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Glucose Production from Cellulosic Sludge Innovating Wastewater Recovery

Federico Micolucci*, Nicola Frison

University of Verona, Strada le Grazie 15, 37134 Verona, Italy
federico.micolucci@univr.it

The transition from conventional wastewater treatment toward resource recovery and energy efficiency has become a central focus in wastewater treatment plant optimization. This study investigates the integration of pre-filtration and cellulosic primary sludge (CPS) hydrolysis as a strategy to enhance carbon recovery while reducing energy consumption. Using pilot-scale and batch experiments, the efficiency of CPS recovery via rotating belt filtration was compared with conventional pre-sedimentation, and hydrolysis conditions were optimized to maximize cellulose degradation and fermentable carbon production. The results demonstrated that mesophilic conditions (38°C) enabled up to 42% cellulose degradation of the CPS without pH adjustment, while alkaline hydrolysis (pH 12, at thermophilic 55°C) achieved the highest soluble chemical oxygen demand (sCOD) production. The observed correlation between total suspended solids reduction and sCOD increase confirms that CPS hydrolysis enhances the availability of bioavailable organics (e.g. Glucose, Xylose), which can serve for example as an internal carbon source for biological nutrient removal processes. Additionally, the hydrolysate's potential for volatile fatty acid production highlights new opportunities for biopolymer synthesis and resource recovery. Energy balance calculations indicate that CPS removal before biological treatment could reduce aeration energy consumption by 5–15%, translating into annual savings of 149,480–442,776 kWh for a treatment plant of 150,000 people equivalent (PE). These findings support the role of CPS pre-filtration and hydrolysis in transforming wastewater treatment plants into energy-efficient water resource recovery facilities.

1. Introduction

The paradigm of wastewater treatment is shifting from pollutant removal toward resource recovery and energy efficiency, driven by environmental sustainability concerns and regulatory advancements. The 2024 European Urban Wastewater Directive mandates a significant reduction in energy consumption across treatment facilities, emphasizing the need for more efficient wastewater management strategies (European Commission, 2024). Traditional wastewater treatment plants (WWTPs) primarily focus on pollutant removal but often fail to maximize resource recovery, especially regarding organic carbon, which is abundant in sewage. Conventional primary treatment methods, such as pre-sedimentation, require substantial energy inputs and generate large volumes of sludge, contributing to high operational costs and environmental burdens. This highlights the necessity of transitioning toward energy-efficient treatment strategies that not only purify water but also facilitate the recovery of valuable organic components, effectively transforming WWTPs into water resource recovery facilities (WRRFs) (Foglia et al., 2021). A promising alternative to pre-sedimentation is pre-filtration, a process that employs rotating belt filters (RBFs) or other fine-mesh filtration systems to separate suspended solids from wastewater more efficiently. This method enables 50% removal of suspended solids (Da Ros et al., 2020), significantly reducing the organic load entering the biological treatment stage and, consequently, lowering energy demands for aeration. Pre-filtration also allows for targeted recovery of cellulosic primary sludge (CPS), a sludge fraction rich in cellulose, primarily derived from toilet paper. Given that cellulose constitutes 30–40% of suspended solids in municipal wastewater, CPS represents a valuable yet underutilized resource (Wang et al., 2023). Following its separation, CPS can undergo hydrolysis under oxygen-limited conditions, breaking down complex carbohydrates into fermentable substrates. This hydrolysate, rich in glucose and partially volatile

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fatty acids (VFAs), holds significant potential as an internal carbon source for biological nutrient removal (BNR) processes, including enhanced biological phosphorus removal (EBPR), especially if further treated anaerobically to enhance VFAs concentrations. By reducing reliance on external carbon additives, this approach fosters a circular economy within wastewater treatment, minimizing environmental impact and operational costs (Ossiansson et al., 2023). Moreover, hydrolysis-derived VFAs can serve as precursors for value-added bioproducts, such as polyhydroxyalkanoates (PHAs), which have applications in biopolymer production. This further supports the transformation of WWTPs into urban biorefineries, integrating wastewater treatment with sustainable resource recovery. Despite its advantages, the implementation of pre-filtration and CPS hydrolysis remains underexplored, particularly regarding process optimization and large-scale feasibility. Computational modeling suggests that pre-filtration can lead to an 8% reduction in aeration energy consumption while extending sludge age and enhancing nitrification efficiency (Behera et al., 2018).

