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Microwave Heating as a Method to Improve Sanitation of Sewage Sludge in Wastewater Plants

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ABSTRACT For long-term sustainable agriculture, it is critical that we recycle nutrition to the soil that it came from. One important source is sewage sludge, but it must be sanitized from undesired pathogens before it may be spread on arable land. One common method today is deposition in about six months or more. Not only is such a long deposition-time costly due to the required storage-space, in the future usage of the method is likely to be more restricted from a regulatory perspective. To heat up sewage-sludge is a known method to speed up the sanitation process. However, achieving an even guaranteed temperature is not easy with porous sewage sludge. This is mainly due to the limited heat conductivity of the sludge. Microwaves at a frequency of 2.45 GHz have a penetration depth of a few centimeters and therefore has an advantage compared to other heating methods which only heats the surface. In the proposed system, the sewage sludge is continuously processed through a series of microwave cavities. The pathogen removal effectiveness was studied for different exposure settings, e.g., conveyor speed and applied microwave power in each cavity.

INDEX TERMS Biohazard, high power microwave generation, microwave ovens, microwave technology, sanitary engineering, sustainable development, waste handling, wastewater.

I. INTRODUCTION

Long-term sustainability in food production requires that nutrition in wastewater can be returned to the soil in arable land, i.e., nutrients bound in sludge of the wastewater. Before any processed sewage sludge can be spread on arable land, one must make sure that it is safe and that all undesired bi-product amounts are below their respective limits [1]. U.S. Environmental Protection Agency (U.S. EPA) classifies sewage sludge into Class A and B Biosolids ratings [2]. Class A and B have several things in common but one thing that differs is the regulation of pathogens. Class A requires a fecal coliform density below 10^3 most probable number (MPN)/g of total dried solids (TS) while Class B requires a level below 2×10^6 MPN/g [2], [3]. It means that there are restrictions to use Class B sludge as fertilizer (Such as quarantine from application to harvest.) while Class A can be used without any special constraints [2]. As a member of the European Union (EU), Sweden base its legislation and generally adopts the regulations stipulated by the EU [4]–[6]. Currently, there are several approved processes to treat sewage sludge [5], [6]. Long term deposition is today the most commonly used process to reduce pathogens [6]. The legislation is currently undergoing a major revision where one goal is increased nutrient recycling [4], [6]. In the revision, it is also proposed to rule out long term deposition, which would then cause issues for the current sewage sludge sanitation at many wastewater plants [6].

An alternative to long term deposition is to heat the sewage sludge to speed up the sanitation process [1], [7]. To directly (within a few minutes) sanitize the sludge a temperature considerably above room temperature is needed, and that temperature needs to be maintained for an adequate time [1], [7]. For instance, bacterial activity reduces rapidly above 57 °C [7]. It has been reported that at 60 °C it is effective within a few minutes, and above 80 °C even within a single minute [1], [7]. One challenge is to get even heating, if some spots are hotter and some cooler, the reduction is less predictable [8].

Microwave technology has previously been investigated for various wastewater process-related purposes. Some

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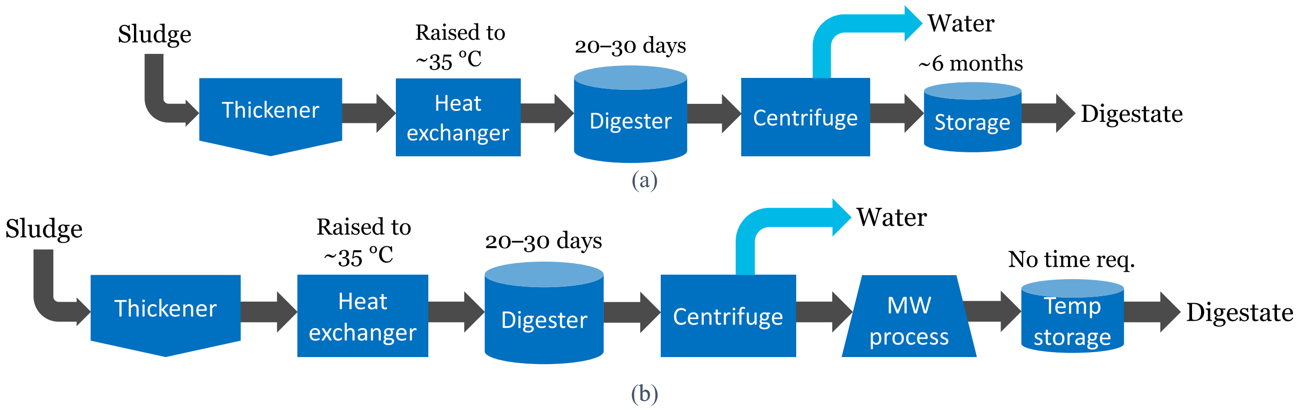


