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# High-rate thermophilic bio-methanation of the fine sieved fraction from Dutch municipal raw sewage: Cost-effective potentials for on-site energy recovery

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## HIGHLIGHTS

- Fine sieved fraction (FSF) from raw municipal sewage was used a sole substrate.
- Various mesophilic and thermophilic BMP tests were run at different $R_{I/S}$ ratios.
- Thermophilic digestion of FSF is highly efficient for on-site energy recovery.
- Biogas production rate of 9.3 $m^3/m^3$ d at OLR of 22.8 $kgCOD/m^3$ d is predicted.
- The net recoverable energy of 287 MJ/ton FSF and 237 kW h/ton FSF was found.

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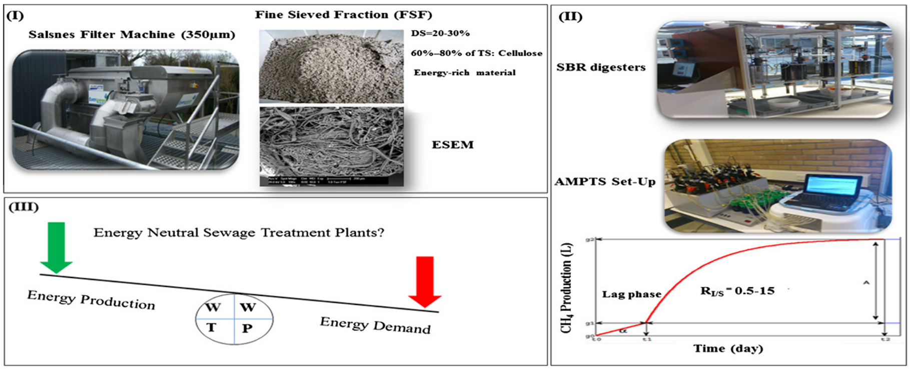
## GRAPHICAL ABSTRACT



## ABSTRACT

Sieving of Dutch raw sewage over a 350 µm screen, produces a cake layer called fine sieved fraction (FSF), an energy-rich material that contains mainly cellulosic fibers originating from toilet paper. The FSF bio-methane potential (BMP) was studied under both mesophilic (35 °C) and thermophilic (55 °C) conditions, whereas the stability of the fed-batch digesters at both 35 °C and 55 °C was researched by varying the inoculum to substrate ratios ($R_{I/S}$: 0.5–15). Results clearly showed advantages of thermophilic conditions over mesophilic conditions at all tested $R_{I/S}$. Stable digestion was even possible at an $R_{I/S}$ of 0.5 at 55 °C.

Following the results of the batch tests, a compact high loaded thermophilic digester for on-site energy recovery from FSF was proposed. Based on the results of the study, high biogas production rates at high organic loading rates (OLRs) were predicted. In the energy balance calculations, surplus heat production from combined heat and power (CHP) was utilized to dry the digestate sludge before transportation to an incineration plant or for use in pyrolysis or gasification processes. Overall results showed the potential of generating 46% of the required energy for wastewater treatment via high rate FSF digestion and subsequent conversion of the bio-methane into electricity and heat. The net recoverable energy from fine sieving, anaerobic digestion of FSF, dewatering of digestate sludge and drying of dewatered digestate sludge amounted 287 MJ/ton FSF and 237 kW h electric/ton FSF at 23% TS.

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## 1. Introduction

Energy recovery from raw municipal sewage for on-site use will minimize the fossil energy demand and contribute to the development towards energy neutral wastewater treatment plants (WWTPs). In principle this should be possible since the energy content of sewage is several times higher than the energy required for its treatment [1,2]. For indeed achieving energy neutrality, or even energy production, at WWTPs, the energy balance should be optimized which requires a dual approach. Firstly, the total energy consumption during wastewater treatment requires optimization, such as more energy-efficient aeration and less energy losses in pumping and sludge dewatering. Moreover, implementing enhanced primary sludge production and alternative routes for nitrogen removal can drastically reduce the use of fossil fuels for aeration. Secondly, the recovery of chemically bound energy should be maximized, requiring an upgraded anaerobic digestion (AD) technology as well as the implementation of AD at those WWTPs that so far are not served by AD, such as extended aerated biological nutrient removal plants [1–5]. The biggest energy gains per $m^3$ of sewage can be made in small WWTPs that are not equipped with primary clarifiers and that apply low sludge loading rates. In these systems, all incoming biochemical oxygen demand (BOD), as well as a large extent of the newly grown sludge is converted aerobically. With a biomass growth yield of 0.6 g volatile suspended solids (VSS)/g BOD and a sludge degradation efficiency of 30–50% during digestion, one can easily reason that a large part of influent BOD is lost for energy recovery during the activated sludge treatment process [6]. In Western industrialized countries, a significant part of the sewage BOD consists of cellulose (60–80% of total solids content), originating from the use of toilet paper [7,8]. Conventionally, a significant part of this cellulose fraction is removed in large conventional primary settlers. If primary settlers are absent, or only part of the cellulose is retained, the cellulose BOD is (partly) oxidized in the aeration tanks [8]. A very compact and efficient solution to minimize oxidation of filterable matter in extended aeration tanks is the recovery of cellulose-rich slurries from raw sewage with a fine-mesh (<500 μm) sieve. The derived fine sieved fraction (FSF) can then be used for on-site energy recovery through anaerobic digestion, instead of oxidation in the aeration tank. However, care should be taken that the required nutrient removal capacity remains unaffected.

