material purities. Therefore, pre-treatments were tested, and an acceptable process flow was found. In this chapter, the steps taken from lab-scale tests to until the production of the first kilograms of pure PET material are shown by describing the biggest breakthrough experiments that contributed to the success of the project.

2.1 Methods

2.1.1 Identification of the material composition

To check the purity of the used cotton/PET mixed fabrics before and after enzymatic treatment, the sulphuric acid procedure according to DIN 1833-11:2010 (Din, 2010) was used. In the procedure, 75% sulphuric acid was heated to 50°C in a beaker. After adding approximately 1 g of the textile to be tested to the acid, the beaker was periodically shaken for one hour. Then, the textile was strained, neutralized, dried and subsequently weighed. Since only cotton was removed with this procedure, the PET content could be determined.

2.1.2 Mechanical preparation of fibre materials

For the maximum surface contact between the fibres and the fluid in the enzymatic hydrolysis step, the textile structure of the raw material had to be disintegrated. To achieve this disintegration, it was to be necessary to grind the raw materials in a standard cutting mill using a trapezoid screen with a screen size of 0.5 mm. Using larger screen sizes only reduced the size of the textile structures without breaking them apart into single fibres.

2.1.3 Pre-treatment of fibre materials

To significantly reduce the time needed to completely hydrolyse cotton, pre-treatment steps were necessary. Different pre-treatments were tried in the course of the project. Alkaline pre-treatments were deemed the most effective, the most promising of which was soaking in sodium hydroxide solutions of approximately 20%. As a result, the hydrolysis speed was accelerated from needing more than a month to merely needing a few hours for complete degradation in the hydrolysis step. However, it should be noted that sodium hydroxide also damages the PET fibres.

For the actual pre-treatment procedure, it was therefore

important to keep the contact time between the textiles and the NaOH as short as possible. The pre-treatment was performed at room temperature simply by soaking the textiles in a large enough amount of NaOH solution to completely cover them. After one hour, the treatment was quickly stopped by pressing the NaOH out of the textiles and, in the case of the lab-scale experiments, thoroughly washing them with tap water until a neutral pH value was achieved.

In the case of the scaled-up experiments, the wash was only repeated two times, leaving a varying amount of NaOH in the textiles, which was used for the in situ preparation of the buffer solution needed for the enzymatic treatment.

2.1.4 Cellulase activity assay

The filter paper assay (FPA) was used as recommended by IUPAC (Ghose, 1987). Rolled filter paper (7.5-75 mm², approximately 50 mg each) was submerged in a glass tube with 1 mL of 50 mM sodium citrate buffer at pH 4.8. Therefore, 100 L of enzyme (diluted 1:1000) was added to the substrate. The reaction was stopped at different time points (0, 5, 10, 20, 40, and 60 min) by adding 500 L of 1 M NaOH. Specifically, for the first time point at 0 min, NaOH was added before the enzyme, which was considered to be the reaction blank. Then, 3,5-dinitrosalicylic acid (DNS) reagent was added, and the sample was boiled for 5 min, followed by the addition of 1 mL of mQ-H₂O (Miller, 1959). Two hundred litres of each sample was transferred into a 96 well-plate, and the absorbance was measured at 540 nm. All measurements were conducted in triplicate.

2.1.5 Enzymatic hydrolysis

For enzymatic hydrolysis, a constant pH value of 5 and temperature of 55°C needed to be ensured. These parameters were determined in pre-experiments not described in this work, but looking at the manual of a commercially available cellulase mixture, these parameters seem to be a good fit for various cellulases (Novozymes A/S, 2019).

To provide a constant pH throughout the entire process, in the case of the lab-scale experiments, a 50 mmol/l citric acid buffer was made with citric acid monohydrate, water and sodium hydroxide to adjust the pH to the exact value. These lab-scale experiments were performed in one-litre glass bottles that were heated to 55°C in a water bath. After reaching the desired temperature, the fibres and the cellulase enzyme mixture were added to each bottle. Each bottle was periodically shaken for the duration of the experiment.

For the larger scale experiments, the buffer solution was made by first dissolving the citric acid monohydrate in water directly in a 60 l reaction vessel and then adding the unwashed pre-treated fibre material, which resulted in an increase of the pH value since the material was still alkaline from the pre-treatment. Adjustments to reach pH 5 were subsequently made by adding more monohydrate or sodium hydroxide as needed. The enzyme was only added after reaching the correct pH value; otherwise, the enzyme could have been damaged. The reactor was heated with a stainless steel pipe spiral that was connected to a pump and a temperature controlled water bath. The reactor was continuously stirred throughout the experiments.