FIGURE 1. Sewage sludge process: (a) standard process, and (b) proposed microwave accelerated process.

objectives that have been studied are improved digestion and dewatering, increased biogas production, and sanitation [1], [7]–[27]. Ultrasonic technology has been used either instead of or together with microwaves to improve the digestion process [17], [18], [21]. Infrared ray technology has also been used to dry sludge [19]. Microwave irradiation has been used to enhance anaerobic digestion [9], [11], to recover energy-rich biogas [8], [10], and to reduce pathogens [1], [8], [22]–[27]. Microwave treatment was proven effective on coliform bacteria [1], the total bacterial activity including *Clostridium perfringens* [8], on *Escherichia coli* (*E-coli*) [23]–[27], and on *Enterococcus* [24]. Unlike other heat sources, microwave at 2.4 GHz heats a volume rather than a surface. They have a penetration depth of a few centimeters when applied on sewage sludge [7]. This is an advantage compared to conventional heating methods since it enables a more effective and even heating [7].

The specific heat capacity of sewage sludge is dependent on the water content [4]. It varies between dry matter: ∼1.23 W·s/(g·°C) [4], and that of water (4.19 W·s/(g·°C)) [28].

Currently, solutions are lacking for how microwave irradiation can be applied in an existing mesophilic sewage sludge process. Therefore, the objective of this work was to design a scalable solution. A pilot system consisting of four modules (microwave cavities), each fed with two magnetrons, was designed and evaluated. We performed microwave irradiation experiments on *E-coli*, *Enterococcus*, and *Salmonella* using our developed pilot system to evaluate its pathogen sanitation performance. The goal was to verify if the pilot system could continuously process and sanitize sewage sludge directly taken from a wastewater plant.

II. MATERIALS AND METHODS

A. SEWAGE SLUDGE PROCESS

The wastewater treatment plant Slottshagen in Norrköping, Sweden has a process typical for a plant using a long-term deposition as primary sanitation method. Fig. 1(a) shows an illustration of the current wastewater process used at Slottshagen and Fig. 1(b) shows the process, including the proposed microwave heating stage (''MW process''). The two processes have identical stages to the centrifuge stage. The first stage in both the processes is a sludge thickening stage. Water is filtered out to reduce volume, and to thicken the sewage sludge. In the second stage ''Heat exchanger'' uses central heating to preheat the sludge before the digestion stage. In the third step ''Digester'' the sludge is digested in an oxygen-free environment for about 20 to 30 days. The digestion is either mesophilic (20 – 40 °C) or thermophilic (above 50 °C). As a reference, the Slottshagen plant currently uses mesophilic digestion at ∼35 °C. Due to a high temperature of the thermophilic process, it reduces *E-coli*, *Enterococcus*, and *Salmonella* more than what mesophilic digestion does. The next stage is the centrifuge stage where water is separated from the sludge. In this stage, the proportion of dry substance is increased from (3 to 8) % to (20 to 45) % [1]. After this stage, the sewage sludge is prepared for final storage.

B. PILOT SYSTEM

A pilot system for the proposed microwave sewage sludge processing has been designed and manufactured. The pilot system has been designed with the workflow of the sewage sludge process in mind. Thus, a continuous flow concept was chosen over a batch-based. How the microwave at 2.4 GHz interacts with a material is dictated by its dielectric properties. These properties were measured for the sewage sludge and the data was used in the optimization of the microwave heating system. Also, the geometry of sludge flow through the tunnel was carefully chosen in order to get an efficient and even heating avoiding any over- or under-heated volumes of the sludge. Overheating would mean efficiency loss, whereas under-heating must be avoided in order to reach the desired bacteria killing effect. The system consists of four active modules in which microwave power was fed, and two passive in/out modules with microwave attenuating structures integrated, see Fig. 2. The active modules were designed to give a complimentary microwave pattern, meaning that

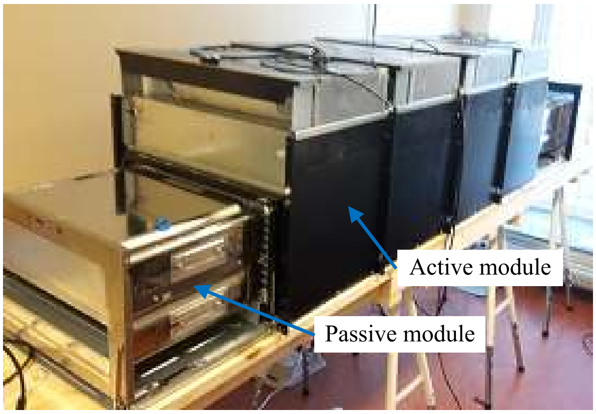


FIGURE 2. Pilot system.

geometrically different parts of the sludge flow were given maximum heating in each module.

