

Article

Production of Bio-Ethanol from the Organic Fraction of Municipal Solid Waste and Refuse-Derived Fuel

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Abstract: The organic fraction of municipal solid waste (OFMSW) and refuse-derived fuel (RDF) mainly consisting of paper/cardboard can be used as feedstock for the production of cellulosic ethanol. In this paper, an efficient technology is described to convert waste paper/cardboard into cellulosic ethanol. The process involves separation of the OF from the other components in the waste stream. An acid pretreatment is used to liberate the cellulosic fibers and the accessibility of the enzyme Cellic CTEC3 loading 3.75–11.25 FPU/g paper in a fed-batch addition up to 22.5% solid yield, 15 g sugars/l with a saccharification yield up to 90%. A semi-simultaneous fermentation process (SSFP) with a *Saccharomyces cerevisiae* strain MDS130 capable of fermenting both pentoses and hexoses are growing an ethanol titer (%v/v) of 8.4% on pilot-plant scale.

Keywords: MSW; municipal solid waste; refuse-derived fuel; RDF; bio-ethanol



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1. Introduction

In the last decennia, the production of bio-ethanol as a biofuel has been growing continuously. However, the production of first-generation bio-ethanol is using feedstocks which are in competition with food crops and land use. Therefore, other feedstocks such as natural lignocellulosic materials and components in waste streams have been the subject of numerous research programs and industrial projects. However, the costs of second-generation biofuels is higher than for first-generation ones due to the requirement of more expensive technologies and reactants. In the framework of the EU research program Horizon 2020, the BioRen project has the objective to realize the production of drop-in fuels ethanol, isobutanol and glycerol tertiary butyl ethers (GTBE) from the organic fraction of municipal solid waste (OFMSW) and refuse-derived fuels (OFRDF), which, in addition, will lead to a substantial decrease of the waste stream disposal.

The disposal of solid waste is a continuing serious problem. As the extent of recycling is not at all sufficient, a large proportion of waste streams are either incinerated or landfilled creating environmental problems, compromising land use, water and air quality, and creating health concerns. Therefore, energy from waste resources becomes attractive for the production of power and heat. The most suitable waste streams for energy generation are paper/cardboard, plastics, textiles and wood, which must be separated from ferrous and non-ferrous metals, glass and inorganic inert substances. In the framework of the

circular economy, valuable components can be lost as actual energy recovery is highlighted. Generally, MSW and RDF have an average composition of 40–50% plastics (mainly PE) and 25–35% biomass, next to a variety of other substances. Plastics can be mechanically, chemically or biochemically recycled leading to waste-to-materials or waste-to-energy applications.

The majority of the bioethanol as green biofuels is produced using sugar and starch commodities, which gives rise to a debate: “food versus fuel”. Therefore, non-food-related raw materials such as agricultural waste (straw, corn stover), food residues and waste foresting are used for the production of cellulosic ethanol. Additional resources are available in waste streams (municipal solid waste and refuse-derived fuels). Especially, the organic fraction mainly consisting of paper/cardboard represents a valuable source for the production of cellulosic ethanol [1–3]. The objective of this paper is to highlight an efficient technology for the conversion of mainly paper/cardboard into bio-ethanol. The process involves a series of steps that includes separation and sorting, a thermal–chemical pretreatment and saccharification of cellulose/hemicellulose to a sugar solution, followed by fermentation to ethanol.

2. Materials & Methods

2.1. OFMSW Samples and Reagents

Pretreated OFMSW samples were obtained from the Renasci plant in Ostend, Belgium, and from the Vossen Laboratories Group, Weert, The Netherlands. The OFMSW contained mainly paper and cardboard fiber. It was obtained after passing through the separation line in the Renasci plant (Figure 1) before the acid pretreatment. Mild acid pretreatment was performed using 1% HNO_3 . At laboratory scale, the isolated OFMSW was pulped using 1 kg of OFMSW and 12 kg of 1% HNO_3 solution, and the slurry was stirred slowly for 6 h at 75 °C. The OFMSW was then washed 5 times with 1 kg of water to remove soluble components, mainly $\text{Ca}(\text{NO}_3)_2$. A second treatment with 12 kg of 1% HNO_3 was performed under the same conditions, followed by a two-step process of a fine sieving and a washing cycle by adding 5 times the volume of water. During the second washing step, the pH was adjusted to 5.0 by adding KOH (in a 50% solution). The solids were sieved and dried for 24 h at 80 °C and were used as the starting material for subsequent enzymatic saccharification.

