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Microwave treatment of municipal sewage sludge: Evaluation of the drying performance and energy demand of a pilot-scale microwave drying system

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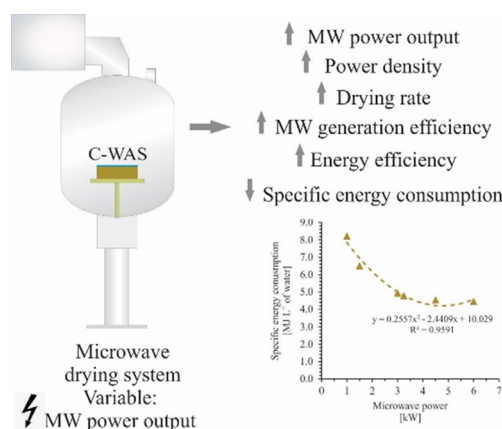
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HIGHLIGHTS

- MW drying offers an effective and flexible alternative for sludge treatment at a centralised and decentralised levels.
- MW promotes long constant rate drying periods associated with the removal of free water and relatively low energy consumption.
- The sludge power absorption density is directly related to the MW system's overall energy efficiency.
- The MW drying system exhibits specific energy consumption similar to conventional thermal driers.

GRAPHICAL ABSTRACT



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ABSTRACT

Sewage sludge management and treatment can represent up to approximately 30% of the overall operational costs of a wastewater treatment plant. Microwave (MW) drying has been recognized as a feasible technology for sludge treatment. However, MW drying systems exhibit high energy expenditures due to: (i) unnecessary heating of the cavity and other components of the system, (ii) ineffective extraction of the condensate from the irradiation cavity, and (iii) an inefficient use of the microwave energy, among others issues. This study investigated the performance of a novel pilot-scale MW system for sludge drying, specifically designed addressing the shortcomings previously described. The performance of the system was assessed drying municipal centrifuged

Abbreviations: C-WAS, centrifuged waste activated sludge; D_R , drying rate [$\text{kg of water kg of dry solid}^{-1} \text{ min}^{-1}$]; DS, dry solids [%]; E, electric field intensity [V m^{-1}]; f, frequency [Hz]; H, hydrogen; h_{fg} , latent heat of water [kJ kg^{-1}]; m_d , total mass of dry solids in the sample; m_{evap} , amount of evaporated moisture (water) [kg]; m_{sample} , sample mass [kg] at a time t; MW, microwave; P_d , amount of absorbed power per unit volume [W m^{-3}]; $P_{\text{in,elect}}$, input power [kW]; $P_{\text{out,micr}}$, output power [kW]; PP, polypropylene; S, sulphur; SEC, specific energy consumption [kJ L^{-1} of water]; SEI, specific energy input [kJ kg^{-1} of sludge]; SEO, specific energy output [kJ kg^{-1} of sludge]; S_{11} , the reflection coefficient [—]; t, exposure time [min]; T, temperature [$^{\circ}\text{C}$]; TC, total carbon; TN, total nitrogen; TS, total solids; $\tan\delta$, loss tangent coefficient; VS, volatile solids; WWTP, wastewater treatment plant; X, sludge moisture content [$\text{kg of water kg of dry solid}^{-1}$]; ϵ'' , dielectric loss factor [—]; ϵ' , dielectric constant [—]; ϵ_0 , permittivity of free space [$8.85 \times 10^{-12} \text{ fm}^{-1}$]; μ_{en} , energy efficiency [%]; μ_{gen} , microwave generation efficiency [%].

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Sludge drying
Municipal sludge
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Microwave generation efficiency
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wasted activated sludge at MW output powers from 1 to 6 kW and evaluating the system's drying rates and exposure times, specific energy outputs, MW generation efficiencies, overall energy efficiencies, and specific energy consumption. The results indicated that MW drying significantly extends the duration of the constant rate drying period associated with the evaporation of the unbound sludge water, a phase associated with low energy input requirement for evaporating water. Moreover, the higher the MW output power, the higher the sludge power absorption density, and the MW generation efficiency. MW generation efficiencies of up to 70% were reported. The higher the power absorption density, the lower the chances for energy losses in the form of reflected power and/or energy dissipated into the MW system. Specific energy consumptions as low as 2.6 MJ L^{-1} (0.74 kWh L^{-1}) could be achieved, well in the range of conventional thermal dryers. The results obtained in this research provide sufficient evidence to conclude that the modifications introduced to the novel pilot-scale MW system mitigated the shortcomings of existing MW systems, and that the technology has great potential to effectively and efficiently drying municipal sewage sludge.