2.1.6 Washing and drying of fibre materials

For the one litre laboratory-scale experiment, drying was simply a matter of rinsing the material on a very fine mesh with tap water, followed by drying on a piece of paper towel without any heating. The mass of the remaining solid fraction could then be easily determined with a laboratory scale.

Washing by hand and subsequent air-drying was, however, not sufficient for the material in the scaled-up experiments and resulted in the growth of mould while drying. Therefore, the material was placed inside a 100% cotton pillow cover and was washed inside a conventional top loading washing machine using a custom detergent. Immediately afterwards, the material, still inside the pillow cover, was dried in a conventional tumble drier for multiple hours. Not only did this process result in very clean and white material, it was also the first step in the direction of industrial application.

2.1.7 Analysis of PET (DSC IV)

Differential scanning calorimetry (DSC) analyses were performed on several material samples. The measurements were performed according to the standard DIN 11357-1:2017 (Din, 2017). In polymer science, DSC analyses are an important method to determine the thermal properties and crystallinity of polymers. In the testing, two samples, the actual sample and the reference sample, sealed in separate crucibles were heated using a special temperature profile. The maximum test temperature T_{max} was chosen to be 280°C, which is the standard test temperature for PET and allows for covering all the important thermal effects without damaging the material. The heating rate was constant at 10 K/min, which is a standard value.

Due to the specific heat and endothermal and exothermal processes, a difference in the temperature for the sample and the reference occurred. From this temperature difference, a heat flow from the sample was calculated, and certain material characteristic thermal properties (glass transition temperature T_G , melting temperature T_M , melting enthalpy, etc.) could be determined.

2.2 Proof of Concept

The hydrolysis trials started at the laboratory scale with reaction vessels of approximately one litre. To provide a large contacting surface, both the pre- and post-consumer cotton/PET mixed textiles were milled to a small particle size, as described in the methods section.

Subsequently, hydrolysis was performed with the specimen according to the method described in the previous section. Approximately 10 g/l cellulase enzyme with an activity of 1850 U/ml was used (results to approximately ~20.000 U/l in the reaction liquid). In addition to the milling of the fibres, no further pre-treatment was performed in these first trials. It was immediately evident that the speed of hydrolysis was far too slow for commercial use, as seen in the untreated cotton line in Figure 1. The untreated materials lost only approximately 17% of their weight in 24 h with a reduction of speed over time, suggesting treatment times of well over a month.

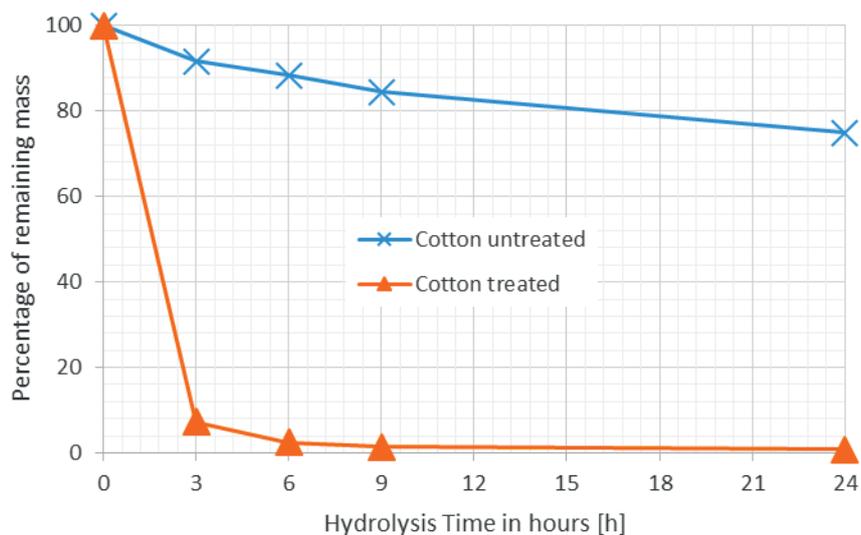


FIGURE 1: Residual mass of textile after hydrolysis for both treated and untreated materials.