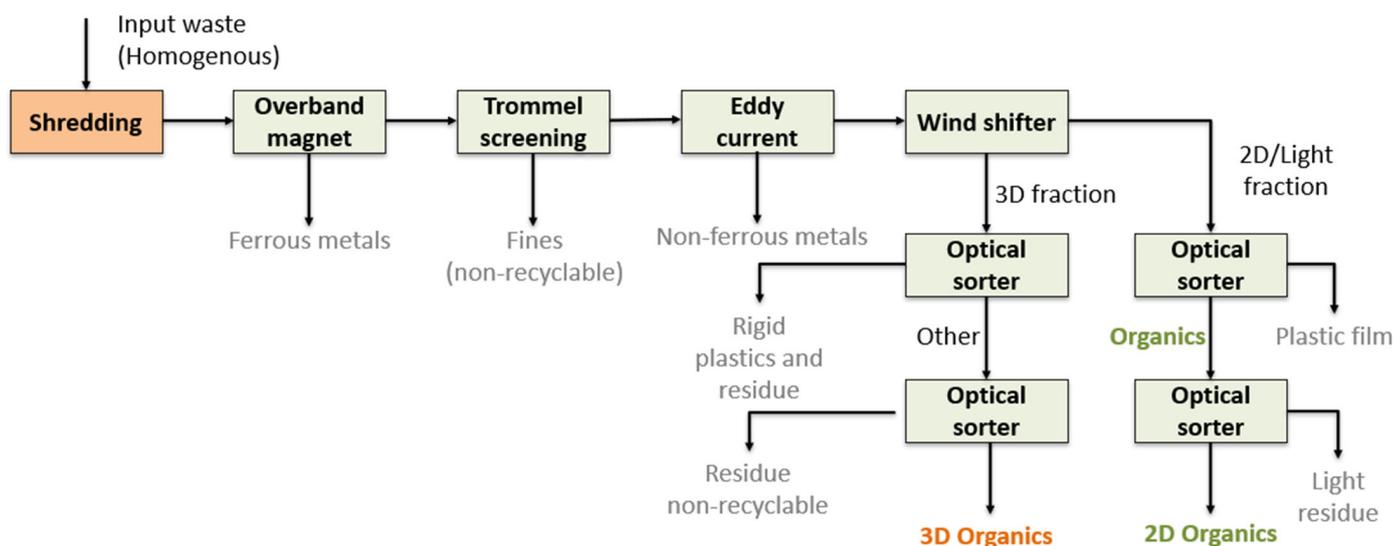


Figure 1. Schematic overview of the separation of paper and cardboard from waste.

2.2. Compositional Analysis of the Mild Acid Pretreated OFMSW Feedstock

Direct chemical analysis of the biochemical composition of the mild acid pretreated and untreated OFMSW materials was performed by the Celignis Biomass Analysis Laboratory, Limerick (Ireland). The content of ash, lignocellulosic sugars and lignin was analyzed in the samples.

2.3. Enzymatic Hydrolysis

Enzymatic hydrolysis of the pretreated OFMSW materials was performed in 250 mL screw-capped Erlenmeyer flasks starting with initial solids of 16% (*w/v*) and a commercial enzyme blend Cellic CTEC3 (Novozymes, Denmark) with an activity loading of 3.75 FPU/g pretreated OFMSW fiber. The solids were added to the flask in fed-batch mode to reach a final total solid loading of 21% (*w/v*). The pH was adjusted to 5.0 before the start of the saccharification and was not further adjusted during the enzymatic hydrolysis step.

2.4. Microorganisms

Fermentation of pre-saccharified OFMSW pulp was carried out with genetically modified *Saccharomyces cerevisiae* strain MDS-130 developed at the VIB-KU Leuven Center for Microbiology. The pH of the pre-saccharified pulp was adjusted to 5.5 with 4 M KOH and 2 g/L of urea was added before the fermentation. The strain MDS-130 was pre-grown in YPD (yeast extract 1%, peptone 2%, D-glucose 2%) seed propagation medium at 30 °C for 16 h. Yeast cells were pitched at 1 g dry weight/L to start the fermentation. The fermentations were performed at an initial pH of 5.5, which was not further adjusted during the fermentation. The cultures were stirred at 200 rpm agitation during the fermentation, which was performed at 35 °C. The MDS-130 strain was developed by a novel method of genome shuffling and adaptive evolution as detailed by Demeke et al. [4] and Belo [5]. The strain was shown to have improved xylose fermentation capacity in inhibitor-rich 2G biomass hydrolysates.

The fermentations were performed on a lab scale in 10–150 L fermentation and on a pilot plant scale (100 L). The pilot plant trials were carried out at the installation of the Bio Base Europe Pilot Plant, Ghent, Belgium.

2.5. Analysis of Fermentation Substrates and Products

Glucose, xylose, acetic acid, glycerol and ethanol were analyzed using a Shimadzu UPLC system equipped with a Bio-Rad Aminex HPX-87 column and an RID-10A detector. Samples obtained during the enzymatic hydrolysis and fermentation steps were centrifuged twice at 14,000 × rpm and filtered through a 0.22 µm filter, after which 10 µL of the filtrate was injected in the column at 70 °C with 5 mM H₂SO₄ eluant at a flow rate of 0.6 mL/min.

3. Results

3.1. Separation of the Organic Fraction in MSW and RDF

The separation of the organic fraction from the remainder of the waste streams has been realized at Renasci, Ostend, Belgium, where an industrial plant has been capable of treatment of 100,000 tons of waste per year. An efficient separation process developed by Drysep (a partner in the BioRen project) has supervised the construction of the separation line aiming at preferential sorting out of the paper and cardboard from the other components (Figure 1). The aim of the sorting line is to generate a 95% pure fraction of paper/cardboard. The system has been designed to properly sort out organic fractions by means of purity and efficiency; however, other sub streams are also sorted out properly for other valorization steps out of scope in this paper. This combination is novel compared to traditional waste-to-incineration facilities in western Europe. The main differentiator are optical sorters.