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1. Introduction

Municipal sewage sludge is a by-product of the treatment of municipal and industrial wastewater. Depending on the source of the wastewater, the sewage sludge may contain pathogenic organisms, antibiotic-resistant microorganisms, and inorganic and organic pollutants such as polycyclic aromatic hydrocarbons, dioxins, furans, heavy metals, and pharmaceutical compounds, among others (Raheem et al., 2018). Consequently, the disposal of sewage sludge may pose a risk to the environment and human health. Due to these concerns, the direct utilisation of sludge for agricultural activities has been limited or banned in many countries especially in Western Europe. Among the limited disposal options available, (co-)incineration is emerging as the most viable alternative for the final disposal of sludge (Kacprzak et al., 2017). However, it comes at a higher cost than other conventional treatment options such as the reuse of stabilised sludge in agriculture. According to Jakobsson (2014), the cost of (co-)incineration varies from between 250 and 330 EUR per tonne of dry solids (DS), which is much higher than the cost of the sludge treatment (stabilisation) commonly used to enable sludge to be reused in agriculture (160 to 210 EUR per tonne of DS). A major factor contributing to the fluctuations in sludge treatment costs is the cost of transporting the sludge from its source to the treatment and final disposal locations. To achieve economies of scale, sludge (co-)incineration facilities are often centralised installations serving more than one wastewater treatment plant (WWTP) in densely populated areas. Such sludge incineration facilities usually charge between 80 and 120 EUR per tonne of wet sludge (Kacprzak et al., 2017). Sludge management and treatment can represent up to approximately 30% of the total operational costs of a WWTP (Jakobsson, 2014).

Sludge originating from municipal WWTPs consists primarily of water (98–99%). Therefore, most of the sludge treatment interventions (and related costs) are associated with large volumes of water requiring frequent collection, transport, and treatment. Typically, most of the water content is reduced using mechanical and/or thermal dewatering processes. Mechanical dewatering technologies utilise gravity or the application of external pressure to achieve their ends (Schaum and Lux, 2010; Vesilind, 1994). Mechanical dewatering technologies such as centrifuges, decanters, belt filter presses, hydraulic filter presses, and screw presses can reduce the sludge moisture content by up to approximately 70% (i.e., 30% DS) (Schaum and Lux, 2010). Further removal of water can be achieved by applying conventional thermal processes involving the use of heated air, steam, or flue gas in belt conveyors, fluidised beds, spray dryers, or drums (Schaum and Lux, 2010). However, there are drawbacks to all of these conventional drying processes including low drying efficiencies, long exposure/treatment times, and substantial energy requirements (Mujumdar, 2014; Ohm et al., 2009).

Microwave (MW) radiation is proposed as a promising alternative for sludge treatment (Afolabi and Sohail, 2017; Mawioo et al., 2017). MWs are a form of nonionizing electromagnetic waves with wavelengths from 100 to 0.1 cm and corresponding frequencies of between

300 and 300,000 MHz. MW frequencies of 915 and 2450 MHz are employed for industrial, scientific, and medical (ISM) applications corresponding to wavelengths of 37.24 and 12.14 cm, respectively (Bilecka and Niederberger, 2010; Thostenson and Chou, 1999). These frequencies are widely used in MW drying applications. The advantages of MW drying applications over conventional drying systems include higher throughput capacity, faster process start-up and shutdown, smaller carbon footprint, and lower negative effects on global warming (renewable energy sources can satisfy the electrical energy needs of MWs), among others (Kouchakzadeh and Shafeei, 2010; Maskan, 2001). As such, MW drying technology may promote the development of containerised/movable systems for the treatment of either sewage sludge generated at centralised WWTP facilities or of septic/faecal sludge generated in remote decentralised areas without access to sewerage such as informal settlements and/or emergency camps (Afolabi and Sohail, 2017; Mawioo et al., 2017).

