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Ethanol-Production from Waste Textils

Converting Cellulose Molecules of Textile Waste into Ethanol using Simultaneous Saccharification and Fermentation

This thesis deals with the production of ethanol from used textiles. The process of simultaneous saccharification and fermentation is used to convert the cellulose molecules of the textile fabric into ethanol. In addition, the potential of textile biomass in Switzerland is analysed in this thesis, which allows the potential of ethanol production from used textiles to be evaluated on a national level.

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1. Introduction

Textiles currently represent a major global waste problem. The resource and energy intensive production of textiles already has disastrous consequences for the environment. However, consumers have no direct influence on this problem. Textile waste accumulates in large quantities, and it is often not clear what should be done with it. Most textile waste is incinerated in waste incineration plants (WIP) or shipped in huge quantities to developing countries, where it often ends up in landfills. Many developing countries are now suffering from these textile imports because they can no longer handle these quantities.

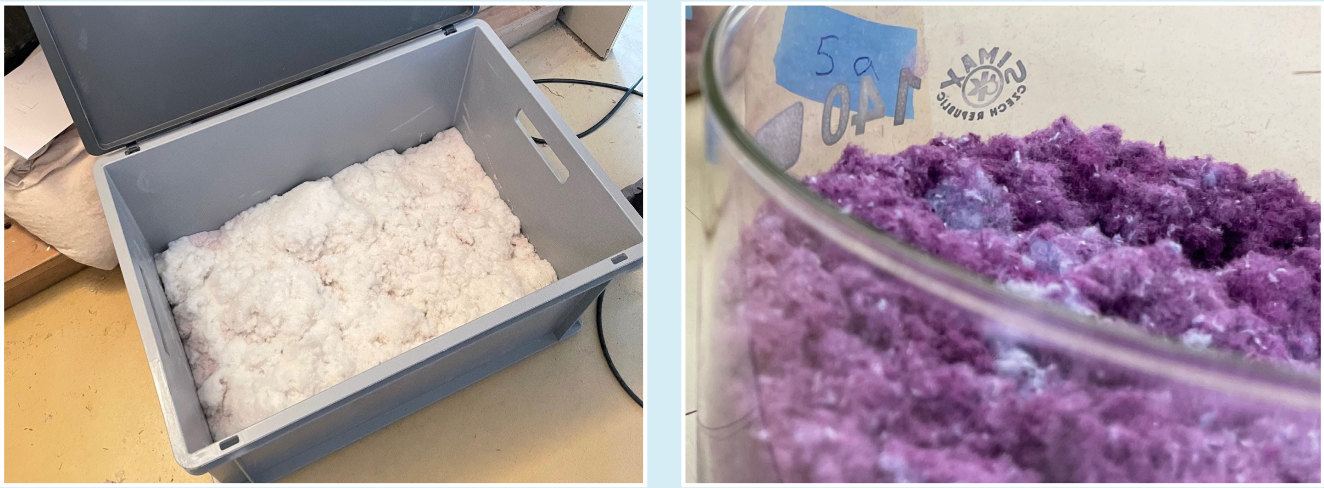
One approach to solve the problem of textile waste is to locally recycle these waste textiles. In addition to reusing the textiles as secondhand clothes, the cellulose-based fabric of the waste textiles can also be converted into commercially valuable ethanol by using relatively straight forward biochemical processes. The textile fabrics are first decomposed through enzymatic hydrolysis and then fermented to ethanol. Ethanol is an alcohol that is used in large quantities. It has wide applications as a solvent in industry, fuel additive and starting material for many useful chemical building blocks, as well as being used in the beverage industry. In addition, ethanol has recently seen significant growth in the adoption of hand sanitizer. In the global market share of ethanol from 2019, about 40 % was used in the fuel sector, and 20 % each in the industrial (solvents) and beverage sectors [1].

Ethanol for fuel, so called bioethanol is considered a very promising, renewable and environmentally friendly fuel and can be used as a gasoline substitute [2]. In several countries, gasoline is blended with ethanol. For example, in Brazil, the E85 fuel, which consists of 85 % ethanol and 15 % gasoline, is very common [3].

Ethanol is produced by fermenting biomasses containing sugar or starch. The biomasses used are often plants grown specifically for this purpose. For example, in 2022, 135 million tons (metric tons) of corn, 35 % of the total U.S. corn production, were fermented to ethanol [4]. In Brazil, ethanol is produced mainly from sugar cane [5]. This means that ethanol is in direct competition with food and feed industry. With growing population and increasing need for primary foods like corn and sugar, agricultural waste, and other waste biomasses like waste textiles, should be used instead for ethanol production (second generation ethanol).

In this thesis, an analysis of textile biomass in Switzerland is carried out to estimate the biomass potential of waste textiles on a national level. Before starting the actual process, the studied textile samples are analyzed to determine their exact composition. This data serves as a basis for further steps of the process.