This study investigates the efficiency of CPS pre-filtration and hydrolysis through pilot-scale and batch experiments. The primary objectives are to evaluate CPS recovery via pre-filtration, compare its performance with conventional pre-sedimentation, and optimize hydrolysis conditions such as sludge residence time, pH, and temperature to maximize cellulose conversion into sugars as fermentable carbon sources. The hydrolysate is characterized through glucose analysis to assess its suitability as a substrate for subsequent fermentation. Additionally, the scalability and energy-saving potential of integrating CPS pre-filtration and hydrolysis into full-scale WWTP operations are explored.

2. Material and methods

This paper presents part of the REFRAME project (HORIZON-MSCA,10/23, *Figure 2*). Municipal wastewater and sludge from the Källby Wastewater Treatment Plant (Lund, Sweden) underwent an initial pre-treatment stage to remove coarse solids and sand at the full-scale plant. The process began with mechanical screening, employing grids with gap widths between 2 and 10 mm to capture larger debris, such as rags and other non-biodegradable materials that could interfere with downstream processes (Ossiansson et al., 2023). Following this preliminary step, fine particle separation was performed using a Salsnes SF:2000 drum filter with a total filtration area of 2.4 m². This rotating belt filter (*Figure 1*), equipped with 350 µm mesh elements, was selected based on its ability to effectively retain suspended organic matter. Unlike conventional setups that incorporate chemical dosing, wastewater was filtered directly without prior coagulation or flocculation. Solids retained by the filter were continuously removed through backwashing and directed into a sludge collection channel. The operational hydraulic capacity of the filtration system was determined by the available filter area and influent flow conditions.

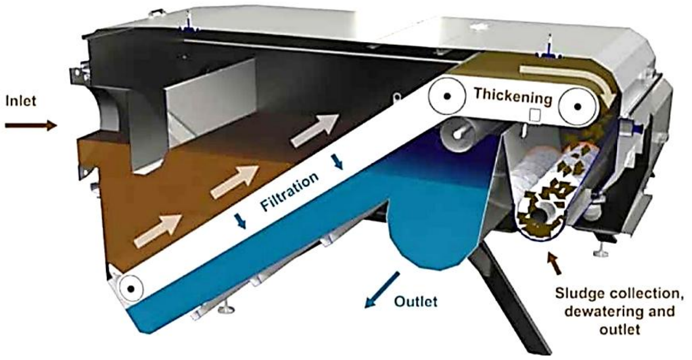

Figure 1: Salsnes SF:2000 drum filter, chemical-free pre-filtration Process

The recovery of cellulose from retained solids was assessed by quantifying the organic fraction captured through the filtration process. To evaluate the hydrolysis potential of CPS, batch experiments were conducted on triplicates in 5 L reactors under controlled and non controlled conditions. Hydrolysis trials were performed at three different temperatures under different pH conditions: an unaltered control (CTRL), an unaltered pH control (NO pH CTRL), acidic (pH 4), and alkaline (pH 12). Retention times of 1 and 2 days were investigated to determine the influence of reaction time on cellulose degradation and the composition of the hydrolysate.

The pre-treatment step aimed to solubilize organic matter, including volatile solids (VS) and cellulose present in CPS, thereby increasing glucose concentrations and soluble chemical oxygen demand in the liquid phase.