The entering waste stream is first shredded in which the waste is conditioned to obtain the selected size and dimensions. The shredding is followed by drum screening to select the desired midsized fraction 50–400 mm from the fines smaller than 50 mm. The

oversized fraction is shredded again. The separation of the components in the selected waste streams is based on differences in size, dimension, density, magnetic properties, optical and spectrometric properties using magnets (ferrous components), eddy current (non-ferrous materials), wind shifters and optical sorters (NIR). In a wind shifter, the separation is based upon differences in density and surface. In the first wind shifter, a light fraction (2D) consisting of the organic fraction (mainly paper/cardboard and plastic film) is separated from the heavy fraction (3D), mainly rigid plastics and inerts. With a second wind shifter, the heavy fraction is separated from the mid-heavy fraction (3D) and a ballistic separator is added to sort the last remaining 2D fraction. In the next step of the 2D processing, the bio fraction is separated from the plastic film in a near-infrared sorter based on the interference of NIR light with the different chemical structures of the organic fraction and the plastic film (mainly PE and PP). The organic fraction is purified by an additional optical sorter and conditioned by shredding, and is now ready to undergo the transformation into bio-ethanol.

3.2. Pre-Treatment of Paper and Cardboard

The concept of transforming waste paper and cardboard into ethanol has been intensively studied during the last years [1–16]. In the production of cellulosic ethanol, the main obstacle is the conversion of the cellulose/hemicellulose from the waste into sugars in an economically feasible process. The polysaccharides are present in tightly packed cellulosic fibrils and surrounded by hemicellulose and lignin. Paper/cardboard contains, on average, 60% cellulose/hemicellulose next to a series of additives dependent on the type of paper. The majority of additives are calcium carbonate, titanium dioxide, clay, talc, starch and starch derivatives, ink, etc. In addition, about 200 chemicals are used to enhance the quality of paper/cardboard. The composition of the waste paper/cardboard is largely dependent on the type of paper, regional and seasonal variations and also contamination with plastics, metals and organic residues. In general, paper/cardboard consists of 35–55% glucan, 15% xylan, 8% mannan, 1–2% galactan and arabinan, 6–17% lignin, 2–10% calcium carbonate, and 8–25% ash (L. Wang, [6]).

Therefore, a pretreatment step is necessary to arrange for ready accessibility of the enzymes (cellulases, hemicellulases) to the cellulose/hemicellulose fibers needed for saccharification. A number of pretreatment technologies have already been developed such as steam explosion, acid or alkaline treatment, organosol process, ammonia fiber expansion, hydrogen peroxide treatment and superheated water treatment. In addition, the pretreatment is also used for the removal of the non-cellulosic components in paper/cardboard as these components can hinder the accessibility of the enzymes to the cellulosic backbone and/or deactivate the enzymatic hydrolysis and the fermentation. Therefore, a physical–mechanical (shredding, heating, stirring, washing) and a chemical treatment with, for example, dilute acids (sulfuric, hydrochloric, phosphoric and nitric acid) will enhance the enzyme performance due to the liberation of the cellulose fibers.

In this project, enzymatic hydrolysis has been selected as the most favorable pathway for the saccharification of cellulosic compounds available after a mild acid treatment. Acid or alkaline hydrolysis with strong acids or bases at high temperature and pressure is producing high levels of inhibitors, such as furfural and hydroxymethyl furfural, which severely inhibit fermentation of the released sugars. Additionally, the milder reaction conditions have a lower energy consumption and are more environmentally friendly. Nevertheless, the high cost of the enzymes are forming an obstacle for an economically feasible process to produce bio-ethanol. Therefore, in this study, emphasis will be given on a minimal use of the enzymes by investigating the optimal reagents and process conditions for the mild acid treatment and the saccharification.

The optimal acidification is using nitric acid, and a general procedure has been developed to obtain a suitable substrate for enzymatic hydrolysis. Nitric acid is preferred as the resulting calcium nitrate is water soluble and can be easily separated instead of calcium sulfate and calcium phosphate, which are insoluble in the reaction medium after using

sulfuric acid or phosphoric acid. A general procedure has been developed, which can be used on laboratory scale as well as in pilot plant trials. The chemical composition of the pretreated pulp is outlined in Table 1.

Table 1. Lignocellulosic composition of the pretreated pulp.

Chemical Data—Lignocellulosic Composition (% Dry Mass)				
	Cellulose content	Hemicellulose content	Lignin content	Total lignocellulose
Sample 1	58.51	11.92	15.3	85.72
Sample 2	59.76	12.53	15.92	88.21
Sample 3	63.97	11.82	13.6	89.39
Sample 4	59.49	11.73	15.75	86.97
Sample untreated	55.33	11.85	14.61	81.79
Chemical Composition of the Lignocellulosic Sugars (% of Total Sugars)				
	Hexosans		Pentosans	
Sample 1	89.38		10.62	
Sample 2	88.96		11.04	
Sample 3	90.56		9.44	
Sample 4	89.59		10.41	
Sample untreated	88.69		11.31	

The next step in the pretreatment is the enzymatic hydrolysis of the separated cellulase and hemicellulose in order to produce a sugar solution. According to numerous tests, enzymatic saccharification can produce a 12% sugar solution. These tested were performed aiming at a desired solids concentration of 25% (*w/v*). Beyond this point, there is significant feedback inhibition from the free glucose. The most optimal procedure involves the preparation of a pulp of 16% (*w/v*) dilute acid pretreated solids under stirring at 52 °C at pH 5.0. The blended pulp was incubated after 1 h with the enzyme Cellic CTEC₃ dosed at 3% *w/w*. The saccharification was performed in fed-batch mode during 48 h with gradual solids addition to reach a final pretreated waste paper and cardboard fiber solids concentration of 21% *w/v*. The initial pH was adjusted to 5.0 and not further modified.