To convert the textile fabric into ethanol, in this work the simultaneous saccharification and fermentation (SSF) process is carried out. In this process, the cellulose fibers are broken down into glucose molecules by enzymatic hydrolysis (EH) and then fermented to ethanol. The product concentration of ethanol is measured by High Performance Liquid Chromatography (HPLC). In doing so, the ethanol yield of textiles can be determined.



a) b)

Fig. 1: The shredded samples (a) sample 1 originates from a used pair of old judo pants and consists of 100 % cotton, (b) sample 2, a former sweater, consists of 55 % cotton and 45 % polyester

The research questions of this thesis are:

- What is the usable biomass potential of textile waste in Switzerland?
- How much cellulose of the textile fabric can be converted into ethanol by the process of simultaneous saccharification and fermentation?
- What do the results of the fermentation of textile cellulose mean for the usable biomass potential of textiles?

2. Theoretical Principles

2.1 Composition of Textiles

When it comes to the components of clothing or textiles, a rough distinction is made between natural fibers and man-made fibers. The natural fibers will be discussed in more detail since these fibers are based on cellulose. Only the cellulose can be processed in the process performed in this thesis. Any other substances cannot be processed by the enzymes used in this work during the EH and are left over.

Cotton fiber is a widely used and popular type of fiber in the world. It consists of 96 % cellulose and is a natural fiber [6]. Cellulose is the most common polysaccharide and consists of several hundreds, to tens of thousands of glucose units chained together. These chains form tear-resistant fibers, which often have structural functions in plants [7].

2.2 Hydrolysis

Hydrolysis is a chemical reaction in which chemical bonds are broken by the addition of water. Catalysts can be used to accelerate the reaction.

In an enzymatic hydrolysis (EH), also called saccharification, polysaccharides are broken down into monosaccharides with the help of enzymes. The EH is used in this thesis to break down the long-chain cellulose molecules into individual glucose molecules.

2.3 Fermentation

Fermentation refers to the microbial or enzymatic conversion of organic substances into more primary building blocks like acid, gases, or alcohols. This is not a simple chemical process, but occurs in several steps [8].

Alcoholic fermentation is a biochemical process in which microorganisms ferment carbohydrates (e.g. glucose) to generate ethanol and carbon dioxide [9]. Alcoholic fermentation is carried out in this thesis to convert the glucose molecules produced by hydrolysis into ethanol.

The ethanol obtained by fermentation can be purified by distillation. This last step is not discussed in this work since distillation is an established process in industry.

3. Materials and Methods

In this chapter, the operational steps of the potential analysis, the preparation of the biomass, the composition analysis of the textile samples as well as the simultaneous saccharification and fermentation (SSF) are described.

The experiments performed in this thesis were carried out in the laboratories of the University of Agricultural, Forest and Food Sciences (Hochschule für Agrar-, Forst-, und Lebensmittelwissenschaften, HAFL) in Zollikofen (Bern, Switzerland).

3.1 Potential Analysis of Textiles in Switzerland

The potential of ethanol production from waste textiles in Switzerland was

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determined through data acquisition. This includes the amount of textiles collected and recycled per year in Switzerland, the amount of textiles disposed of as waste and incinerated, and the fabric composition of these waste textiles.

To determine the energetic potential of the available biomasses, the lower heating value of textiles was used. The measured biomass conversion was multiplied by the available waste textiles in Switzerland to estimate the energy potential.

3.2 Preparation of Textile Biomass

Two samples with different fiber composition were selected and shredded for the experiments. The textile fabric of the first sample consists of 100 % cotton. The fabric originates from a used pair of old judo pants. It is very dense and not dyed, but probably bleached and is therefore a white textile. The fabric of the second sample consists of 55 % cotton and 45 % polyester. The fabric originates from a used old sweater. It is less dense than sample 1 and was dyed light blue / violet.

The mixed cotton and polyester sample was used to determine whether the polyester, which cannot be further processed, influences the processing of the cellulose. The mixing ratio of sample 2 was selected to reflect the worldwide distribution of fiber types (cotton representing natural fibers / polyester representing man-made fibers) [10].

To prepare the biomasses for the following experiments, the textiles were cut and torn into pieces of approximately 10 cm x 10 cm. These pieces were then milled using a cutting mill (Retsch SM100, Haan, Germany) with a 4 mm sieve insert. After milling, the textile samples looked as shown in Fig. 1.

3.3 Compositional Analysis of Textile Samples

The goal of the composition analysis was to precisely determine the cellulose contents of the biomasses as well as their dry matter (DM). This data served as a basis to determine the amount of biomass required in the SSF.

The DM of the two textile samples were measured by using a moisture analyzer (Mettler Toledo HB43-S, Greifensee, Switzerland). The composition of the textiles was determined according to the protocol of the National Renewable Energy Laboratory (NREL) (Determination of Structural Carbohydrates and Lignin in Biomass, NREL, 2012, [11]).