Alkaline and acidic hydrolysis tests were performed by adjusting the pH to 12 and 4 using 3.0 M NaOH and H_2SO_4 solutions, respectively. Thermal pre-treatment was carried out with temperature control maintained through a temperature-controlled chamber. For the combined pre-treatment approach, the pH was set to 12.0 or 4.0 or without adjustment, while temperature was controlled at 55°C, as well as at 38°C and 20°C. Each experimental condition was tested in triplicate using 5.0 L glass bottles, with reaction times of 24 and 48 hours. In addition to laboratory experiments, a study was conducted based on real annual data (2023) from a municipal WWTP designed for 150,000 population equivalents (PE). The WWTP employed an activated sludge system with enhanced biological phosphorus removal (EBPR). CPS was characterized to assess its contribution to the organic load of the plant, providing insight into its potential for resource recovery and energy consumption optimization.

2.1 Analytical methods

Samples were collected at the beginning and end of each experiment for the analysis of chemical oxygen demand (COD), soluble COD (sCOD), total suspended solids (TSS), cellulose content as glucose and other sugars content, along with pH measurements. During sampling, the bottles were opened and maintained under a nitrogen (N_2) flux for 15 minutes to restore anaerobic conditions. For the quantification of total suspended solids TSS, sCOD the analyses were performed in accordance with Standard Methods (APHA et al. 1998). The analysis of cellulose content, as glucose, xylose and eventually other sugars, in the hydrolyzed sludge and the CPS substrate followed a standardized protocol commonly used for plant-derived materials in environmental studies (Suiter et al., 2008).

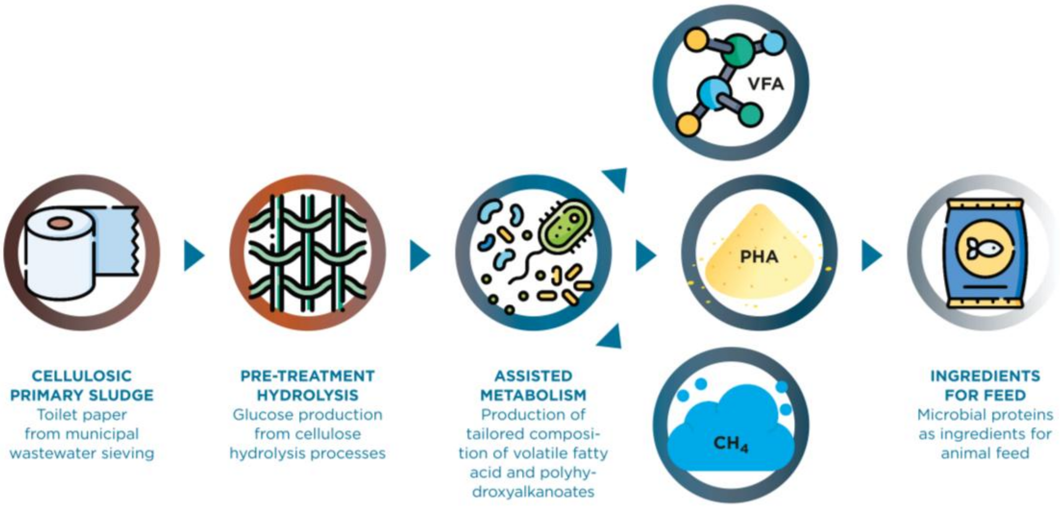

Figure 2: REFRAME process scheme

3. Results and discussion

3.1 Cellulose hydrolysis efficiency

The characteristics of CPS are summarized in table 1. The hydrolysis of CPS was assessed under various temperatures, pH, and retention time conditions to determine their impact on cellulose degradation, glucose and xylose production, and the generation of soluble organic compounds. The results demonstrated that temperature and pH were the most influential parameters, with trends in TSS reduction and notable decrease of cellulose concentration and sCOD increase, both of which indicate the extent of hydrolysis. CTRL stands for untreated sample control (red column, cellulose, *Figure 3*).