At the WWTP Blaricum, the Netherlands, a 350 μm mesh size fine sieve (Salsnes Filter, Norway) for raw sewage mechanical pretreatment is installed after the coarse screen (6 mm) as a pilot study. This sieve was implemented as a compact alternative to primary clarification taking into account that the composition of the material coming from the fine sieve deviates from conventional primary sludge [8]. At present, application of fine sieves receives growing interest in countries like the Netherlands, and water authorities are even exploring the recovery of cellulosic fibers for reuse. On the other hand, onsite bio-methanation of FSF at high dry solids contents, could contribute to the objective of drastically minimizing the fossil energy requirements at conventional WWTPs, eventually leading to energy neutral WWTPs [9]. The FSF is a heterogeneous substrate, sequestered from raw sewage, which mainly consists of partly dissolved toilet paper (with a high cellulose fraction), hair, lignin compounds such as leaves and shell of fruits as well as sands and undefined materials. FSF composition was determined to consist of 60–80% of cellulose, 5–10% of hemicellulose, 5–10% of lignin, 5–10% of oil and the rest accounted for inorganic salts (5–10%) [10,11].

For anaerobic digestion, thermophilic (50–60 °C) or mesophilic (30–40 °C) conditions can be chosen [12–14]. Mesophilic anaerobic digestion of organic solids is often reported as most convenient, stable and reliable form of substrate conversion leading to stable methane production rates. However, mesophilic hydrolysis rates are lower than thermophilic conversion rates [15], since the rate of many, if not most, (bio)chemical reactions double as the reaction temperature increases by 10 °C [16]. On the other hand, thermophilic digestion requires higher energy input, and is regarded more sensitive to changes in operational conditions, such as changes in temperature and organic loading rates, as well as to changes in substrate characteristics [17,18]. The higher vulnerability could be due to a less diverse microbial community [19], persistence of propionate [20] and increased toxicity of intermediates at the thermophilic temperature range [18]. Lignocellulosic biomass, which has similar characteristics to FSF, has been widely used for bio-methanation by coupling cellulolytic microorganisms, fermenting bacteria and methanogenic archaea in one or two-stage anaerobic bioreactors [21,22]. Thermophilic anaerobic digestion of lignocellulosic biomass, such as FSF, might be more effective than mesophilic digestion [23]. Furthermore, high temperatures can also increase substrate solubility [24] and decrease the bulk liquid viscosity [25], leading to improved mixing performance and thus an increased hydrolysis of (hemi-)cellulose to monomers [26].

A filter cake containing very high dry solids concentrations (20–30%) without any chemical additions is one of the main advantages of fine sieving [7]. For comparison, primary and secondary sludge reach only 6% after thickening or 20% when polymer dosage is applied [27]. It is noteworthy that dewatering of FSF to 40–50% dry solids content is simply possible by applying mechanical pressure [8].

The high dry solids concentrations of FSF make the use of (semi) dry digesters possible, a technique that is usually applied in the digestion of the organic fraction of municipal solid waste (OFMSW) or food and yard waste digestion [23,28]. During past research in fed batch laboratory scale systems, digestion of FSF under thermophilic conditions has been shown to be more efficient and reliable than under mesophilic conditions [7]. Higher substrate doses could be applied and the measured higher reaction rate is expected to lead to a more efficient process with a lower retention time, thus leading to smaller reactor volumes [29–31]. The additional amount of required heat for thermophilic operation might be offset if higher biogas production yields are attained under these conditions [29]. In general, at a fixed solids retention time, a thermophilic digester indeed produces more methane per weight of biomass than the mesophilic counterpart [32–34].

Allowable substrate loading, bio-methanation rates as well as the maximum substrate conversion rates, are parameters required for the design and operation of a biogas plant [35,36]. Besides, the optimal inoculum to substrate ratio ($R_{I/S}$) is considered a crucial parameter for design of batch-wise or plug flow operated solid state anaerobic digestion processes, since it indicates the allowable substrate loading [37]. Therefore, the hydrolysis kinetics, and optimal $R_{I/S}$ were assessed using biochemical methane potential (BMP) tests. The BMP tests were conducted with well-adapted sludges at different $R_{I/S}$ under both mesophilic (35 °C) and thermophilic (55 °C) conditions. Based on these results, the energy potential of FSF was found and the digestion of FSF for onsite energy recovery was evaluated towards energy neutrality at WWTPs using the design of a compact plug flow digester.

## 2. Materials and methods

### 2.1. Substrate

FSF was collected from a 350 μm mesh fine sieve (Salsnes Filter, Norway) at WWTP Blaricum, the Netherlands and was stored at 4 °C prior to conduct the BMP tests. Total solids (TS) and volatile