The main mechanism of the conversion of nonionizing electromagnetic energy into heat during MW irradiation of sludge is the dipolar polarisation mechanism (Stuerga, 2006). The torque applied by the electric field induces the rotational motion of all molecules exhibiting a permanent dipole moment such as the water molecules within the sludge (Stuerga, 2006). The water molecules try to resist the changes caused by the oscillating field, producing elastic, inertial, frictional, and molecular interaction forces and resulting in a temperature increase throughout the material (Mishra and Sharma, 2016). That is, the transformation of energy into heat is attributed to the ability of the electromagnetic energy to couple and induce the polarisation of charges inside the irradiated material. This ability is governed by the dielectric loss tangent ($\tan \delta$) of the material, that is, the ratio between the dielectric loss factor (ϵ'') and the dielectric constant (ϵ').

The potential application of MW radiation for sludge heating, including drying and sterilisation, has been successfully demonstrated in a laboratory setting. For example, a study carried out by Dominguez et al. (2004) on MW heating of sewage sludge showed a 10-times reduction of the exposure time compared with conventional heating technologies. Specifically, a conventional hot air furnace operating at 2 kW required 55 min to reduce the moisture content to less than 1% while a MW unit operating at 1 kW required just 5 to 8 min. Similarly, MW technology has shown promising results for pathogen inactivation in sludge. Hong et al. (2006) investigated the effects of both MW and conventional heating systems (water bath) on faecal coliform removal in municipal primary sludge. The MW radiation system reduced the number of faecal coliforms in the sludge below the detection limit at a temperature of 65 °C within a minute. The same results were achieved by the conventional heating system but at a higher treatment temperature of 100 °C and after a longer exposure time of 4.8 min. In addition to the inactivation of faecal coliforms, MW sanitisation of sludge has also been proven to be effective for inactivating other microorganisms such as *E. coli*, *Ascaris lumbricoides* egg, *Staphylococcus aureus*, and *Enterococcus faecalis* below detection limits (Mawioo et al., 2017; Mawioo et al., 2016a; Mawioo

et al., 2016b). The reduced processing time observed for MW treatment systems compared with conventional drying techniques may be due to the selective and penetrating nature of MWs. MW radiation generates heat from within the material being heated and causes heat generation throughout the volume of the material, resulting in a heating profile that emanates from the inside to the outside of the material. The generated heat caused by molecular friction leads to internal evaporation and the corresponding generation of internal pressure (Fu et al., 2017; Ni et al., 1999). Such pressure induces moisture to move to the surface of the material where it is then removed. Using MW radiation, a much higher flowrate (up to 10 times) of water from the inside of the material to the surface has been reported compared with convection drying processes (Kumar et al., 2016). Due to the selective heating properties of MW radiation, only dielectric materials such as water can be heated. Other materials such as teflon, polypropylene, and bulk metals are largely unaffected by MW radiation (Bhattacharya and Basak, 2016). Therefore, MW selective heating is one of the most advantageous attributes of MW technology as it reduces the energy inefficiencies associated with the indirect heating of the atmosphere, the surface of the MW irradiation cavity, or other components of the system commonly observed with conventional heating systems (Kappe et al., 2012). Thus, MW technology can offer an effective, fast, and flexible treatment option for the sanitisation and drying of sludge.