Due to the insufficient grade of degradation in the experimental timeframe, various pre-treatments of the textile materials were tested. Alkaline pre-treatments turned out to be the superior choice due to their low cost and high effectiveness. The best choice after multiple tests seemed to be 20% NaOH, and an exemplary comparison between treated and untreated fibres can be seen Figure 1. After 3 hours, less than 10% of the material remained, and after 24 h, there was less than 1% left, which mainly consisted of seed capsules, etc. The next step was optimization of the enzyme concentration. The concentration was step-wise lowered from 10 g/l until a significant drop in the hydrolysis speed was observed. In Figure 2, it can be seen that even with concentrations as low as 1 g/l, 99% degradation was achieved. While for the larger scale experiments, high concentrations above 5 g/l were used as a safety precaution.

Due to these data confirming that the process could work in practice, the next step was a scale-up to generate enough material for the production of fibres. For this scale-up step, a 60 l barrel was modified with a heat exchanger

and a stirrer (Figure 4 left). With this reaction vessel, 3 kg of the cotton/PET textile substrate could be hydrolysed at the same time. Over the course of the project, a total of approximately 30 kg of pure PET was created using this procedure. This amount was necessary to create a sufficient amount of PET for spinning trials and the creation of new textiles in the next step.

Before the full amount needed for textile production was produced, however, the suitability of the created rPET (recycled PET) for spinning fibres needed to be checked. The DSC method was chosen for this check because thermal values allow conclusions to be drawn regarding differences between samples of different origins and what has influenced or damaged the material during processing and usage. The DSC method also hints at potential substantial (molecular) degradation. The material used in this project originated from different sources in terms of the raw material, application and lifetime and went through a highly alkaline pre-treatment. Therefore, the aim was to determine whether there was a significant difference or decrease in

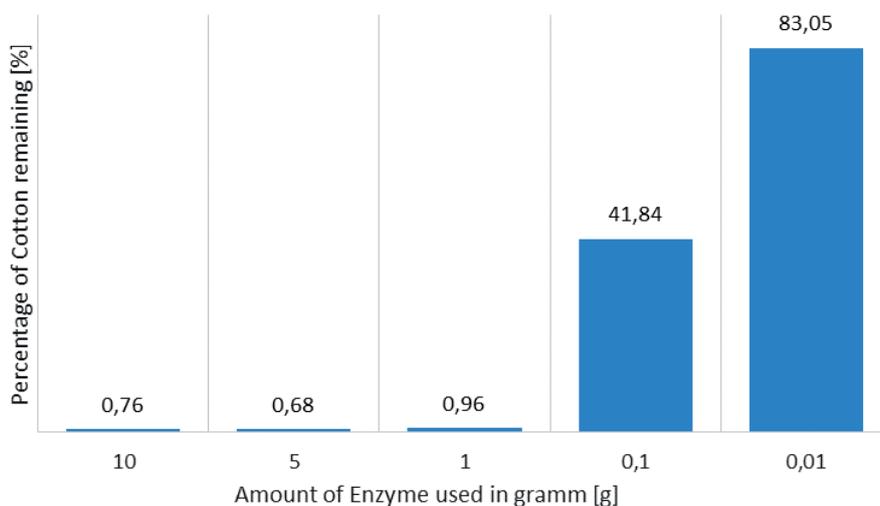


FIGURE 2: Residual mass in percent after 24h of hydrolysis for different enzyme concentrations.

the molecular weight of the various samples. A shift in the T_M to lower temperatures is an indicator that the molecular weight has been reduced (Berger et al., 1993).

Samples were chosen along the complete value chain to observe any changes or influence due to the processing steps and usage, which included virgin fibre grade PE and the rPET created in the enzymatic process, and the fibres spun from said rPET were also included as a reference, as shown in Figure 3.

As a result, no significant differences in the T_M (peak value) or melting enthalpy (normalized integral value) were observed between all of the samples. Thus, it can be assumed that the various samples did not suffer significant molecular degradation (molecular weight) and spinning should be possible. Further spinning trials confirmed that despite the greyish colour of the once white PET after regranulation, the material was still suitable for spinning into new fibres, as was proven by the first round of spinning trials. The re-spun fibres can be seen on the right side

of Figure 4. With these results, the proof-of-concept was finished, and the case studies were started with the developed Tex2Mat workflow.

3. THE TEX2MAT WORKFLOW

After successfully hydrolysing all of the cotton in the blend at the 60-l scale (netting approximately 1.5 kg PET per batch) on a reasonable timescale, the case studies could start in their entirety. In the sections chapters, all of the steps in the procedure are described, and it is discussed why these steps are necessary and what the goal of each step is. Additional methods used for the full workflow are discussed directly in the corresponding sections.