Table 1: Cellulosic primary sludge characteristics

Parameter	Value	%
Total Solids (TS)	50,373 mg/L ± 11,550	
Volatile Solids (VS)	45,738 mg/L ± 6,340	
VS/TS ratio		90.8% ± 4.5
Cellulose		52% ± 3 COD

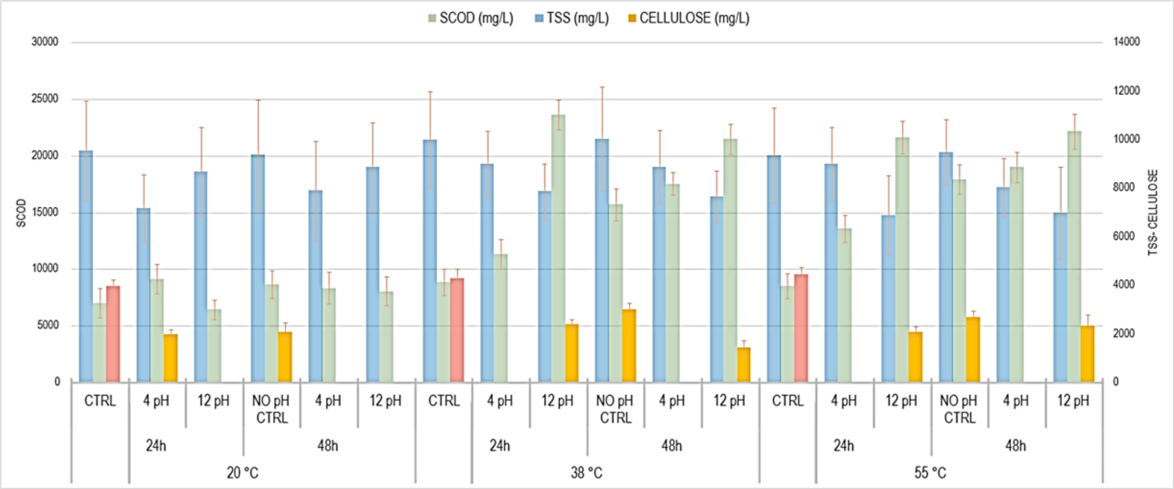

Figure 3: SCOD, TSS and Cellulose concentration in the triplicate trials.

3.2 Impact of temperature on cellulose degradation

A clear temperature dependency was observed in the hydrolysis process, with cellulose degradation rates increasing with temperature across all tested conditions (20°C, 38°C, and 55°C). At mesoophilic conditions (38°C, pH 12), cellulose content decreased significantly from 48.9% at 24 hours to 22.5% at 48 hours, yielding a hydrolysate composition of 57% glucose and 4% xylose and 39% VFAs of the total sCOD. Higher temperatures further enhanced degradation efficiency, as seen at 55°C (pH 12), where cellulose degradation exceeded 50% at both 24 and 48 hours. These findings align with previous studies reporting that thermophilic conditions (≥50°C) accelerate the enzymatic and microbial degradation of polysaccharides, thereby enhancing the release of fermentable organic substrates (Yi et al., 2022). At 38°C without pH adjustment, 42% of cellulose was converted into glucose, with an additional 2% conversion into xylose, suggesting that temperature and retention time alone can drive substantial hydrolysis, potentially eliminating the need for chemical additives.

The superior performance of hydrolysis at 38–55°C is attributed to enhanced reaction kinetics, microbial activity, and enzyme functionality at elevated temperatures. Increased thermal energy likely weakens hydrogen bonds in cellulose fibrils, promoting their breakdown into monomeric sugars. These results support the potential for mesophilic hydrolysis (38°C) as an energy-efficient approach, as it offers high cellulose degradation without the excessive energy demand associated with thermophilic (≥50°C) conditions.