The saccharification was then continued for another 120 h and reached a maximum concentration of 10.8% (*w/v*) soluble sugars. After 70 h, the sugar concentration was already 10%.

Different dosages of the enzyme cocktail have an effect on both glucose and xylose accumulation. A decrease from 200 to 100 µL/g substrate had a slight impact on xylose liberation but lowering the substrate resulted in a reduction of total sugar release by 17%. In preliminary results, the saccharification efficiency on a paper cardboard mixture has been calculated.

On deinked and deashed paper with a composition on dry basis of 63% cellulose, 12% hemicellulose, 16% lignin, 5% calcium carbonate and 4% rest compounds, an optimization study has been performed for the enzymatic hydrolysis.

The saccharification was performed in fed-batch mode with solids addition to bring the desired final solids to 20%, 22.5% and 25% (*w/v*) solids within 12 h. Different enzyme loadings (15, 11.25, 7.5, 3.75 and 1.875 FPU/g DS) were tested. The results are shown in the Table 2 below.

Table 2. Testing different enzyme dosages of Cellic CTEC₃ on deinked and deashed waste paper pulp during fed-batch addition of dry solids to reach 20%, 22.5% and 25% total solids concentrations.

Enzyme Dosage Tested (FPU/g DS)	Highest Concentration of the Total Sugars Released % (<i>w/v</i>)	Saccharification Yield (%)
20% Solids		
15	17.09	93
11.25	16.65	91
7.5	15.09	83
3.75	11.95	65
1.875	11.05	52
22.5% Solids		
15	15.23	74
11.25	14.95	73
7.5	14.33	70
3.75	14.15	69
1.875	10.71	52
25% Solids		
15	16.51	72
11.25	15.78	69
7.5	15.53	68
3.75	15.15	66
1.875	10.68	46

In all cases, the saccharification yield decreased at lower enzyme dosage and at a higher total solids loading. The lowest dosage at 1.875 FPU/g DS gave poor results. The higher the enzyme dosage, the higher the saccharification efficiency, but the lower the enzyme efficiency. The enzyme loading at 3.75 FPU/g DS liberated 70% of sugars from 20–22.5% solids and produced up to 9% ethanol *v/v*, see below paragraph on fermentation. The results are shown in Table 3 and Figure 2.

Table 3. Fed-batch saccharification with 3.75 FPU/g DS Cellic CTEC₃.

S.No	Time (h)	Initial Solids % (<i>w/v</i>)	Dry Solids Added (g)	Final Total Solids in the Pulp (% <i>w/v</i>)	Sugars Released % (<i>w/v</i>)		Total Sugars Released % (<i>w/v</i>)	Saccharification Efficiency (%)
					Glucose	Xylose		
1.	0	12.5	-	12.5	0	0	0	0
2.	12	12.5	1.66	14.16	6.48	2.02	8.51	66.04
3.	20	14.16	1.66	15.82	7.34	2.31	9.65	67.03
4.	36	15.82	1.66	17.48	7.98	2.53	10.51	66.07
5.	48	17.48	1.66	19.14	9.01	2.86	11.88	68.20
6.	60	19.14	1.66	20.80	9.59	3.05	12.65	66.83
7.	72	20.80	1.70	22.5	10.17	3.17	13.34	65.15
8.	84	22.5	-	22.5	10.74	3.20	13.94	68.08
9.	96	22.5	-	22.5	11.39	3.23	14.62	71.40

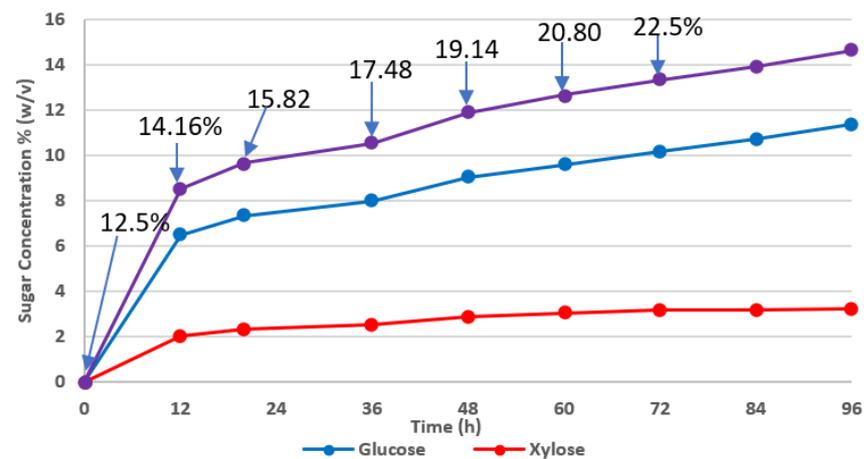


Figure 2. Total sugars released during fed-batch addition of dry paper to reach 22.5% solids with 3.75 FPU/g DS Cellic CTEC₃. Numbers on the graph indicate the total percentage of solids added during fed-batch with dried material.