The biomasses were hydrolyzed using sulfuric acid according to the protocol and the amount of sugars obtained from the cellulose as a result was measured by HPLC (HPLC analyzer: Waters e2695 with Waters e2414 Refractive Index Detector, Massachusetts, United States of America). The following equation was used to calculate the cellulose concentration:

Cellulose concentration of biomass

$$= \frac{C_G \cdot 0.087}{m_B \cdot DM \cdot 1.111} \cdot 100\ \% \qquad (1)$$

With:

C_G	measured glucose concentration in g/l
0.087	total volume in l
m_B	weighed mass of biomass in g
DM	biomass dry matter
1.111	conversion factor (glucose to cellulose)

3.4 Simultaneous Saccharification and Fermentation (SSF) of Textile Samples

SSF was performed according to the NREL protocol (SSF Experimental Protocols – Lignocellulosic Biomass Hydrolysis and Fermentation, NREL, 2008, [12]). The enzyme Accelerase 1500 (Novozymes, Bagsvaerd, Denmark) was used for EH in this process. Distillers Yeast (Saccharomyces cerevisiae) was used for the fermentation. The test series carried out can be taken from Table 1.

Tab. 1: Test series of SSF of textile samples

Number	Sample description
1a,b,c	Cotton 100 %, white, 15 filter paper unit (FPU) enzyme
2a,b,c	Cotton 100 %, white, 60 FPU enzyme
3a,b,c	Cotton 55 %, Polyester 45 %, dyed, 15 FPU enzyme
4a,b,c	Cotton 55 %, Polyester 45 %, dyed, 60 FPU enzyme
5a,b,c	Control Avicel, 15 FPU enzyme
6a,b,c	Control, 60 FPU enzyme

For the preparation of the yeast culture (inoculum culture), YP medium (1 liter of medium contains 3.0 g yeast extract, 3.0 g malt extract, 5.0 g peptone and 10.0 g glucose), which is the nutritional basis of the yeasts, was added to the yeast cells. This was done in a sterile bench to prevent contamination of the yeast culture. The amount of yeast used for the experiments was determined by measuring the optical density. By measuring the optical density of the yeast at 600 nm (nanometer) (UV/

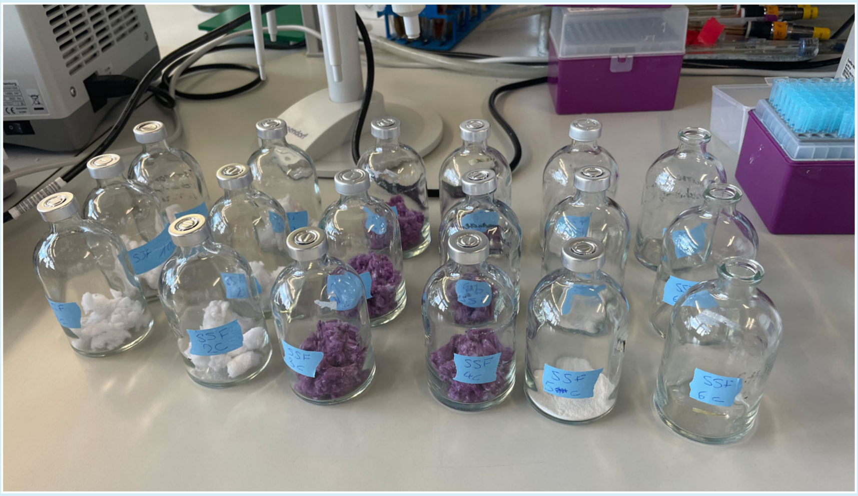

Fig. 2: Glass flasks for the simultaneous saccharification and fermentation filled with biomasses

Vis Photometer DR5000, Hach Lange, Rheineck, Switzerland), the amount of yeast cells in the solution can be determined. Like this, with a target density of 0.5, the amount of yeast cells for the samples can be calculated.

For the SSF, 0.5 g of cellulose was chosen as the initial weight for each test series. The required amount of biomass was calculated as follows:

$$\text{Mass of the biomass} = \frac{m_C}{C_{CB} \cdot DM} \qquad (2)$$

With:

m_C	desired mass of cellulose in g
C_{CB}	cellulose concentration of biomass
DM	dry matter of biomass

The calculated masses were weighed precisely and filled into glass flasks for the SSF (see Fig. 2). These glass flasks are suitable for autoclaving, which means they are heat resistant to temperatures up to at least 121 °C. A buffer solution was then added to the biomasses according to the protocol. This buffer solution keeps the pH stable during hydrolysis and prevents hyperacidity. The samples were then autoclaved, i. e. kept at 121 °C for 1 h, to destroy all microorganisms and to sanitize the samples. Subsequently, the enzyme Accelerase was added, which was diluted with water at a ratio of 1:10. This was done in a sterile bench to prevent contamination. Then the yeast culture was added, which was also done in a sterile bench. The amount of the substances added to the different test series are listed in Tab. 2. Finally, the flasks were filled with water to a volume of 50 ml so that the cellulose concentration was 1 w/w %. The flasks were sealed with rubber lids. A needle was then inserted through these rubber lids, through which the CO_2 produced by the yeast during fermentation could escape. The needle was also used for sampling. Then, the flasks were placed in the shaking incubator (HT Multitron Pro, Bottmingen, Switzerland) at 38 °C. The duration of the experiment was 168 h (7 d).