3.3 Effect of pH on hydrolysis efficiency and sCOD production

pH played a crucial role in influencing cellulose degradation and the solubilization of organic matter, with both acidic (pH 4) and alkaline (pH 12) conditions showing significant effects compared to unmodified pH control samples. Alkaline hydrolysis (pH 12) at 55°C resulted in the highest sCOD values, indicating extensive solubilization of cellulose into bioavailable dissolved organic matter. The increased sCOD production under alkaline conditions suggests that cellulose fibrils underwent enhanced glycosidic bond cleavage, facilitating the release of glucose and other fermentable intermediates. Acidic hydrolysis (pH 4) also promoted cellulose degradation, particularly at lower temperatures (20–38°C). The effectiveness of acid-catalyzed hydrolysis is well-documented in biomass conversion processes, where protonation of glycosidic linkages accelerates cellulose breakdown. However, compared to alkaline hydrolysis, acidic conditions resulted in lower sCOD values, suggesting a slower solubilization rate. The differences in hydrolysis efficiency between acidic and alkaline conditions could be attributed to the distinct mechanisms governing cellulose breakdown, whereas acid hydrolysis primarily facilitates protonation-driven bond cleavage, alkaline hydrolysis enhances the swelling of cellulose fibrils, making them more susceptible to enzymatic or microbial degradation (Sun et al., 2005). The reduction in TSS across all experimental conditions indicated that cellulose degradation was accompanied by extensive solubilization, leading to a measurable increase in dissolved organic matter availability. The greatest TSS reduction was observed at 55°C, pH 12, aligning with the highest sCOD production, further confirming that hydrolysis under these conditions maximizes the conversion of solid-phase organic matter into bioavailable soluble compounds. This relationship between TSS decrease and sCOD increase has direct implications for biological wastewater treatment. The hydrolyzed cellulose contributes directly to the pool of soluble organics, which can serve as an internal carbon source for microbial metabolic processes. Interestingly for full-scale treatments, hydrolysis occurred even in the absence of pH control, although at a lower efficiency. Given that many WWTPs rely on external carbon sources (e.g., ethanol or acetate) to support biological nutrient removal (BNR) processes, the ability to recover and solubilize carbon-rich CPS within the treatment plant itself, even without pH control, represents a significant advancement in resource recovery strategies. The hydrolysis of CPS not only facilitates cellulose degradation and sCOD production but also enhances the bioavailability of organic substrates for microbial fermentation. The release of glucose and xylose in substantial quantities suggests high potential for subsequent conversion into VFAs, which serve as key intermediates in biological phosphorus removal and biopolymer synthesis.

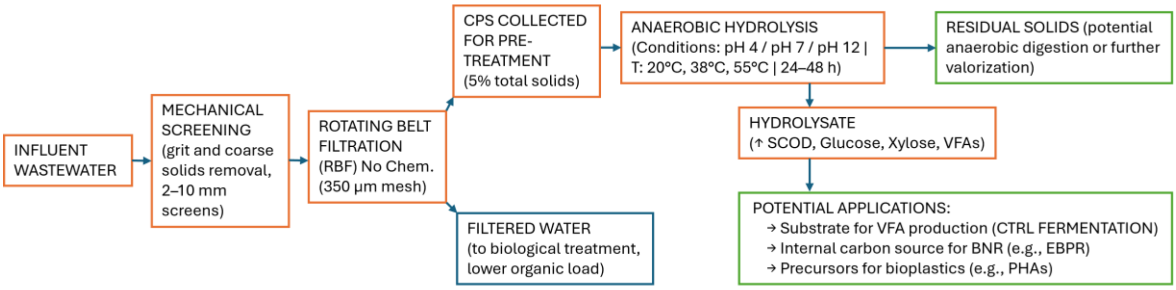

Figure 4: Flow chart of the process.