Despite the potential benefits of using MW radiation for sludge treatment, most of the evaluations of this technology have been carried out in a laboratory setting. To date, only limited attempts to scale-up testing have been made. Mawioo et al. (2017) evaluated the performance of a pilot-scale MW reactor treating centrifuged waste activated sludge (C-WAS) and reported promising results regarding the sterilisation and drying of the sludge. However, the authors reported very high specific energy consumption (SEC) values (the energy consumed per litre of evaporated water) of 14.5 MJ L^{-1} . That is, Mawioo et al. (2017) reported SEC values that were three to six times higher than those of conventional thermal convective systems such as belt driers, direct drum dryers, and flash dryers (Léonard et al., 2011). Mawioo et al. (2017) identified several issues with the MW pilot system that could lead to such low SEC values: (i) poor design of the extraction of the condensate (water vapour) from the irradiation cavity, (ii) the occurrence of water condensation inside the MW irradiation cavity, (iii) cold ambient (winter) temperature, (iv) cold start-up of the system, (v) lack of thermal insulation, (vi) inefficient use of the microwave energy, (vii) unnecessary heating of the irradiation cavity, (viii) uneven distribution of the MW energy on the irradiated sludge, and (ix) absence of energy recovery features. Other researchers have also reported similar and additional factors that may contribute to such energy inefficiencies including the non-uniform distribution of both the electromagnetic field and temperature within the irradiated material and overall failures in the design of the MW system (Vadivambal and Jayas, 2010). Previous research into sludge with MW systems at the pilot-scale have included the use of low power magnetrons that have achieved MW generation efficiencies of approximately 50% (Mawioo et al., 2017; Mawioo et al., 2016a; Mawioo et al., 2016b). Treating sludge using a MW generator with a higher quoted conversion efficiency may reduce the sludge treatment time and energy consumption. Previous research on MW sludge treatment has also failed to evaluate the impact of the different MW power outputs on the optimisation of energy efficiencies to identify an optimum MW power output to sludge load ratio (Bermúdez et al., 2015). In addition, vapour extraction has been incorrectly implemented, and the uniformity of the MW electric field on the irradiated sample has not been emphasised. Some of these shortcomings have been overcome by combining MW radiation with hot air treatment (Fennell and Boldor, 2014; Fennell et al., 2015). The water evaporated by the action of the MW radiation is removed by the introduced stream of hot air, avoiding condensation and the rewetting of the irradiated sample. Moreover, the addition of the hot air treatment can contribute to the uniform heating of the material, improving the energy efficiency of the process (Cravotto and Carnaroglio, 2017; Kumar et al., 2014b). Additionally,

intermittent MW convective drying with hot air can be applied (introducing the MW energy as sequential pulses), which provides more uniform heating than MW radiation alone (Joardder et al., 2013; Joardder et al., 2017; Kumar and Karim, 2019; Kumar et al., 2014b) (Kumar et al., 2016; Kumar et al., 2014a; Welsh et al., 2017). Several other options are available that can overcome non-uniform electric field distribution and the corresponding heating pattern within the samples such as the use of travelling wave applicators, and/or the introduction of moving parts in the irradiation cavity such as agitators or turntables (Boldor et al., 2005; Fennell and Boldor, 2014; Fennell et al., 2015).

MW technology has thus shown potential advantages in terms of pathogen inactivation and drying compared with conventional drying technologies. However, several limitations associated with the energy efficiency of large-scale MW systems for sludge treatment remain and threaten the practicality of such systems. This research evaluated the performance of a pilot-scale MW reactor for the treatment of C-WAS. The pilot-scale MW system evaluated in this research was designed to address all the shortcomings described in the previous paragraph, notably: (i) improvements on the overall design of the MW irradiation cavity to achieve the uniform distribution of MW radiation while avoiding heating the irradiation cavity, (ii) the inclusion of a more efficient extraction system to allow the condensate to leave the irradiation cavity, and (iii) the provision of a MW generator with a high quoted MW generation efficiency to more efficiently use the MW energy. The treatment performance of the pilot-scale MW system was assessed at different MW output powers, which determined the overall treatment/exposure times, the sludge drying rates, the specific energy consumption, the drying energy efficiencies, and the overall MW system energy efficiencies.

2. Materials and methods

2.1. Sludge samples

C-WAS samples were collected from the WWTP located in Ptuj, Slovenia. Polymer was added at the WWTP to improve the dehydration of the sludge.

2.2. Analytical procedures

2.2.1. Total solid (TS) and volatile solid (VS) determination

The TS and VS concentrations of the sludge were determined twice weekly according to the gravimetric methods SM-2540D and SM-2540E, respectively, as described in American Public Health et al. (2005). The sludge DS concentration was calculated from the TS concentration.