A conveying system with variable speed was designed. The amount of energy exposure on the sludge could thus be regulated by choosing microwave power in each active module and the speed of the conveyor.

Table 1 shows the processing speeds that were available with the conveyor. Five fixed speeds could be set: 13, 19, 25, 36, or 49 centimeters per minute. With those speeds, the time to pass through four active modules was 13 minutes and 40 seconds on the lowest speed and 3 minutes and 40 seconds on the fastest speed setting, respectively.

TABLE 1. Available processing times.

Speed (cm/min)	Module proc. time (s)	Process time (s)
13	205	820
19	142.5	570
25	105	420
36	73	292
49	55	220

Each active module was equipped with two 900 W magnetrons, thus a maximum of 1800 W per module (a total of 7200 W) microwave power can be generated. The actual power could be regulated through the magnetron power supply in seven fixed steps.

All the modules were bolted together, and the pilot system can therefore freely be redesigned. For example, expanded with another active module to increase capacity.

Table 2 shows the available microwave power settings, the measured electrical power consumed for one module, and the efficiency. The electrical power consumed by one module at full power (1800 W microwave power) is 3.531 kW, and 752 W at the lowest power setting (180 W microwave power). The overall efficiency is limited by losses in the magnetron, electrical power supply, and other components, but can be improved with further optimization of the system.

TABLE 2. Available microwave power settings per active module.

MW-power (W)	Electrical power (W)	Efficiency (%)
2 x 90	752	23.9
2 x 160	1017	31.5
2 x 350	1678	38.1
2 x 500	2241	44.6
2 x 650	2786	46.7
2 x 750	3167	47.4
2 x 900	3531	51.0

The passive modules, one at each side of the oven, are used to enter and exit sludge batches during experiments. Fixed power settings were also used for comparison, typically a high heating power in modules one and two, and a lower "keep warm" power in modules three and four. In a possible wastewater plant implementation in the future, infrared (IR) temperature sensors should be mounted between each module to continuously monitor the temperature between each module. IR-sensors were the primary choice because of the matureness of technology and availability. Other non-contact sensor technologies such as radar temperature sensing may also be used but this was not of interest in this project. Continuous temperature observation makes it possible to adjust and optimize the applied microwave level, dependent of variation in the load.

C. EXPERIMENTAL SETUP

The experiments were conducted at the Slottshagen wastewater plant in Norrköping, Sweden. Sample sludge was taken directly from the running process at Slottshagen. The focus of the study was feasibility in a real-world case, so a real sludge was preferred over any idealized test-sample prepared in a lab.

Two experiment series were identified as shown in Table 3. In one experiment series, the speed was kept constant and the applied power in the heating stage was changed. In the second series, the applied heating power was kept constant, but the speed was changed. The column speed is the speed of the conveyor. The four columns listing power are the applied microwave power, where #1 is the first active module and #4 is the last active module. Modules #1 and #2 together form the heating stage, while Modules #3 and #4 form the keep-warm stage. The processing time is given as heating time plus keep-warm time. Energy and MW energy show the energy and microwave energy used per gram sludge.

In the experiments, the temperature was measured both with IR-camera and with temperature probes, i.e., the final temperature was measured with both types of sensors. The probe gives a reading of the bulk temperature inside each sludge batch, while the IR camera gives a reading of the surface temperature. Moreover, the IR reflection coefficient of the sewage sludge is not well documented, so a comparison

TABLE 3. Experiment series.

Experiment	Mass (g)	Speed (cm/min)	Power #1 (W)	Power #2 (W)	Power #3 (W)	Power #4 (W)	Processing time (min:s)	Energy (W·s/g)	MW energy (W·s/g)
Serie F1: Constant conveyor speed, varied power.									
F1A	400x8	19	1 800	1 800	320	320	04:45+04:45	810	378
F1B	400x8	19	1 500	1 500	320	320	04:45+04:45	745	324
F1C	400x8	19	1 300	1 300	320	320	04:45+04:45	677	288
F1D	400x8	19	1 000	1 000	320	320	04:45+04:45	580	235
Serie F2: Constant power, varied conveyor speed.									
F2A (= F1A)	400x8	19	1 800	1 800	320	320	04:45+04:45	810	378
F2B	400x8	25	1 800	1 800	320	320	03:30+03:30	597	278
F2C	400x8	49	1 800	1 800	320	320	01:50+01:50	313	146

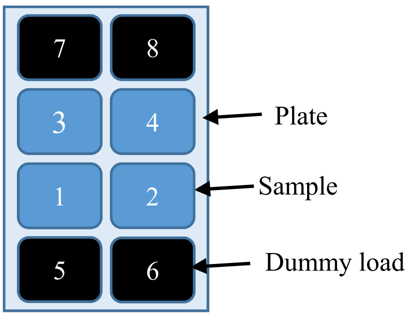


FIGURE 3. Experimental setup.

is also of interest from this point. The sensor correlation data is also necessary for any future implementation of IR-sensors between the modules.