Further optimization was performed with normal fed-batch (NFB) (12 h), slow fed-batch (SFB) (24 h) and very slow fed-batch (VSFB) (48 h), providing sugar solutions up to 14.6%.

3.3. Ethanol Fermentation of Saccharified Paper/Cardboard

A strain engineered by VIB, *Saccharomyces cerevisiae* strain MDS130 [13,14], has been used. This strain is capable of efficiently fermenting both pentose (xylose) and hexose sugars in different agricultural waste streams. In the BioRen project, a 2G ethanol yeast strain has been developed from the MDS130 strain with a higher xylose fermentation performance. The strain engineering will be the subject of a different publication. The strains tested were capable of utilizing all the sugars within 20 h. After this point, a slight further increase of the ethanol production was observed due to the further release of sugars by the enzymes during fermentation. See Figure 3 for the results. This can give rise to yields higher than 100% (calculation based on initial fermentable sugars). In one example, an ethanol titer was obtained of 8.02% *v/v* corresponding to a yield of 104% after 24 h, and 8.6% with a yield of 111% after 48 h at 35.5 °C.

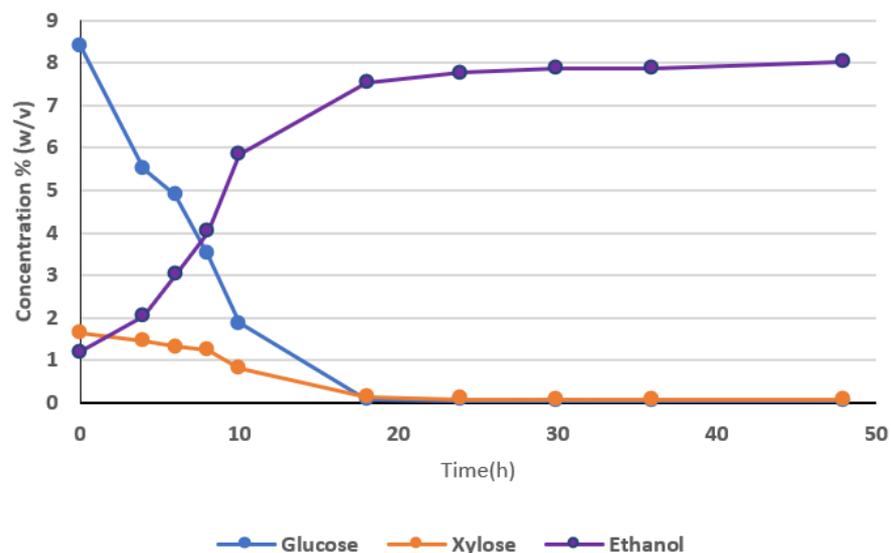


Figure 3. Consumption of glucose and xylose and production of ethanol with saccharified paper/pulp hydrolysate.

Several experiments have been performed on a fermenter scale (7–15 L). The final ethanol concentration was mainly determined by the following factors: initial sugar concentration, remaining enzyme activity during fermentation, metabolic state of the yeast cells, yeast pitching rate and added nutrients. The first two factors determine the amount of sugars available, while the last two elements are related to the biological efficiency of ethanol production. The pitching rate (g CDW/kg broth) is 0.5–1 g/kg for second-generation ethanol and further cell growth during fermentation is not desired as this would convert glucose and xylose to biomass instead of ethanol. In order to reach the highest production of ethanol and the shortest time of production, a simultaneous saccharification and fermentation (SSF) has been used. In SSF processes, the decrease in sugar concentration as a result of the sugar consumption by the yeast cells enhances the hydrolysis rate of the enzymes. Sugar concentration will decrease as long as the consumption rate exceeds the hydrolysis rate. However, the sugar consumption rate decreases when the fermentation progresses as more yeast cells die due to stress and nutrient deficiency. Similarly, the hydrolysis rate will decrease due to enzyme denaturation. Eventually, a dynamic equilibrium will set in. See Figure 4 for the results. Different types of experiments have been performed to optimize the SSF process.

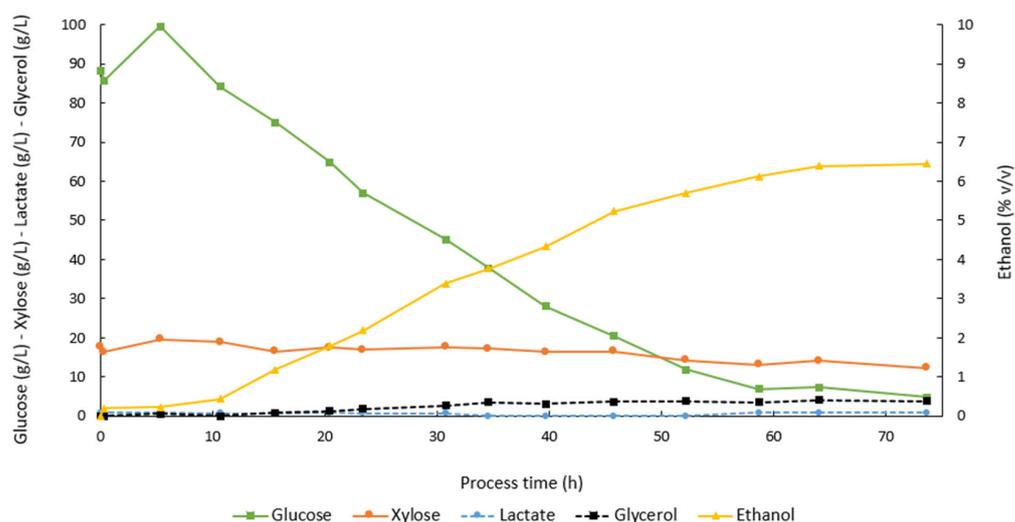


Figure 4. Course of an SSF process on 150 L scale.