During SSF, samples were collected after 24 h, 72 h (3 d), and at the end of the experiment, after 168 h (7 d). These samples were analyzed by HLPC. An example of an HPLC chromatogram can be seen in Fig. 3. The measured ethanol concentration is used to determine the percentage of cellulose in the textile fabric that has been converted into ethanol. Thus, the progress of the SSF can be calculated.

To calculate the proportion of cellulose converted to ethanol by SSF, the following equation was used:

$$\text{Converted cellulose} = \frac{C_E}{0.51 \cdot C_C \cdot 1.111} \cdot 100\ \% \qquad (3)$$

With:

C_E	measured ethanol concentration in g/l
0.51	conversion factor (glucose to ethanol)
C_C	cellulose concentration in g/l
1.111	conversion factor (cellulose to glucose)

4. Results and Discussion

In this chapter, the results of the experiments are presented and discussed.

4.1 Potential Analysis of Textiles in Switzerland

There is little data available on disposal and recycling in the textile and clothing sector in Switzerland. While worldwide data is available, this thesis focuses solely on the national biomass potential of Switzerland.

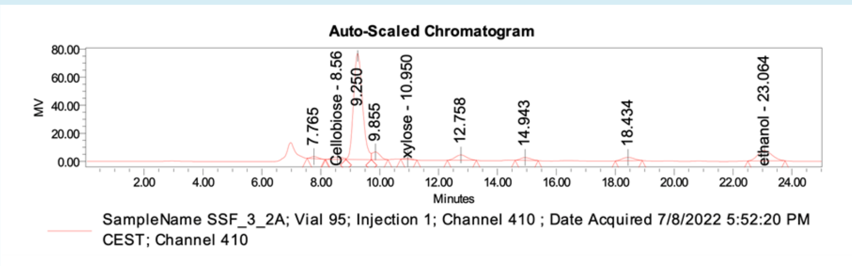

Fig. 3: HPLC Chromatogram example

Tab. 2: Experiment SSF added substances. In addition, for all test series: 50 g total mass, 1 % cellulose content, 0.5 g desired cellulose, 2.5 ml 20X CA buffer (1M), 5 ml YP 10x

sample number	enzyme content in FPU/g cellulose	cellulose content of biomass according to composition analysis	biomass dry matter	biomass in g	yeast Inoculum in ml	enzyme 1 : 10 dilution in ml	Water in ml
1a,b,c	15	0.981	0.939	0.543	9.025	1.278	40.680
2a,b,c	60	0.981	0.939	0.543	9.025	5.111	36.847
3a,b,c	15	0.585	0.963	0.887	9.025	1.278	40.335
4a,b,c	60	0.585	0.963	0.887	9.025	5.111	36.502
5a,b,c	15	1	0.963	0.519	9.025	1.278	40.703
6a,b,c	60			0.000	9.025	5.111	37.389

The amount of textiles imported into Switzerland per year is used as the basic potential. In 2018, this was about 300,000 t of textiles and clothing [13]. This quantity can therefore be regarded as the baseline quantity.

In Switzerland, around 50,000 t of used textiles are collected per year in clothing collection stations [14]. About 10 % of these collected textiles will still be disposed of by incineration [15]. Thus, a quantity of 5,000 t of textiles per year ends up in the waste incineration plants (WIP) despite having been collected in a clothing collection. In addition, according to an extrapolation, more than 100,000 t of textiles per year end up in Switzerland's municipal waste and are thus directly incinerated [16]. Fig. 4 shows the management of waste textiles in Switzerland.

It is not clear what happens to the remaining textiles. This means that there is an unrecorded volume of around 150,000 t of textiles per year. The poor data situation shows that there is a lot of potential for improved management of textiles. The association of Swiss Recycling also sees this potential in the field of recycling of textiles [17]. In the future, the path of textiles should be tracked more carefully to create more transparency regarding the biomass potential of textiles in Switzerland.

Data concerning the breakdown by fiber type of the Swiss waste textiles was not found. However, an estimation can be made by the worldwide fiber breakdown of the textile industry. Thus, worldwide, almost 45 % of the fibers for the production of clothing and almost 30 % of the fibers for the production of household textiles consist of cellulose-based natural fibers [10].

Textiles have a lower heating value of about 22 MJ per kg DM (dry matter of biomass) [16]. With the theoretical potential of 300,000 t per year, a theoretically available energy of 6.6 PJ per year can be calculated. The realistic usable potential is the amount of textiles that is disposed of by incineration today. This value is 105,000 t of textiles per year, which corresponds to an available energy of 2.3 PJ per year.

The total energy consumption in Switzerland was 795 PJ in 2021 [18]. Hence the biomass potential of waste clothes corresponds to 0.3 % of the yearly energy consumption in Switzerland.