Fig. 3 shows the experimental setup used in the experiments. A batch with eight samples was prepared for each run and placed on a plastic plate, see "Plate" in Fig. 3. Each sample was placed in a 1.2-liter plastic box with a base size of 130 mm × 175 mm, see "Sample" in Fig. 3. The height of the sewage sludge samples was limited to 50 mm to ensure even heating due to good microwave penetration. The overall dimensions were chosen to fit the desired sludge mass. A mass of 400 g per box was chosen to give a suitable range of available energy settings in W·s/g. Samples 5-8 (Noted "Dummy load" in Fig. 3.) contained the same kind of sludge, but they were not evaluated. The reason for these dummy loads was to make sure that the active oven module had a full load during the whole processing of the evaluated samples. This had two advantages. Firstly, the experiment setup became closer to an intended production processing. Secondly, it was easier to regulate applied energy per mass since the mass was constant during the whole processing time. It also made sure that each cavity had a full load when sample 1 to 4 was processed.

D. PATHOGEN ANALYSIS

All measurements of pathogens were conducted by Eurofins Environment Testing Sweden AB. The company has Swedac accredited labs for pathogen analysis. The presence of *E-coli* was measured according to the method Nordic Committee on Food Analysis (NMKL) 125, 4. Ed., 2005, *Enterococcus* with NMKL 68, 5. Ed., 2011, and *Salmonella* with NMKL 71, 5. Ed., 1999 [29]. The detection limit of *E-coli* and *Enterococcus* was 10 colony-forming unit (CFU)/g wet weight. The *Salmonella* detection method detected the presence of *Salmonella* in 25 g growth samples [29].

To further evaluate pathogen reduction below the detection level, a change in the lethal rate of bacteria was investigated theoretically. The pasteurization value (F) is given by:

$$F = \int_0^t 10^{\frac{T-T_{ref}}{z}} dt, \qquad (1)$$

where t is the actual time, T is the actual temperature, T_{ref} is the reference temperature, and z is the temperature rise required for one log10 reduction of pathogen's decimal reduction time [22].

III. RESULTS

A. SANITATION

Table 4 shows measured results, and reduction levels calculated from the measured results. All reduction levels are calculated with F0 as the reference sample. Total solids (TS) is the quota dry matter of the wet weight in percent. "TS ignition residue" is the ignition residue in the TS. The column "*E. coli*" is the presence of *E. coli* measured in wet-weight, and "*E. coli* TS" is the presence in the dry weight of the sludge. The reduction is given both in reduction percentage and the corresponding log-reduction. *Enterococcus* is abbreviated "*Ent.*" in Table 4, and the data style abbreviations are the same as for the corresponding *E. coli* data columns.

From experiment series F1 shown in Table 4, it is seen that the amount of *E. coli* reduced down to the measurement limit even for the lowest applied energy, i.e., a guaranteed minimum log-reduction of 4.5 even at the lowest applied energy (580 W·s/g). For the *Enterococcus*, the concentration barely stayed above the measurement threshold at the lowest applied energy, i.e., a 1.7 log reduction at 580 W·s/g. At 677 and

TABLE 4. Measurement results.

Exp.	Total solids (%)	TS ignition residue (%)	*E. coli* (CFU/g)	Reduction (%)	Log reduction	*E. coli* TS (CFU/g)	*Ent.* (CFU/g)	Reduction (%)	Log reduction	*Ent.* TS (CFU/g)	*Salmonella*
Serie F1: Constant conveyor speed, varied power.											
F1A	27	35	<10	99.997	>4.5	<37	<10	98.947	>2.0	<37	No
F1B	27	34	<10	99.997	>4.5	<37	10	98.947	2.0	37	No
F1C	26	35	<10	99.997	>4.5	<38	10	98.947	2.0	38	No
F1D	26	34	<10	99.997	>4.5	<38	20	97.895	1.7	77	No
Serie F2: Constant power, varied conveyor speed.											
F2A	27	35	<10	99.997	>4.5	<37	<10	98.947	>2.0	<37	No
F2B	26	34	<10	99.997	>4.5	<38	10	98.947	2.0	38	No
F2C	26	34	16 000	94.545	1.3	61 538	3 600	-278.947	-0.6	13846	Yes
Reference sample.											
F0	25	34	293 333			1 173 332	950			3800	Yes

745 W·s/g, the level was down to the measurement threshold, but activity was still detected. At 810 W·s/g no presence was detected, which means that the level was with a margin below the measurement threshold. No presence of *Salmonella* was found in any of the measured samples.