2.2.2. Calorific value and carbon, hydrogen, nitrogen, and sulphur determination

The calorific value of the raw sludge was measured in a bomb calorimeter (IKA-Calorimeter C 400 adiabatich IKA®-Werke GmbH & Co. KG, Staufen German) according to the SIST-TS CEN/TS 16023:2014 standards. The elemental sulphur (S) and hydrogen (H) content in the sludge were measured using the Dumas method. The elemental total carbon (C) was determined using the dry combustion method according to SIST EN 13137:2002. The elemental total nitrogen (N) was determined according to SIST EN 16168:2013. Both the calorific value and the elemental analyses were determined at the Institute of Chemistry, Ecology, Measurement and Analytics (IKEMA, Lovrenc na Dravskem polju, Slovenia).

2.3. Experimental pilot-scale MW system

The pilot-scale MW system was designed and manufactured by Tehnobiro d.o.o (Maribor, Slovenia) for the treatment of diverse types of sludge with different water and solids content such as fresh faecal sludge, septage sludge, and waste sewage sludge. A detailed schematic drawing of the system is presented in Fig. 1. The MW system consisted of a stainless

steel cylindrical MW irradiation cavity provided with a polypropylene (PP) oval vessel with a maximum sludge load capacity of 6 kg and a holding vessel stand on a rotating PP turntable provided with an electromotor to rotate the sludge sample at a speed of 1 rpm. This rotational effect could potentially increase the uniform irradiation of the sludge. Ancillary equipment included a ventilation unit for the extraction of the condensate, a MW power supply, a MW magnetron with a maximum output power of 6 kW at a frequency of 2450 MHz, and an air filtration system for odour control. The MW magnetron delivered the desired power along a standard rectangular waveguide WR340 (86.36×53.18 mm) connected to a circulator. An isolator connected to the MW head allowed the MW power to pass to the MW cavity (forward power) but not to flow in the reverse direction (reflected power). The reflected power was absorbed by a dummy load connected to the waveguide circulator. A teflon window was placed between the isolator outlet and the inlet of the MW chamber to prevent humidity, dust, and other elements that could damage the magnetron's antenna and/or the isolator. A magnetron-cooling water-based system was incorporated to reduce the temperature in the MW magnetron and power supply. Demineralised water was provided at a flowrate of 600 L h^{-1} . Three different types of fillers were used to selectively increase the adsorption capacity of the air filtration system. These fillers were activated carbon soaked in phosphoric acid (H_3PO_4), activated carbon soaked in sodium hydroxide (NaOH), and aluminium oxide (Al_2O_3) with potassium permanganate (KMnO_4). The changes in the sludge weight that occurred during the sludge's exposure to the MW drying process were continuously measured by a single point load cell (Mettler Toledo) with an error lower than 0.016 g and a resolution of 5 g. The electrical energy supplied to the MW unit was continuously measured using a power network analyser (Etimeter).

2.4. Experimental procedure

The C-WAS samples were collected on the same day prior to each evaluation. Fresh samples were weighed and placed in the PP holding

vessels. The vessels were then placed on the rotating turntable inside the MW cavity. The experimental conditions for the evaluated samples are described in Table 1. The MW output powers were increased from 1 to 6 kW, while the initial sludge mass load and thickness remained constant at 3 kg and 60 mm, respectively. The experiments were finalised when the sludge moisture reached a value of approximately 0.18 kg of water per 1 kg of dry solid $^{-1}$ (i.e., 85% DS). The evaluations were performed in either duplicate or triplicate and the average results were reported. The evaluation of the MW pilot-scale unit was carried out in the research hall of the municipal WWTP located in Ptuj, Slovenia.

2.5. Data analysis

2.5.1. Specific energy consumption (SEC)

The SEC was calculated as shown in Eq. (1):

$$SEC = \frac{P_{in;elect} \cdot t}{m_{eva}} \quad (1)$$

where the SEC is the specific energy consumption [kJ L^{-1} of water], $P_{in;elect}$ is the input power consumed by the system during the drying process [kW], t is the exposure time [s], and m_{eva} is the amount of evaporated water at a specific exposure time [L]. The $P_{in;elect}$ was measured using a power network analyser (Etimeter), as described in Section 2.3.