3.4. Pilot Plant Ethanol Fermentation from Paper/Cardboard

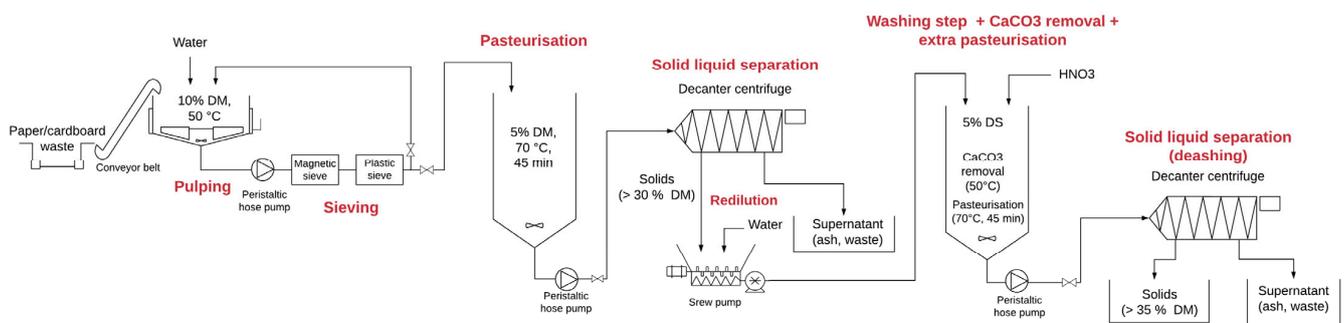
A pilot plant (2 m³) process performed at BBEPP and involving pulping, acidic pre-treatment, semi-simultaneous enzymatic saccharification and fermentation, and post-treatment has been realized for the production of ethanol.

The pretreatment of the paper and cardboard waste resulted in homogeneous solids of paper/cardboard, free from undesired particles (metals and plastic) and with an increased specific fiber surface area. The paper and cardboard solids, with a final dry matter concentration of 40% w/w, were stored at 4 °C until saccharification.

The results of the semi-SSF run at 2 m³ pilot scale with paper and cardboard waste are shown in Table 4 and present the sugar concentration, ethanol production, glycerol production and lactate accumulation. An ethanol concentration of 8.4% v/v (=66.4 g/L) was reached after 57 h of fermentation. The process overview is demonstrated in Figure 5, the set-up is demonstrated in Figure 6. The course is shown in Figure 7. The mass balance is shown in Table 5.

Table 4. SSF process results (2 m³ scale), demonstrated on pretreated cardboard and paper waste.

Saccharification	
End glucose (g/L)	84
End xylose (g/L)	23
End lactate (g/L)	0
Simultaneous saccharification and fermentation	
Ethanol titer (% v/v)	8.4
Ethanol productivity (g/L·h)	1.16
Ethanol productivity—first 24 SSF hours (g/L·h)	1.65
End glucose (g/L)	1.4
End xylose (g/L)	10
End lactate (g/L)	4.6
Ethanol yield—initial free sugars (%)	122
Ethanol yield—total sugars (%)	55

**Figure 5.** Pretreatment of paper and cardboard waste—process overview.

More efficient deashing if nitric acid is used to remove CaCO₃



Ca(NO₃)₂ is soluble in water and can be removed by solid liquid separation!

If sulfuric acid is used: $\text{CaCO}_3 + \text{H}_2\text{SO}_4 \rightarrow \text{CaSO}_4 + \text{H}_2\text{O} + \text{CO}_2$

CaSO₄ is not soluble in water and remains in solid fraction after solid liquid separation; only neutralization by H₂SO₄ pretreatment.

CaSO₄ leads to:

- Higher medium viscosities;
- Lower enzyme efficiency during saccharification;
- Lower quality of pellets after HTC.