From experiment series F2 shown in Table 4, it is seen that the amount of *E. coli* reduced in all cases. With the lowest applied energy, the amount of *E. coli* reduced with a log factor of 1.3, and in all other cases, the *E. coli* once again reduced to the measurement limit. The measured results regarding *Enterococcus* are mixed. For the lowest applied energy-setting (313 W·s/g), the *Enterococcus* actually increased with a log "reduction" of −0.6. This was likely due to two reasons. Firstly, the applied energy level was not enough to sanitize the sludge, the slightly increased temperature might even have benefitted growth. Secondly, there ought to be some variation in bacteria concentration in the sludge to start with. Hence, the zero-sample did not have the maximum concentration. Presence of *Salmonella* was found in the sample with the lowest applied energy but not in any of the other processed samples. This fact strengthens the first above-mentioned reason. For the other cases, 587 and 810 W·s/g, the reduction of *Enterococcus* was once again down to the measurement resolution threshold.

B. HEATING PERFORMANCE AND EVENNESS

Fig. 4 shows the final temperature versus applied energy. The initial temperature of the sludge was 24 °C in all experiments. Fig. 4(a) shows the results for experiment series F1, and Fig. 4(b) shows the results for experiment series F2. It is shown that with a fixed speed and with a varied applied power the temperature as expected rises linearly within the applied energy interval. The dash-dot curves show the aggregated min and max temperatures of probe measured temperatures. The dashed curves show the aggregated min and max temperatures of IR measured temperatures. Moreover, the solid black curves show the respective average of each measurement. The trend was the same for both IR and probe measurements. The difference between the minimum and the maximum temperature was about the same, a span around 10 °C. The only deviation was that the temperature min/max spread increased slightly for the lowest applied energy. Except for

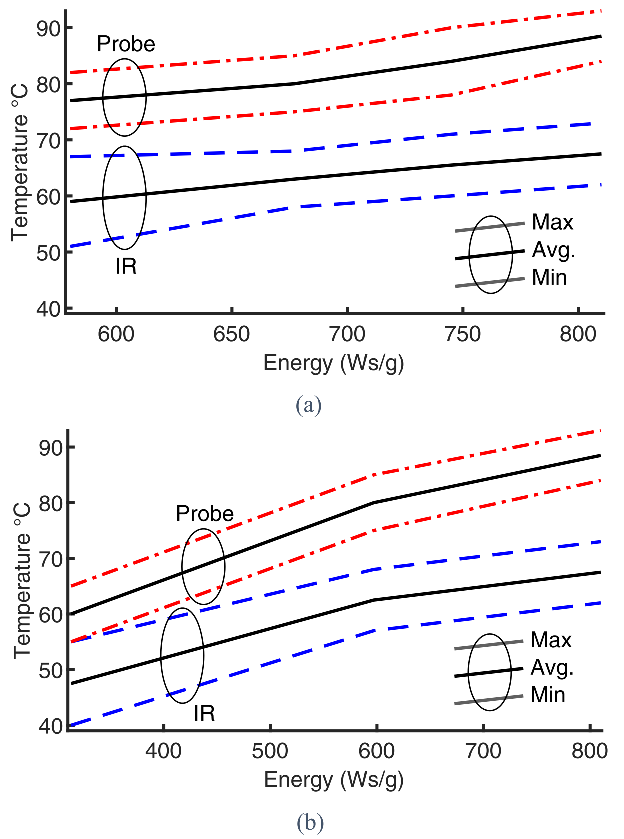
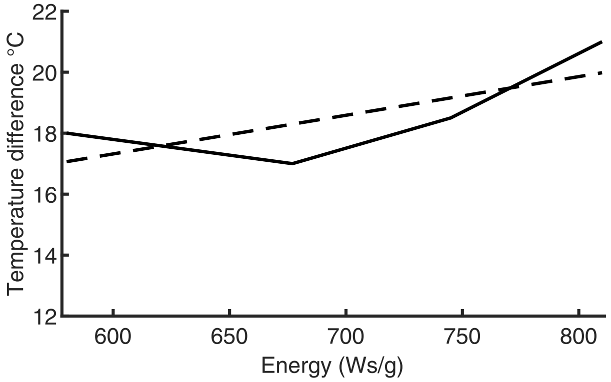
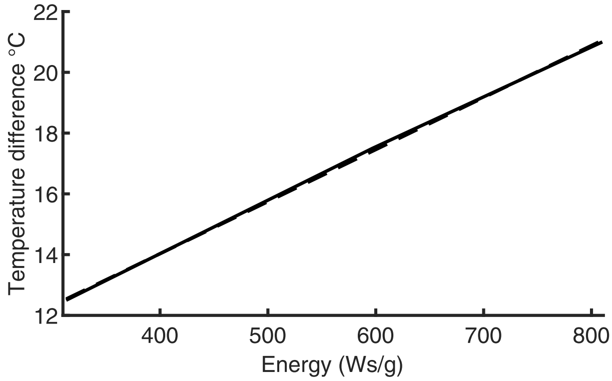