2.5.2. Specific energy output (SEO)

The SEO was calculated as shown in Eq. (2) (Robinson et al., 2007):

$$SEO = \frac{P_{out,micr} \cdot t}{m_{sample}} \quad (2)$$

where the SEO is the specific energy output [kJ kg^{-1}], m_{sample} is the initial mass of sludge (kg), t is the exposure time [s], and $P_{out,micr}$ is the output power (nominal power) supplied to the MW chamber [kW]. The MW output power was set according to the

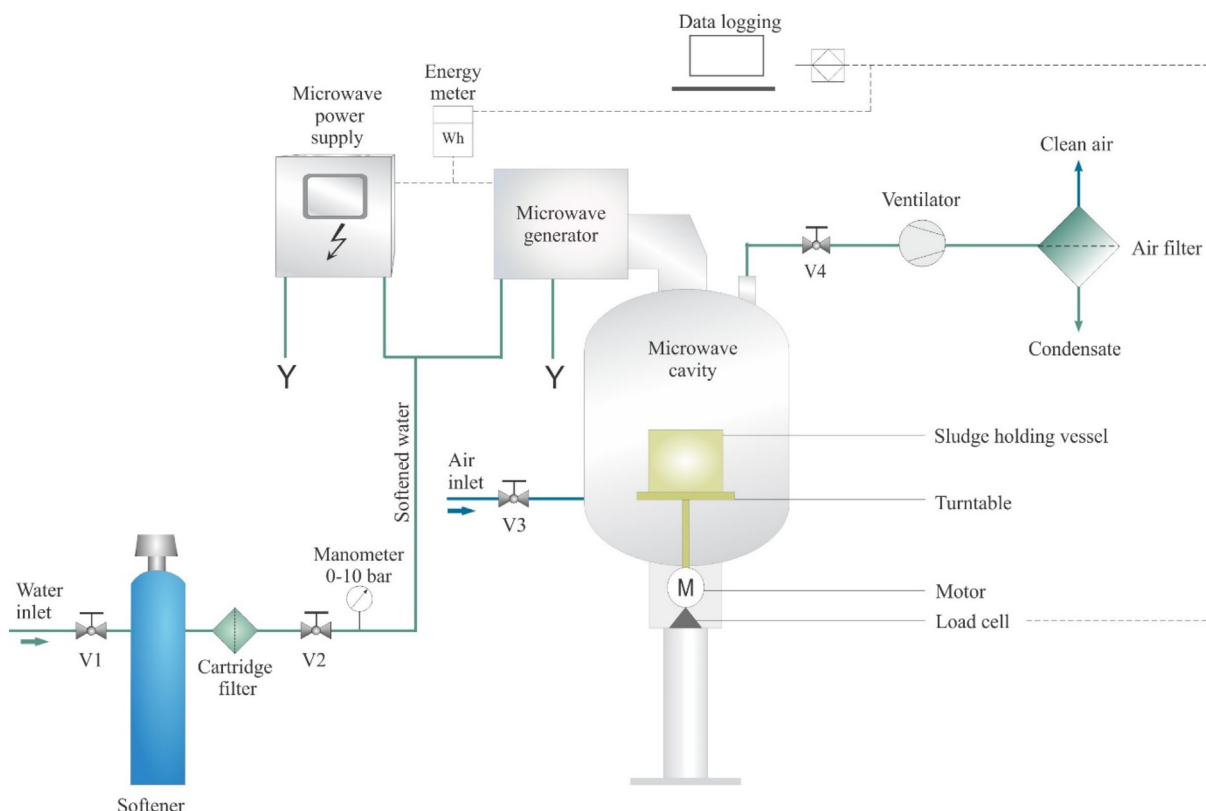


Fig. 1. Schematic representation of the experimental pilot-scale MW system.

Table 1
Experimental design.

Experiment no.	Experimental parameters and variables		
	MW output power	Sludge mass	Sludge layer thickness
	[kW]	[kg]	[mm]
1	1.00	3.0	60
	1.50	3.0	60
2	3.00	3.0	60
3	3.25	3.0	60
4	4.50	3.0	60
5	6.00	3.0	60
6			

manufacturer's settings and ratings though the MW power supply control panel.