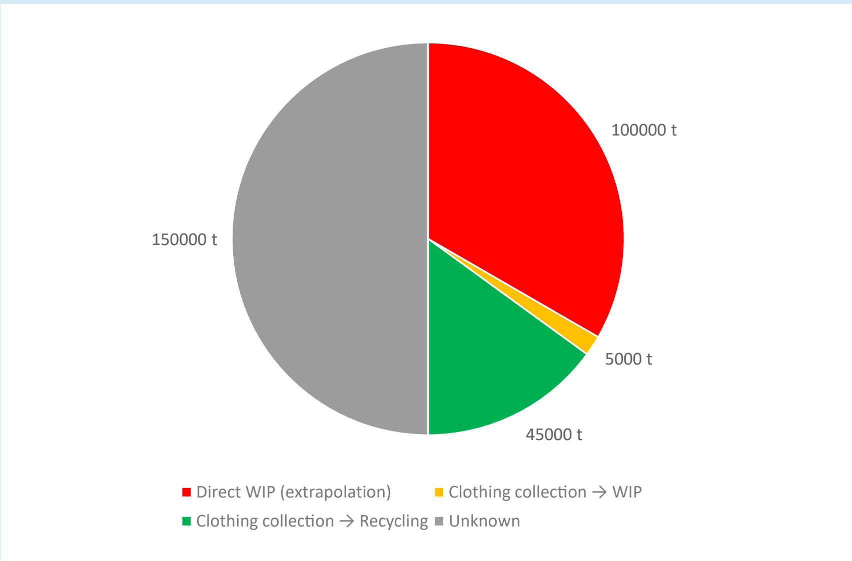

Fig. 4: Waste textile management in Switzerland (WIP: waste incineration plants)

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Tab. 3: Results of the SSF

Test series	Proportion of converted cellulose after 168 h in w/w %	Measured ethanol concentration after 168 h in g/l
Cotton 100 %, white, 15 FPU enzyme	37.00 ± 1.46	2.10 ± 0.08
Cotton 100 %, white, 60 FPU enzyme	51.96 ± 1.21	2.94 ± 0.07
Cotton 55 %, Polyester 45 %, dyed, 15 FPU enzyme	27.24 ± 1.45	1.54 ± 0.08
Cotton 55 %, Polyester 45 %, dyed, 60 FPU enzyme	42.17 ± 0.60	2.41 ± 0.03
Control Avicel, 15 FPU enzyme	54.21 ± 0.57	3.07 ± 0.03
Control, 60 FPU enzyme	0.00	0.38 ± 0.33

4.2 Compositional Analysis of Textile Samples

The measurement of the DM of the biomasses resulted in the following: Sample 1 (cotton 100 %, white) has a DM of 93.9 % and sample 2 (fiber blend, cotton 55 %, polyester 45 %, dyed) a DM of 96.3 %.

Analysis of the composition of the samples showed a cellulose content of 98.08 ± 0.46 % for sample 1 and 58.53 ± 0.96 % for sample 2. These results are within the given composition of the manufacturer. For sample 1, the literature value of up to 96 % cellulose content (chapter 2.1 Composition of textiles) was exceeded by 2.2 %. With a cotton content of 55 %, the expected cellulose content of sample 2 was even exceeded by 10.9 %. However, the fabric cannot be considered perfectly homogeneous, and the collars and hems can also show a different fiber ratio in some cases, which influences the overall ratio and can partly explain the deviation in sample 2.

4.3 Simultaneous Saccharification and Fermentation of Textile Samples

The SSF of the textile samples was carried out as described in chapter 3.4, whereby a cellulose concentration of 1 w/w % was selected. The results, thus the achieved percentages of converted cellulose and the achieved ethanol concentrations at the time of stopping the SSF are shown in Table 3. Fig. 5 shows the cellulose conversion during SSF. The product concentrations of ethanol measured after 168 h concerning the examined textiles are shown in Fig. 6.