FIGURE 4. Sludge temperature vs applied energy: (a) experiment series F1, and (b) experiment series F2.



(a)



(b)

FIGURE 5. Temperature difference at various applied energy levels: (a) experiment series F1 and (b) experiment series F2.

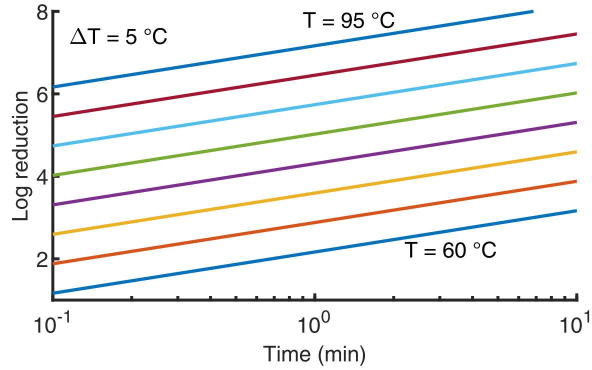


FIGURE 6. Estimated log-reduction of *Enterococcus*.

a measurement error margin, this was likely due to that the applied power was regulated by changing the intermittence of the microwave source. The sample moves through the chamber continuously, therefore some spots pass the field maxima when the microwave source is off and some when it is on. Hence, the result is a slightly increased statistical spread.

Overall the experiment series F2 shows similar results as experiment series F1. This time the applied energy span is higher, and the applied energy level was regulated by changing the conveyor speed. By changing the conveyor speed the processing time was changed inversely proportionally and the applied energy per gram sewage sludge likewise. It is shown in Fig. 4(b) that the increase in temperature declines for higher applied energy levels. Hence, at higher energy settings the sludge has a longer time to lose thermal energy to the surrounding environment. Moreover, some decline should happen, since at higher temperatures the temperature difference and therefore the loss of thermal energy to the surrounding environment increases. This was predicted to happen since the keep-warm power was chosen to the same in all experiments. As a comparison, the sludge should theoretically increase ∼1 °C for 3.4 W·s energy per gram sludge, i.e., energy received by the sludge mass [28].

Fig. 5 shows the difference in average temperature between the probe and IR measurement. Fig. 5(a) shows the results for experiment series F1, and Fig. 5(b) shows the results for experiment series F2. The solid black curves show the measured difference, and the dashed black curves show the linear trend of the temperature difference.

It was observed that there is a predictable correlation between the surface-temperature measured with IR versus the body-temperature measured with the probe. When the power intensity was varied to regulate the applied energy, the predictability was approximately ±1.0 °C from the linear trend when the applied energy ranges from 580 to 810 W·s/g. When instead the speed was used to regulate the applied energy, the deviation was below ±0.1 °C when the applied energy ranges from 313 to 810 W·s/g.

C. EVALUATION OF PATHOGEN REDUCTION

Fig. 6 shows the estimated log-reduction for various temperatures based on the measurement results obtained in series F1 and equation (1). A typical known *z*-value for *Enterococcus* of 7 °C [22] was used in the calculations. It is shown in V that the experiment setting F1C was estimated to have the minimum guaranteed 5.0 log-reduction based on the minimum probe temperature (75 °C) and the keep warm time (4.75 min). F1B was estimated to have a 5.4 log-reduction, with the minimum probe temperature of 78 °C. F1A was estimated to have a 6.3 log-reduction, with the minimum probe-temperature of 84 °C.

IV. DISCUSSION

It may be questioned if using a high-value energy source such as electricity is an appropriate choice for heating compared to low-grade energy sources. However, with the current expansion of renewable energy sources, more and more of the available electrical power is clean power. Moreover, the flexibility of an electrically controlled source is an advantage. The process can easily be monitored and regulated to avoid unnecessary power consumption.