3.4 Energy consumption and saving estimation adopting CPS removal

3.4.1 Aeration Energy Consumption

Aeration basins in the WWTP accounted for 73% of the total biological treatment energy demand, consuming 2,165,297 kWh/year. The specific energy consumption for the biological oxygen demand (BOD) removal was calculated as 0.552 kWh/kg BOD, with CPS contributing 979,242 kg BOD/year of a total incoming BOD of 3,916,968 kg/year.

3.4.2 Filtration Energy Demand

The power consumption of rotary belt filters (RBFs) was monitored throughout the study. The average estimated energy requirement was 0.018 kWh/m³, which is within the expected range of 0.01 kWh/m³ (without compressed air) to 0.04 kWh/m³ (with compressed air). System components such as motors, backwash pumps, sludge transport mechanisms, and high-pressure wash systems contribute to this variability. It was observed that for predominantly cellulosic sludge, high-pressure washing mechanisms were unnecessary, reducing overall energy demand. Total energy consumption for RBFs was calculated as: lower estimate (0.005 kWh/m³) of 97,766 kWh/year and an upper estimate (0.02 kWh/m³) of 391,063 kWh/year. Net energy savings were derived from the difference between aeration energy reduction and RBF energy consumption and have been calculated as lower estimate: 442,776 kWh/year (15% reduction in aeration energy) and upper estimate: 149,480 kWh/year (5% reduction in aeration energy), confirming that removing CPS before biological treatment reduces aeration energy consumption while maintaining treatment efficiency. The cellulose fraction in CPS constitutes a significant organic load, and its removal prior to aeration reduces oxygen demand, resulting in substantial energy savings. Alternatively, retaining this fraction can enhance the availability of organic carbon within the WWTP and the margin for higher organic loads, optimizing biological processes and potentially improving overall treatment efficiency.

4. Conclusions

This study highlights temperature as the key factor influencing hydrolysis efficiency of CPS, with mesophilic conditions (38°C) achieving up to 42% cellulose degradation without pH adjustment. Alkaline hydrolysis (pH 12, 55°C) produced the highest sCOD, though significant degradation occurred without pH control, offering a cost-effective approach with minimal chemical input. The correlation between TSS reduction and sCOD increase supports CPS hydrolysis as a viable strategy for BNR plants. Converting hydrolyzed CPS into VFAs offers opportunities for biopolymer production and resource recovery. The estimated energy savings of 149,480–442,776 kWh per year in a full-scale treatment plant of 150,000 PE, demonstrate CPS separation as a low-energy alternative to traditional treatment. Pre-precipitation and pre-filtration with chemical additives can reduce the availability of organic carbon for biological treatment, often requiring external carbon supplementation. By avoiding chemical treatment, a significant fraction of cellulose from toilet paper remains intact, while soluble

COD remains available for downstream biological treatment, ensuring more readily biodegradable organic substrates for microbial processes. Overall, CPS hydrolysis enhances carbon recovery in WWTPs, reducing reliance on external carbon sources. Integrating CPS separation with advanced treatment can promote energy-efficient, resource-oriented management in WWTPs. The distinction between rotating belt filtration (RBF) and conventional pre-sedimentation is addressed through the energy analysis and resource recovery potential. Traditional sedimentation does not enable targeted cellulose recovery; the resulting primary sludge is generally directed to sludge thickening and eventually anaerobic digestion, limiting opportunities for higher valorization.
In contrast, RBF allows for the selective capture of cellulosic primary sludge (CPS) at an early treatment stage. This enables both a measurable reduction in aeration energy demand and the generation of a carbon-rich stream suitable for further recovery processes, such as volatile fatty acid (VFA) production. The comparative advantage of RBF is thus evident in its dual contribution to energy efficiency and circular resource use, supporting its role as a more sustainable alternative to conventional methods. Future research of REFRAME will focus on controlled fermentation of the hyrolyzed CPS, microbial dynamics, and optimizing CPS-derived bioproducts to maximize both economic and environmental benefits.

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