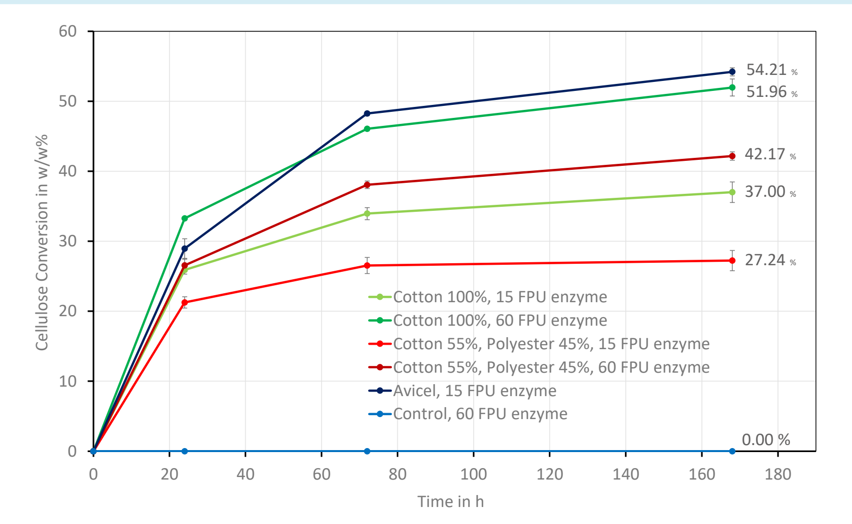

Fig. 5: Cellulose conversion by SSF

Through the SSF process, concerning the examined textile fabrics, as can be seen in Table 3 and Fig. 5, a maximum of 51.96 ± 1.21 % of the initial cellulose could be converted into ethanol, whereby a product concentration of ethanol of 2.94 ± 0.07 g/l was achieved. This value was obtained in test series 2 (cotton 100 %, white, 60 FPU enzyme).

The results show that there is an inhibition effect of the polyester or the dye in the SSF. This can be seen from the fact that regarding the two test series with the higher enzyme content, with a cellulose conversion of 42.17 ± 0.60 % in test series 4 (fiber mixture, cotton 55 %, polyester 45 %, dyed, 60 FPU enzyme), 18.8 % less cellulose was converted than in test series 2 (cotton 100 %, white, 60 FPU enzyme). In the two test series with the lower enzyme content, with a cellulose conversion of 27.24 ± 1.45 % in test series 3 (cotton 55 %, polyester 45 %, dyed, 15 FPU enzyme), 26.4 % less cellulose was converted than in test

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series 1 (cotton 100 %, white, 15 FPU enzyme) with 37.00 ± 1.46 %. No statement can be made as to whether the inhibiting effect originates from the polyester or from the dye. To clarify this definitively, the effects of polyester and dye would have to be investigated separately.

The 5th test series with Avicel (100 % Cellulose, VWR, Pennsylvania, USA) shows that the chemical process of the SSF is probably not yet completed after 168 h. This is because, although a percentage of converted cellulose of 54.21 ± 0.57 % is achieved, the results (chromatogram of the HPLC) show some unassigned concentrations. These most likely belong to intermediate products, which with more time may also have been converted to ethanol. However, these intermediate products could also be the result of contamination.

In the control test series, the expected value of zero for the ethanol concentration is not measured: The concentration of 0,38 g/l after 24 h can be explained by ethanol residues, which were added to the experiment together with the inoculum culture, as the inoculum culture was not separated and cleaned before being added to the test series. The ethanol concentration in the inoculum culture was not measured before adding it to the experiment but could have been used to correct the results of all test series.

But concerning the control test series the ethanol concentration decreases continuously with time and after 168 h the value is 0.38 g/l. This decrease occurs because the yeasts use the ethanol as a substrate and thus consume it. The decreasing ethanol concentration also shows that, as expected, no new ethanol is produced in the control test series. Therefore, the cellulose conversion is zero.

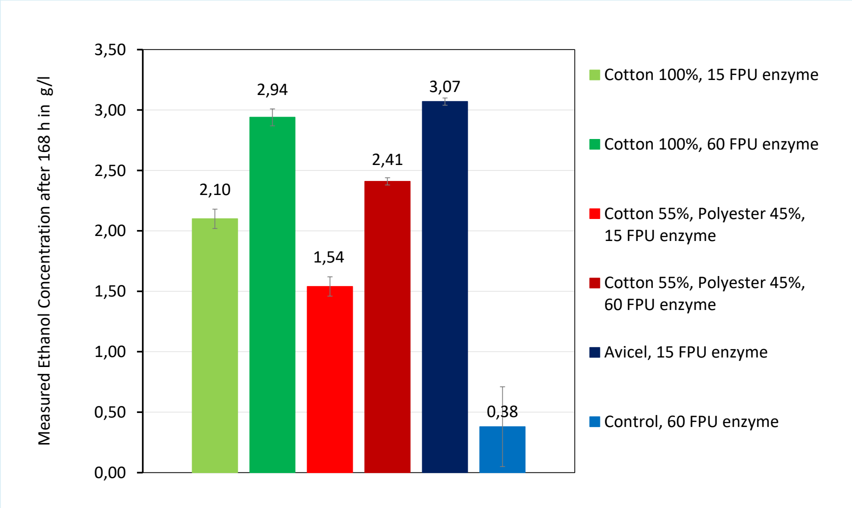

Fig. 6: Product concentrations of ethanol after 168 *h* of SSF

In the SSF, the test series which contained more enzyme achieved a higher ethanol yield. In the test series with less enzyme, too little enzymes were present to completely/fully process the cellulose. For example, test series 1 (cotton 100 %, white, 15 FPU enzyme) achieved 71.2 % of the ethanol yield of test series 2 (cotton 100 %, white, 60 FPU enzyme). For the fiber mixtures, test series 3 (fiber mixture, cotton 55 %, polyester 45 %, dyed, 15 FPU enzyme) achieved 64.6 % of the ethanol yield of test series 4 (fiber mixture, cotton 55 %, polyester 45 %, dyed, 60 FPU enzyme). It can be assumed that the amount of enzyme could be further optimized, increasing the glucose yield, and thereby also the ethanol yield. To determine the optimal amount of enzyme, more measurements would have to be performed with further, probably higher amounts of enzyme.