In the experiments, a sludge height of 50 mm was used. In a full-scale system, the sludge height should still be unchanged. Increasing the sludge height far beyond the microwave penetration depth is not desirable since an even heating is important. Instead to increase the capacity, more active modules

TABLE 5. **Comparison of previous works.**

Work	Test	Temp (°C)	Reduction	Comment	MW energy (Orig.)	(W·s/g)	(W·s/(g·°C))
[1]	Col. bact.	From 45 to 60	1.98 log reduction From 1.9×10^7 to 2.0×10^5 (counts/100mL)	Up to 23 times shorter heating time than conductive heating. 2.2 % TS.	2 kW MW pwr. for 20 s on 100 g.	400	26.7
[1]	Col. bact.	From 45 to 80	>6-log reduction From 1.9×10^7 to 0 (counts/100mL).	Same reduction and up to 23 times shorter heating time than conductive heating. 2.2 % TS.	2 kW MW pwr. for 33 s on 100 g.	660	18.9
[8]	Overall bact.	From 20 to 60	4.88 vs 5.98 log reduction From 8.93 to 4.05 and 2.95 (log CFU/g TS)	No MW pretreatment vs MW pretreated sludge before digestion. 5.3 % TS.	900 W MW pwr. for 438 s on 1kg.	394	9.9
[8]	Overall bact.	From 20 to 70	4.88 vs 6.36 log reduction From 8.93 to 4.05 and 2.57 (log CFU/g TS)	No MW pretreatment vs MW pretreated sludge before digestion. 5.3 % TS.	900 W MW pwr. for 650 s on 1kg.	585	11.7
[23]	*E. coli*	From 24 to 55	0.74 log reduction	Fecal sludge (FS) from urine-diverting toilets. 26 % TS.	465 W MW pwr. for one min on 100 g.	279	9.0
[23]	*E. coli*	From 24 to 78	5.60 log reduction	FS sludge from urine-diverting toilets. 26 % TS.	1085 W MW pwr. for one min on 100 g.	651	12.1
[23]	*E. coli*	From 24 to 60	4.40 log reduction	FS sludge from urine-diverting toilets. 26 % TS.	1085 W MW pwr. for one min on 200 g.	326	9.0
[24]	*E. coli*	From 18 to 73	>6-log reduction	[20] FS sludge due to that it has the most relevant TS quota (23 %).	3400 W MW pwr. for 30 min on 4 kg.	1530	27.8
[24]	*Enterococcus*	From 18 to 73	4.95 log reduction	[20] FS sludge due to most relevant TS quota (23 %).	3400 W MW pwr. for 30 min on 4 kg.	1530	27.8
[24]	*Enterococcus*	From 18 to 88	>6-log reduction	[20] FS sludge due to most relevant TS quota (23 %).	3400 W MW pwr. for 60 min on 4 kg.	3060	43.7
[25], [26]	Fecal col. bact.	From 25 to 45, and to 65	1.25 log reduction >3.77-log reduction	25 °C using 0.34 Wh/g TS was used as a reference. ADS sludge with 29,810 mg/l TS.	0.67 Wh/g TS 1.35 Wh/g TS (MW energy)	405 815	10.0 15.2
[27]	*E. coli*	From 28 to 46, and to 61	2.02 log reduction >4-log reduction	Health care waste: Plastic, fabric, rubber, metals. 67 % TS.	300 W MW pwr. for 5 min, and 10 min on 0.75 kg.	120 240	6.7 7.3
[27]	*E. coli*	From 28 to 63, and to 82	2.76 log reduction >4-log reduction	Health care waste: Plastic, fabric, rubber, metals. 67 % TS.	550 W MW pwr. for 5 min, and 10 min on 0.75 kg.	220 440	6.3 8.3

- Microwave (MW) energy data is presented using original units (Orig.), in W·s per gram (W·s/g), and in W·s per gram per degree.
- Our work, MW energy (W·s/(g·°C)): F1A = F2A = 5.9, F1B = 5.4, F1C = 5.1, F1D = 4.4, F2B = 5.0, and F2C = 4.1.

can be added in series or in parallel, and the cavity can also be made wider. The energy density (W·s/g) strongly affects the temperature rise. Scaling power and processing time for a certain energy density will affect the time the sludge is hot and can vaporize water. This is of little importance since the overall process times are relatively short. Slightly reduced sludge weight will be a benefit but of little importance for a plant using the same kind of process as Slottshagen. However, if drying the sludge is of priority, the system can be modified to achieve it. It simply requires the applied energy to be raised to what is needed for the degree of vaporization and that the steam is ventilated out of the cavity.