2.5.3. Specific energy input (SEI)

The SEI was calculated as shown in Eq. (3):

$$SEI = \frac{P_{in;elect} \cdot t}{m_{sample}} \quad (3)$$

where the SEI is the specific energy input [kJ kg^{-1}], m_{sample} is the initial mass of sludge (kg), t is the exposure time [s], and $P_{in;elect}$ is the input power consumed by the system during the drying process [kW].

2.5.4. Energy efficiency (μ_{en})

The μ_{en} is the ratio between the theoretical energy demand for evaporating the water and the energy consumed by the MW unit during the drying process, the calculation for which is shown in Eq. (4) (Jafari et al., 2018):

$$\mu_{en} = \frac{(m_{sample} \cdot c_p \cdot \Delta T) + (m_{eva} \cdot h_{fg})}{P_{in;elect} \cdot t} \cdot 100 \quad (4)$$

where μ_{en} is the energy efficiency [%], c_p is the specific heat capacity of the water [$\text{kJ kg}^{-1} \text{ } ^\circ\text{C}^{-1}$], ΔT is the temperature difference of the sample between the exposure time t and the start of the treatment, and h_{fg} is the latent heat of the water [kJ kg^{-1}] (2257 kJ kg^{-1} at $100 \text{ } ^\circ\text{C}$ as reported by Haque (1999)). The temperature of the samples was not measured; as such, the influence of sensible heat on total energy efficiency was considered assuming the sludge sample reached a temperature of $100 \text{ } ^\circ\text{C}$ before water evaporation took place.

2.5.5. MW generation efficiency (μ_{gen})

The μ_{gen} is defined as the ratio between the MW energy output and the MW energy input, the calculation for which is shown in Eq. (5) (Lakshmi et al., 2007):

$$\mu_{gen} = \frac{P_{out,micr} \cdot t}{P_{in;elect} \cdot t} \cdot 100 \quad (5)$$

2.5.6. Sludge moisture content (X)

The X was calculated as shown in Eq. (6) (Chen et al., 2014):

$$X = \frac{m_{sample} - m_d}{m_d} \quad (6)$$

where X is the moisture content of the sludge [$\text{kg of water per kg of dry solid}^{-1}$] and m_d is the total mass of dry solids in the sample [kg]. The total mass of dry solids in the samples was determined as the DS of the

raw C-WAS sludge sample, as described in Section 2.2.1. The m_{sample} was continuously determined by the point load cell located in the MW irradiation cavity, as described in Section 2.3. Therefore, X was continuously measured.

2.5.7. Drying rate (D_R)

The D_R was calculated as shown in Eq. (7) (Chen et al., 2014):

$$D_R = \frac{dX}{dt} \quad (7)$$

where D_R is the drying rate [$\text{kg of water per kg of dry solid}^{-1} \text{ min}^{-1}$] and X is the moisture content of the sludge at a specific exposure time. The drying rates were determined by polynomial regression analysis using Microsoft Excel and considered at time intervals of 30 s.

2.5.8. Power absorption density

According to Gupta and Leong (2007) and Stuerger (2006), the power absorption density (i.e., the amount of power absorbed by a material per unit of volume) (P_d) is proportional to the input power, which relates to the electric field intensity (E), as shown in Eq. (8):

$$P_d = 2\pi f \epsilon_0 \epsilon' |E|^2 \quad (8)$$

where P_d is the amount of absorbed power per unit volume [Wm^{-3}], f is the microwave frequency [s^{-1}], ϵ_0 is the permittivity of free space [$8.85 \times 10^{-12} \text{ fm}^{-1}$] and E is the electric field intensity [Vm^{-1}]. The electric field intensity can be calculated as described in Eq. (9) (Pitchai et al., 2012; Soltysiak et al., 2008).

$$E = \sqrt{\frac{2P_{out,micr}}{1 - |S_{11}|^2}} \quad (9)$$

where S_{11} is the reflection coefficient associated with the fraction of the power reflected by the sample.

3. Results and discussion

The effects of the different MW output powers on the drying performance of the C-WAS sludge were assessed and are presented in this section. The drying performance was evaluated by observing the effects of the MW output powers on exposure times, drying rates, specific energy consumption, drying energy efficiencies, and the overall energy efficiencies of the MW system.

Table 2
Physical-chemical characteristics of the raw C-WAS.