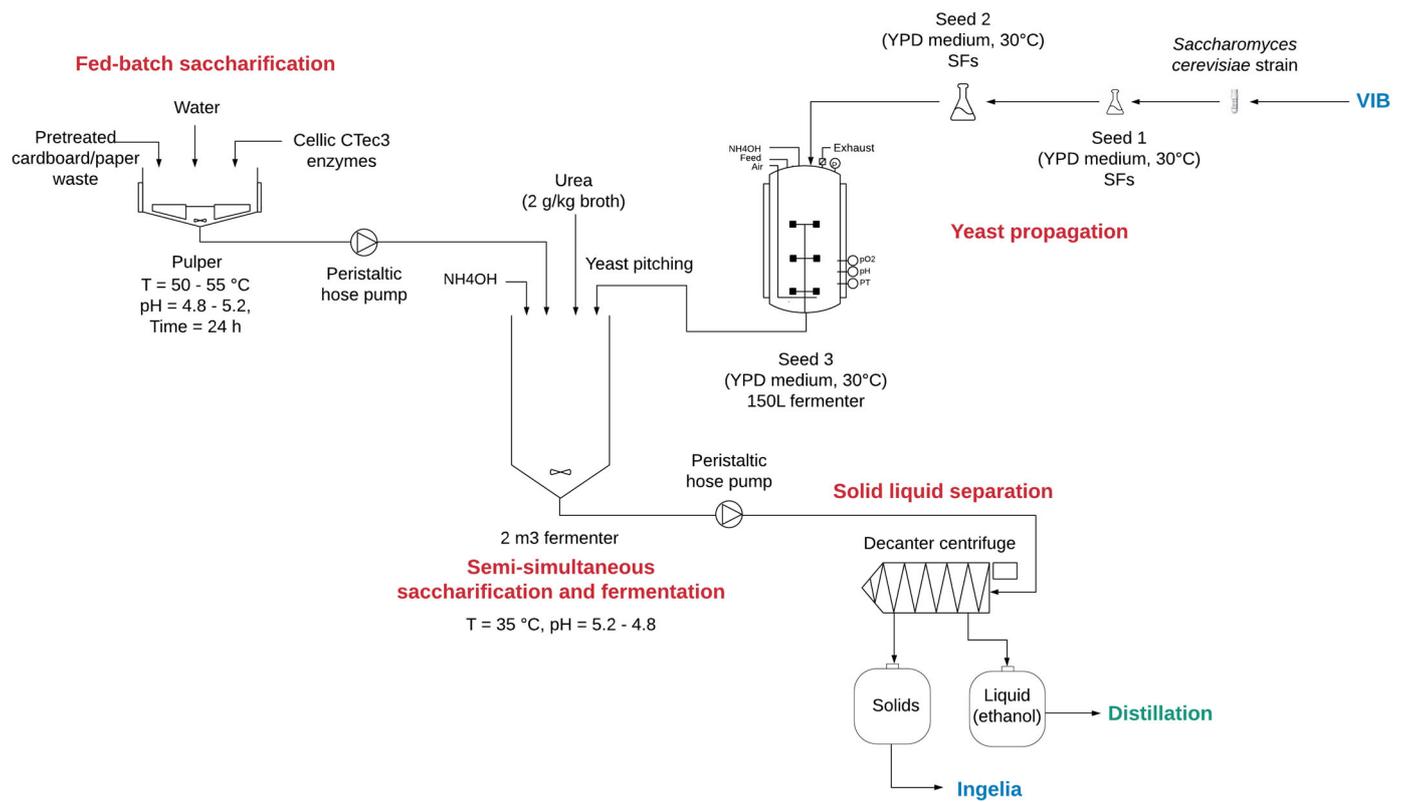


Figure 6. SSF set-up at 2 m³ scale, demonstrated on pretreated cardboard and paper waste—process overview.

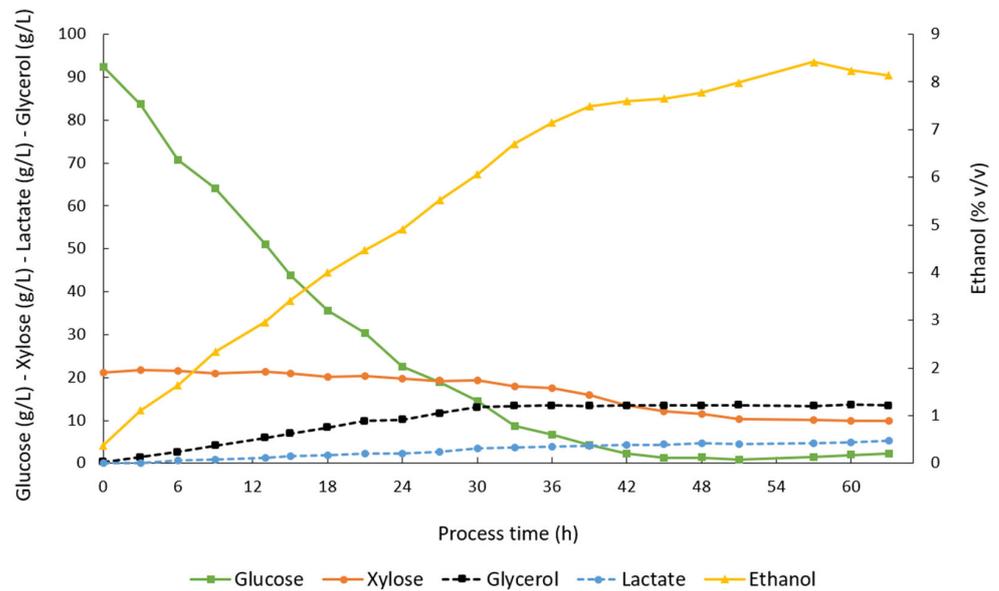


Figure 7. Course of the SSF at 2 m³ scale, demonstrated on a real cardboard and paper waste stream.

Table 5. Mass balance of the demonstrated SSF process (2 m³ scale) with pretreated cardboard and paper waste.

SSF IN	
Dry solid loading (%)	30
Dry cardboard/paper solids (kg)	1000
Cellic CTeC 3 enzyme mix (kg)	80
Yeast (kg)	4.8
Urea (kg)	6.7
SSF OUT = DSP IN (=solids liquid separation IN)	
Dry solid content (%)	17.9
Ethanol (kg)	221
Total dry solids (kg)	597
DSP OUT (=solid liquid separation OUT)	
Solid fraction	
Dry solid content (%)	40.0
Ethanol (kg)	14
Total dry solids (kg)	407
Liquid fraction	
Dry solid content (%)	7.5
Ethanol (kg)	207
Total dry solids (kg)	190

SSF: Semi simultaneous saccharification fermentation; DSP: downstream processing.