The level of micro-bacterial content was reduced to or under detectable level even with moderate settings in the system. Despite this promising result, it would be beneficial to have been able to further evaluate the precise reduction level for all energy levels. This was not possible since the sludge was not enough contaminated to start with.

Good predictability of applied energy versus achieved temperature was observed, see Fig. 5. However, the difference was slightly larger when regulating applied power (<1.0 °C) compared to the case when the speed was regulated (<0.1 °C). This may be due to a minor deviation in efficiency at different power levels.

Table 5 shows a comparison of selected previous works. All the listed previous works show that heating up is an effective method to reduce pathogens in sewage sludge. It has also been shown that the penetration depth of the microwaves makes it possible to heat faster than with conductive heating. The reduction results are comparable with this work when the achieved goal temperature and exposure time are considered. Table 5 shows that for temperatures above 60 °C *E. coli* was reduced >4-log within minutes. *Enterococcus* requires either higher temperature or longer exposure time. For larger samples, a longer exposure time was most often used rather than increased power. This is due to the fact that uneven heating due to limited thermal conduction is a big issue when the size of the sludge sample is larger than the microwave penetration depth. Previously reported experiments are all done in labs where a nonmoving sample was exposed in a closed microwave cavity. In this work, a similar reduction performance was shown when the sludge was continuously processed. The amount sewage sludge (∼28 tons per day in average in a plant size of Slottshagen [6]) in a plant per day implies that the sludge handling is efficient.

Table 5 also shows how much microwave energy that was used in each case. How much energy that was spent per gram sludge (W·s/g) gives, besides a possibility to compare with this work, an insight into the energy cost of each process. The start temperature should also be considered when comparing different experiments. The column presenting degree normalized microwave energy data (W·s/(g·°C)) gives an insight how much of the microwave energy that was used for heating up the sludge and how much that was used to maintain the sludge temperature. It also gives a comparison between different experiments with respect to microwave energy efficiency despite different start temperatures. A well-designed microwave heating apparatus should have a low energy consumption value, when processing time, temperature, and the specific heat capacity of the sludge are considered.

Dewatered sewage sludge with (26 to 27) % TS, such as what used in this work, has a specific heat capacity of ∼3.4 W·s/(g·°C). The difference between the specific heat capacity and the degree-normalized microwave energy corresponds to the microwave energy needed to preserve the achieved sludge temperature. Table 5 shows that our work had lower degree-normalized energy usage. This is partially due to that we conducted experiments with a full load to achieve high efficiency. Some of the referenced experiments had a higher start temperature, which also increased the thermal loss since the average sludge temperature was higher during the experiment. The TS quota varies between those reported experiments as mentioned in the introduction, the water content is the dominating factor of the specific heat capacity, more water means considerably higher energy need. It means that from energy perspective it is preferable to sanitize dewatered sewage sludge than raw sludge. The difference is also because of the shorter processing times that were used in our experiments, which then simply gave less time for thermal energy leakage. It also indicates that intense heating is preferred to achieve an energy-efficient sewage sanitation. The drawback of intense heating is that it gives less time for the heat to spread in the sludge, and therefore makes even heating a more important factor of the microwave system.

Considering all the referenced experiments and this work, it is convincing that microwave technology can be used to reduce pathogens. The continues processing in combination with the possibility to quickly regulate applied microwave power makes the proposed system a candidate to complement existing systems in wastewater plants. Due to the ease of installation, it is also a candidate to be used in remote areas. Especially, in developing countries where adequate wastewater treatment is not always available.

V. CONCLUSION

It has been shown that the proposed microwave enhanced process is a promising solution to sanitize sewage sludge. The presented process enables continuous processing of sewage sludge through a series of microwave cavities. It has been shown that pathogens can be effectively reduced:

- A minimum guaranteed 4.5 log reduction of *E. coli* at an energy consumption of 580 W·s/g, when the minimum sludge temperature was raised from 24 °C to 72 °C.
- A 1.3 log reduction of *Enterococcus* at an energy consumption of 580 W·s/g. Moreover, a 2.0 log reduction of *Enterococcus* at an energy consumption of 677 W·s/g was shown.
- Using experiment F1A as a reference experiment F1C was estimated to have a 5.0 log-reduction of *Enterococcus* based on the minimum probe temperature (75 °C) and the keep warm time (4.75 min). F1B was estimated to have a 5.4 log-reduction, with a minimum probe temperature of 78 °C. F1A was estimated to have a 6.3 log-reduction, with a minimum probe-temperature of 84 °C.
- Presence of *Salmonella* was eliminated with 580 W·s/g or more.

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