If the amount of enzyme is to be increased further, particular attention should be paid to the costs of the enzymes, as these represent a significant proportion of the total production costs of ethanol using such a process.

To increase the yield of ethanol production, the biomasses could be pretreated. Pretreatment breaks the biomass structure, which can increase the yield of hydrolysis and thus increase the ethanol yield of fermentation [19].

For example, steam explosion pretreatment is a common pretreatment method, because there is no cost for chemicals and the product does not need to be separated from chemicals. For textile biomass, pretreatment by bases or acids is also suitable. This is mainly because the chemicals are ideal for breaking up the textile fabric, which is already a very soft biomass. When pretreatment with bases or acids is

Tab. 4: Factors of the potential annual amount of energy

Additional usable amount of waste textiles in Switzerland	105,000 t
Proportion of cellulose-based fiber types in total fiber production	45 %
Maximum cellulose conversion to ethanol obtained in this thesis	51.96 %
Lower heating value of ethanol	26.8 MJ/kg [23]

Fig. 7: Experimental presentation with increased cellulose content

used, attention should be paid to the financial factor because of the reasons mentioned above.

The product concentrations measured by HPLC during SSF are plausible and can be compared with results from published literature. By SSF of cotton samples without pretreatment, a result of 26 % of the theoretical ethanol yield was obtained [20]. In the same thesis, the best result was obtained after pretreatment with NaOH (base pretreatment) with 86 % of the theoretical ethanol yield.

Ecologically, the presented process brings a great approach to solve the big problem of textile waste by producing ethanol. But economic factors must also be considered, as an ethanol production process needs to achieve an ethanol concentration of 40 g/l [21] in order to be economically viable. In this thesis, a product concentration of ethanol of 2.94 g/l was measured at a maximum cellulose conversion by SSF (51.96 % for test series 2, 100 % cotton, 60 FPU enzyme). Since the test series each contained 1 % cellulose content, this value would have to be increased to 13 % cellulose content to be able to produce the required ethanol concentration of 40 g/l mentioned above. 13 % cellulose content means 7 g biomass for 50 g total mass. Such a mixture was made and is shown in Fig. 7. However, in this case there is no free water available in which the enzymes and yeast could be dissolved. Consequently, the enzymes and the yeast cannot be sufficiently brought into contact with the biomass and the process would therefore only function very weakly.

One process engineering solution to this problem is to switch from a batch process to a continuous process. In a batch process, starting materials and products are generally in the same vessel, which can limit the reaction completion. In a continuous process the substances to be processed can flow through one process stage and are subject to only one specific process step (basic process) [22]. A typical continuous reactor is a continuously stirred tank reactor (CSTR). In the CSTR the final product concentration always prevails, meaning the substrate concentration is lower. As a result, the substrate is significantly more diluted than in a batch reactor.

To calculate the annual amount of energy that can be provided by the process of ethanol production from waste textiles in Switzerland, the figures in Table 4 are multiplied together.

This leads to a value of 0.7 PJ, which corresponds to 0.09 % of the total energy consumption of Switzerland in 2021 (795 PJ [18]). With such a small energy potential demonstrated in this thesis, it presents a challenge to be economically viable. However, with process improvement and focused supply chain management of the textile waste, improvements are possible. When other factors such as environmental sustainability and overall carbon footprint calculations are considered, this type of process will be increasingly interesting in the future.

5. Conclusion and Prospects

Through the SSF process, the cellulose of textile fabrics can be converted into ethanol. Since the process can convert waste products into ethanol, the potential of this process was investigated.

The potential analysis of textile biomass in Switzerland has shown that due to insufficient data, the potential cannot be fully determined. With the available data, an additional usable potential of textiles in Switzerland of 105,000 t per year was estimated This corresponds to the quantities of textiles that are incinerated per year in Switzerland.

The highest yield of ethanol by the SSF process in the examined textile fabrics was obtained in the test series of pure undyed cotton with 60 FPU enzyme. An ethanol concentration of 2.94 g/l ± 0.07 g/l was measured, corresponding to a cellulose conversion to ethanol of 51.96 % ± 1.21 %. The fiber blend studied (cotton 55 %, polyester 45 %, dyed, 60 FPU enzyme) achieved 18.8 % less than the pure undyed cotton fabric with a cellulose conversion to ethanol of 42.17 % ± 0.60 %. This can be explained by the inhibiting effect of the polyester or the dye. The trials also showed that more yield could be obtained with the use of larger amounts of enzyme. By optimizing the amount of enzyme, the glucose yield and thus also the ethanol yield could be increased.