3.1 Shredding and milling

One of the most important components of the enzymatic hydrolysis is ensuring the contact between the single textile fibres and the liquid containing the enzymes. There-

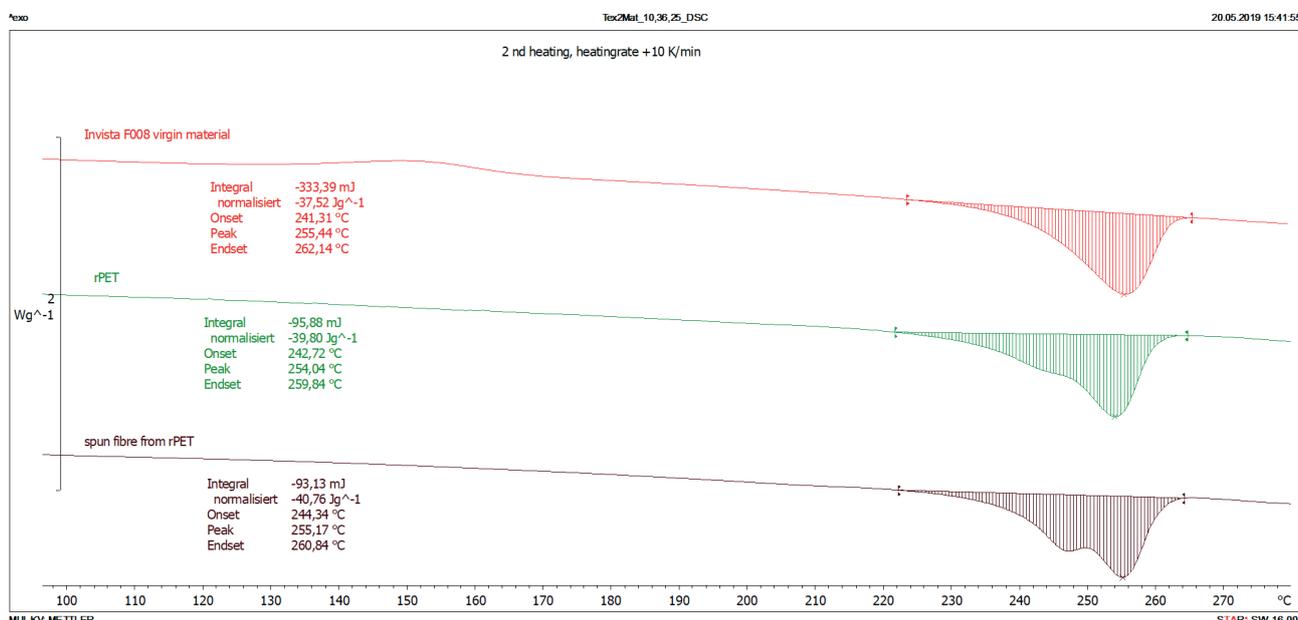


FIGURE 3: DSC-Analysis of PET virgin material (top), rPET (center) and rPET spun fibre (bottom).



FIGURE 4: Residual mass of textile after hydrolysis for both treated and untreated materials.

fore, the textiles were first shredded to a size of approximately 5 cm squares and were then milled in a cutting mill with a screen size of 0.5 mm. This process resulted in the complete disintegration of the textile structure, resulting in single fibres only. In total, approximately 50 kg of textiles was processed in this way over the duration of the case study.

3.2 Pre-treatment

Per batch, approximately 3 kg of the PET/cotton blend could be used in the 54 l reactor, and therefore, that amount was pre-treated. The pre-treatment itself was performed identical to the description of the pre-treatment for the 54-l

scale in the Materials and Methods section. The treatment was performed to greatly enhance the speed of hydrolysis, as described in the previous section.

3.3 Enzymatic hydrolysis

Hydrolysis was performed in the 60 l reactor, as described in the Materials and Methods section. A hydrolysis time of 48 h was chosen along with approximately 1 kg of enzyme per batch to absolutely ensure that only a 100% pure product was generated, as a single faulty batch would have had fatal consequences for the further steps. A total of over 30 kg of PET was produced in the course of the project (approximately 25 batches total).

3.4 Washing/Drying

As described in the Materials and Methods section, the washing and drying of PET after successful hydrolysis had to be performed with the help of a conventional top loading washing machine and a tumble dryer. Since the fibres were very fine, they were placed inside a pillow cover, which allowed water and detergent to reach the fibres but did not let the fibres escape, which would have resulted in a major loss of material.