4. Discussion

In the present study, an optimization of a pretreatment, enzymatic hydrolysis and simultaneous saccharification fermentation has resulted in a very efficient cellulosic ethanol production. The new dilute nitric acid pretreatment and enzymatic saccharification in a fed-batch process resulted in high sugar (mainly glucose and xylose) production. This process is carried out with a lower enzyme concentration of 3.75 PFU Cellic CTEC3 in comparison with a higher enzyme concentration as reported earlier. It is known that the cost of the enzyme is largely influencing the economic aspects of the bioethanol production. A similar ethanol production process was developed by N. Nishimura [6,8] via an H₂SO₄ pretreatment, a pre-saccharification process and simultaneous saccharification and fermentation (13 FPU/g waste paper), yielding a 4.55% (*w/v*)% ethanol solution. R. Maceiras [7] reported a bioethanol production from waste office paper resulting in ethanol production of 0.1035 mL/g paper with a purity of 9.7%. S. Byadgi [8] used dilute H₂SO₄ at 120 °C and a bacteria *Cytophagahutchisonni* hydrolysis producing also a 14–15% sugar solution where only the glucose was fermented into a 6.0–6.9% *v/v*. However, no details are presented on the purity of the bio-ethanol produced. K. Thakare [9] used a chemical hydrolysis with H₂SO₄ for hydrolysis at 121 °C (30–180 min) and fermentation with *S. Cerevisae* (30 °C, 72 h, 15% substrate) providing 0.1 mL/g, a purity of 9.52%. A. Brasselle [10] presented a full techno-economical report of a large-scale production of cellulosic ethanol, however, without mentioning the production yield and reaction conditions. N. Annamalai [11] reported a pretreatment with H₂O₂ (121 °C and 30 min) and separate enzymatic hydrolysis resulted in a sugar yield of 13.26–24.5 g/L giving an ethanol production of respectively 6.65 g/L (0.28 g ethanol/L/h) and 11.15 g/L (0.32 g ethanol/L/h). L. Wang [4] was using diluted H₂SO₄ at 220 °C office paper and Ca(OH)₂ for newspaper and used 12.5 FPU/g glucan. For newspaper, oxidative lime was used at 140 °C and 7.5 FPU/g glucan but no results of fermentation were mentioned. F. Barba [16] reported mass and energy balances for the enzymatic saccharification of MSW pulp and reported that the fed-batch process is producing higher glucose concentration than a batch process and are producing 8–12% g/L of glucose, which is in the range of our results.

Comparison of the results of this study with the numerous literature studies reveals that this process has a number of advantages of the published data. In this process, the organic fraction from MSW and RDF used, which consists of various types of paper and cardboard, which, in addition, are contaminated with various agents. This was not the case in former studies where a single type of waste paper was used [7]. Additionally, the total process shows advantageous characteristics. In the pretreatment, a mild acidic procedure is used in a very mild condition, which did not give rise to contaminants and gives rise to easy accessibility of the enzymes to the cellulose and hemicellulose fibers. A soft enzymatic saccharification is used instead of chemical treatment for hydrolysis. In addition, a much lower amount of the enzymes are used, which is a key parameter in the economic feasibility. The concentration of the enzyme is due to a fed-batch procedure, which also enables the use of higher concentrations of the pretreated OF. Another key parameter is the use of a semi-simultaneous saccharification and fermentation. The enzymatic activity of the enzymes is slowing down at the higher sugar concentration; simultaneous saccharification fermentation is solving this problem. The use of genetic engineered *Saccharomyces cerevisiae* capable of fermenting both glucose and xylose causes a dramatic rise in the ethanol production. This production of cellulosic ethanol can also be applied for other biofuels such as isobutanol. This process is still in development but preliminary experiences showed that the production of isobutanol from OFMSW is successful and reaches already 2% *v/v* isobutanol concentration.

5. Conclusions

The organic fraction of MSW and RDF is an excellent and suitable renewable resource for the production of cellulosic ethanol. The bio-ethanol is produced via several steps involving separation of the organic fraction from the plastic fraction, metals and other inert materials. As the organic fraction contains mainly waste paper and cardboard, the next steps are pretreatment, hydrolysis and fermentation.

The pretreatment involves mild acidic treatment (dilute nitric acid) in order to make the cellulosic fibers accessible to the enzymes and to remove paper additives and contaminants, followed by an enzymatic hydrolysis (saccharification) in fed-batch mode with the cellulase CTEC₃. This step converts the cellulose/hemicellulose into sugars (mainly glucose and xylose) with a saccharification efficiency up to 85%.

The fermentation was performed by the *Saccharomyces cerevisiae* strain MDS 30 capable of fermenting both pentoses and hexoses. The fermentation technology has been upgraded by using a semi-simultaneous saccharification-fermentation (SSSF) process.

In pilot plant operations (2 m³) using this combination of techniques, a high yield of cellulosic ethanol has been realized. Calculated on 1000 kg of paper/cardboard on dry basis, 221 kg of ethanol was produced as a 8.4% aqueous solution, which is one of the highest reported yields of ethanol from waste paper and cardboard.

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