Ecologically, the presented process brings a great approach to solve the big problem of textile waste by producing ethanol. However, economic factors must also be considered. The highest measured product concentration of ethanol of 2.94 g/l is too low to make this process feasible. For economically reasonable ethanol production, the substrate concentration would have to be increased by a factor of 13, which would require a change from a batch reactor to a CSTR.

To increase the ethanol yield and optimize the process, the biomasses could be pretreated. Pretreatment breaks up the biomass structure, which can increase the yield of hydrolysis and thus also that of the fermentation. For textile biomass, pretreatment with bases or acids is suitable. However, attention must be paid to financial factors. By adding additional chemicals, processing steps and waste will increase the total cost of the ethanol production.

The results of these experiments referred to the usable biomass potential of textiles in Switzerland meaning the amount of energy that could be provided by the produced ethanol per year is 0.7 PJ. This value represents only 0.09 % of the total final energy consumption in Switzerland (795 PJ).

Therefore, ethanol obtained by this method should be used in certain sectors where no other substance than ethanol can be used. As mentioned at the beginning, the main applications of ethanol are in the industrial sector (as a solvent), in the beverage industry or as a fuel additive.

With ethanol production from textile waste, the current conflict between ethanol production and food production can be avoided. But if such a process of producing ethanol from waste textiles were to be industrially implemented, some infrastructure would have to be built up. For the selection of suitable locations for the construction of ethanol production plants, it is important to consider that as many waste textiles as possible would be available at these locations. This would also mean that textiles would no longer have to be exported in such large quantities to developing countries after their use but rather be locally recycled to useful materials. In Europe, the focus should be on a central facility for the ethanol production from waste textiles. For this, the population would also have to be sensitized towards a more conscious handling of textile waste, which could increase the amount of separately collected used textiles.

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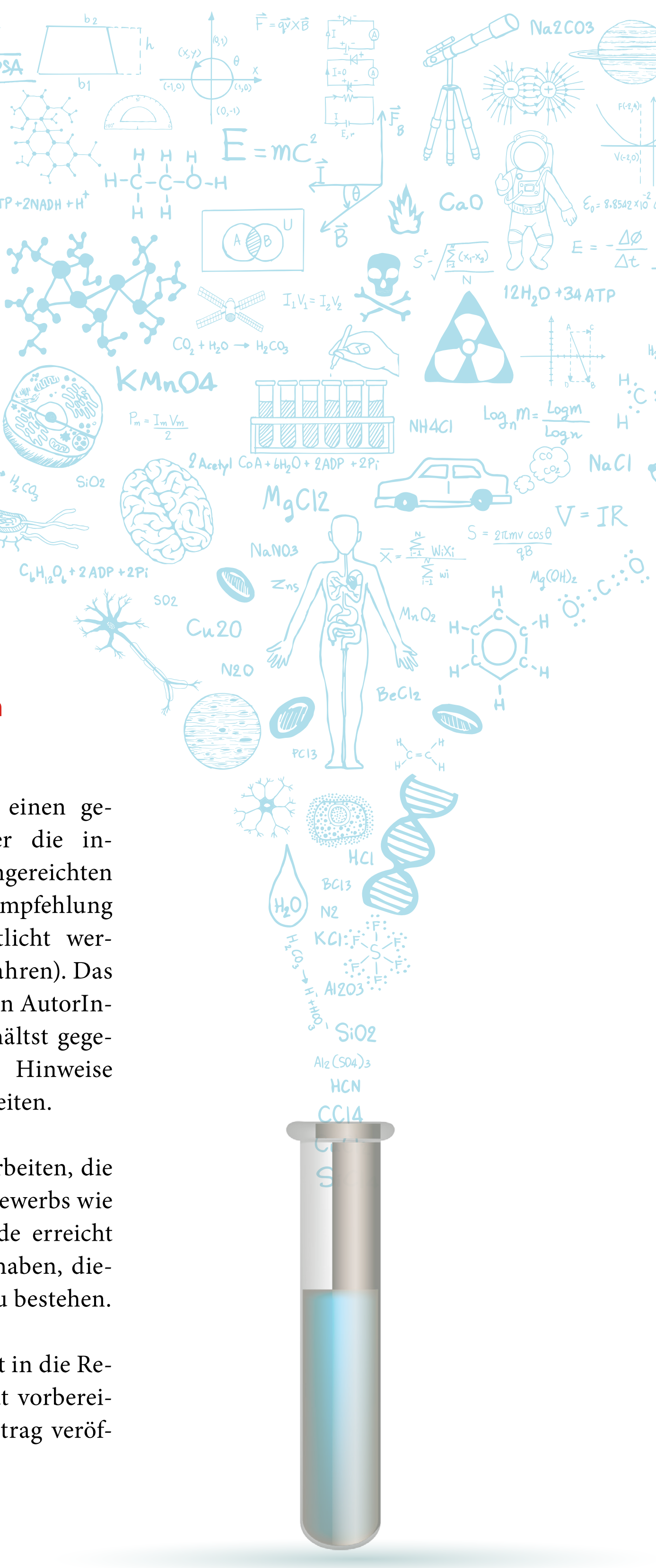

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