3.5 Granulation/recondensation

Before the material was regranulated, first the intrinsic viscosity was measured with a LMI5000 melt flow indexer to obtain a reference point. Then, the material was dried with a Piovan hot air dryer at 150°C for 4 hours since it is essential that no humidity remains. The material was then granulated with a Dr. Collin E25P, and the IV was measured once again. Since the IV was usually below 0.6 dl/g, the material needed to be recondensed, for which a recoSTAR SSP 1800 was used.

Multiple PET batches were processed with this scheme. To give an example, one of the first batches behaved as follows: the IV at the beginning was way too low, with a value of 0.47 dl/g, and after regranulation, it increased to 0.542 dl/g, which was still on the lower end for spinning fibres (MacDonald, 2003). After an additional six hours of treatment in the SSP, the desired value of 0.602 dl/g (over 0.6 dl/g) was reached, and the material was sent to the next production step.

3.6 Spinning

After the PET was properly adjusted, spinning trials were performed. All the experiments were conducted on a pilot spinning line "TS-32" with a 32 mm screw diameter. The spinning temperature was set to 265°C, and the final drawing process speed was 100 m min⁻¹. The experiments started with pure virgin PET to clean the machine; then, spinning with a 25% recycling content was started, and the spinning proceeded for over one hour. After a cleaning procedure with virgin material, a 50% recycled content fibre was obtained.

Additionally, fibres with 100% virgin material were also produced to have a point of reference for further tests. Enough of these monofilament materials could be produced to proceed with weaving trials.

3.7 Weaving

As a product for the weaving trials, a standard bath towel, as is usually produced at the facilities of one of the project partners, was chosen as the desired product for the test. Due to the constraints in regard the amount of available material, it was decided to use the produced recycled PET fibres only in the weft since a too large amount would have been needed for use in the warp.

For weaving of the desired towel design scheme in industrial production, a 50/50 PET/cotton yarn is used, consisting of twisted staple fibres. Creation of such a yarn was unfortunately not feasible at such a small scale; therefore, a 100% PET yarn consisting only of the newly produced monofilament fibres and commercially available 100% cotton yarn were used in the weft together to reach the original mixture. The polyester fibres had to first be twisted with themselves to create a pure polyester yarn. In this way, yarns were created for all three material fractions (0%, 25%, and 50% recycled content, respectively). Since the difference in the yarn structure could make a major difference in the mechanical properties, it was decided to use our 0% recycled content material (100% virgin material) as our point of reference for any comparisons instead of a commercial 50/50 blended yarn.

Without any mayor complications, towels could be produced from all three materials, and there were no significant differences in the processing between the 50% recycled content fraction and the pure virgin material fraction. In Figure 5, the weaving of the 50% recycled content towels is shown.

3.8 Mechanical Tests

To test the properties of the produced towels, a multitude of test procedures were performed. Two of these procedures are described in this work. The first test procedure presented is the washing trial, in which the material was industrially washed multiple times and the change in size of the towels was observed.

The other test procedure investigated the maximum strength the towels were able to withstand with the help of a tensile strength machine. In such a machine, the towels were pulled apart until mechanical failure.

3.8.1 Washing test

The washing experiments were conducted with a Senking P50-16K industrial washing setup consisting of a washing machine and a tumble dryer, as seen in Figure 6.

The washing temperature was above 60°C with a peracetic acid-based disinfectant. The drying temperature was 170°C at the entry and 110°C at the outlet.

For the procedure, every towel was marked, and the length and width were noted. The washing/drying procedure was then performed 36 times, and after each full cycle, the lengths and widths were again recorded. On average, the towels showed shrinkage of approximately 12% in length and 13% in width, as seen in Table 1. All the materials seemed to be approximately the same regarding the length shrinkage, and only small differences could be observed regarding the width shrinkage. Compared to the



FIGURE 5: Weaving of the 50% recycled content towels.

3.8.2 Tear resistance (cross)

To check the mechanical stress that a towel is able to withstand, the tear resistance was measured. With a tensile strength testing machine, the towel was pulled cross to the direction of the longer side until the towel ripped apart. Every measurement was repeated two times, for a total of three tests per towel. On average, the tear resistance of the virgin material towels was 185 N/cm, and that of the 50% recycled content towels was 189 N/cm. Considering the calculated standard deviations (1 N/cm and 4 N/cm, respectively), these values should not be considered to be significantly different.

4. CONCLUSION AND OUTLOOK

The results described in this article impressively show that the new TEX2MAT process is suitable for recycling PET/cotton blends. This material mixture, which is very



FIGURE 6: Industrial washing machine Senking P50-16K.

usual shrinkage values of approximately 7% for towels according to the experience of the washing company, these numbers may seem high. These high numbers can, however, be attributed to the low stretching that was achieved in the laboratory spinning machine compared to industrially produced fibres, which is especially evident considering that the virgin material fibres produced showed the same large shrinkage.

common on the market, cannot currently be recycled, but in the best case, this material ends up in an energy recovery process. With the process presented here, cotton, the fibres of which are often already damaged, can be processed into a platform chemical.

After the removal of cotton, PET remains as a pure material, making recycling possible, similar to PET bottles. The difficulty lies in the re-granulation of the fluffy PET fi-

TABLE 1: Lengths and widths of the tested towels after the corresponding washing cycles.

Cycle	Virgin Material		Tex2Mat RPET	
	Length [cm]	Width [cm]	Length [cm]	Width [cm]
0	92	50	92	50
1	85	47	85	47
2	84	46	84	46
3	84	46	84	46
4	83	46	83	46
5	83	46	84	45
6	83	45	83	45
11	83	44	82	44
16	81	43	82	43
26	81	43	82	43
36	81	44	82	43
Shrinkage [%]	11,96	12,00	10,87	14,00

bre material, and hydrolysis cannot be completely avoided. However, it has been shown that the IV can be brought to a value suitable for spinning fibres by post-condensation. Although the process could not yet be carried out at the industrial scale, the possibility for fibre to fibre recycling was demonstrated. Within the project, the reaction volume per batch could be increased from 1 l to 60 l.

However, to operate the process at the industrial scale, there still is work left to do in regards to optimization. For example, the chemicals used in the pre-treatment and hydrolysis have to be re-used multiple times to create a truly environmentally friendly process. This is also where the main limitations to scale-up are found. For the hydrolysis process itself, only a slightly agitated low temperature vessel is needed, in which the textile hydrolysis will take approximately a day. The investment and operation cost for enzymatic hydrolysis can therefore be estimated to be quite low compared to membrane separation for removal and re-use of the enzyme. The same is true for the purification of the used pre-treatment solutions or the mechanical presses used in the pre-treatment steps.

To evaluate the required procedures, it would be very important to use life cycle assessment tools right now when the process development is still in an early stage because at the end of the development process, changes are difficult to implement. These tools could also be crucial to find the correct dimensions for an optimal scale for the process (Koch, Paul, Beisl, Friedl, & Mihalyi, 2020).

While the development of the industrial process is not finished yet, it can be said with confidence that the process finally opens the door for a significant change in textile waste management by providing an ecological solution for one of the most important textile waste fractions. Furthermore, while the cotton/PET waste stream is very important, it is not the only stream in which enzymatic recycling can be used. Other cellulose-based fibres, such as the man-made regenerated cellulose fibres rayon and lyocell, are gaining market share (Cirfs, 2016). In addition, non-cellulose-based fibres, such as protein fibres, have the potential to be able to be hydrolysed with similar processes.

A major factor in a possible application of all of these processes is the separate collection of textile waste. If the required cotton/PET mixture is contaminated with other organic substances, the processes will potentially not work. Furthermore, the fabrics themselves have to be sorted incredibly well since, e.g., a nylon item in a cotton/PET batch will remain in the PET fraction and will have negative impact on the re-spinning of new fibres.

However, the best chance for this novel process to be used is with industrial textile waste. If the waste supply from a company only includes cotton/PET mixtures, the room for error shrinks. For example, in the case of textile rental companies, the composition of discarded textiles is well known, making them an ideal candidate as a supplier of secondary raw materials.

The interest in textile recycling technologies is currently growing. Recently, the European Commission amended the waste framework directive (European Parliament, 2018), which now takes textile waste into account. Amongst others, by 2025, a separate collection of textile waste will be compulsory within the EU. This legislation will increase the amount of separately collected textile waste and will put pressure on municipalities to improve the collection, sorting and recycling of textiles. This pressure will also give novel technologies such as the one described in this work a chance. While enzymatic recycling cannot and should not be the sole solution to the textile waste problem, it could become an integral part of the bigger picture.

The great interest in this topic was demonstrated by the fact that the TEX2MAT project was awarded the largest Austrian prize for industry cooperation, the "Clusterland Award 2019" (Ramsl, 2019).

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