Parameter	Unit	Value
Total solids (dry solids)	[%]	17 ± 1
Moisture content	[%]	83 ± 1
Volatile solids ^a	[%]	88 ± 2
C ^a	[%]	46.5
H ^a	[%]	5
N ^a	[%]	9.9
S ^a	[%]	1.5
Gross calorific value ^a	[MJ kg ⁻¹]	18.4

^a Dry basis.

3.1. Sludge physical-chemical properties

The raw C-WAS evaluated in this research exhibited the physical-chemical characteristics as presented in Table 2 below.

The sludge was generated by a sequencing batch reactor treatment process at a WWTP in Slovenia that receives domestic and industrial wastewater. Such sludge has a 2% DS concentration. The sludge is dewatered by centrifuges up to a DS concentration of approximately 17% (83% moisture content), as described in Table 2. The waste from several food processing facilities (mostly poultry slaughterhouses) discharge waste into the Ptuj WWTP, which explains the high organic content of its sludge (i.e., 88% volatile solids). The final DS concentration of 17% achieved by the centrifuges is in accordance with conventional DS concentration values between 13 and 21% (87 to 79% moisture content) reported in the literature for municipal sludge dewatering (Léonard et al., 2004; Mawoo et al., 2017). The gross calorific value of the sludge, as well as the elemental C, H, N, and S content, define the inherent energy content of the sludge, as well as the air pollution potential if the sludge is combusted. The dried sludge in this research exhibited a gross calorific value of 18.4 MJ kg⁻¹ of DS. Such calorific value is in accordance with the calorific values of approximately 19 MJ kg⁻¹ previously reported for dried sludge (Chen et al., 2014; Mawoo et al., 2017), as well as with calorific values for wood species such as birch, sapwood, and maple with calorific values ranging from 17.9 to 18.5 MJ kg⁻¹ (Günther et al., 2012). The relatively high calorific value reported in this research was in accordance with the high elemental C content observed in the dried sludge of 46.5% (Table 2), also reported by Akdağ et al. (2018). The elemental composition of H, N, and S represented 5, 9.9, and 1.5% of the dried sludge, respectively (Table 2). Akdağ et al. (2018) reported similar findings related to the elemental H, N, and S concentrations of 3 to 5.3%, 1.88 to 7.7%, and 0.55 to 1.79%, respectively. The elemental N and S content on the dried sludge influences the formation of sludge combustion gases such as NO_x and SO_x, which are harmful air pollutants. Thus, the sludge exhibited a high energetic value that can potentially be recovered as a source of energy.

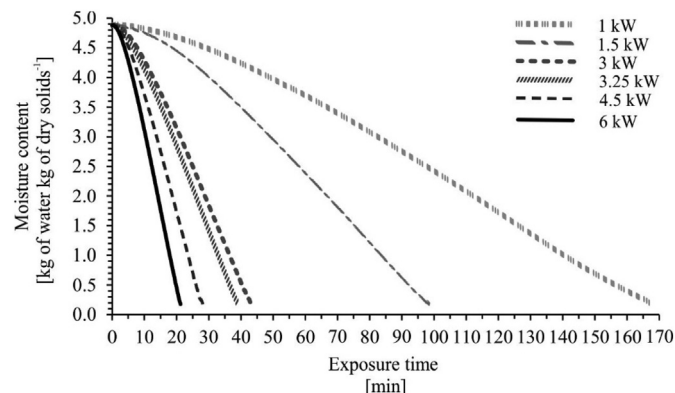


Fig. 2. Effect of the MW output power on sludge drying as a function of the exposure time.

Nonetheless, the generation of combustion gases with the potential to contribute to air pollution should be closely monitored.

3.2. Drying rates and exposure times

Fig. 2 illustrates the sludge exposure time required to reduce the sludge moisture content from 4.88 to 0.18 kg of water per 1 kg of dry solids⁻¹ (i.e., from 17% to 85% DS content) at the evaluated MW output powers. The required exposure time decreased as the MW output power increased.

The sludge drying rates were also calculated at each of the evaluated output powers and are presented in Fig. 3 as a function of the exposure time. The sludge drying rates consistently increased with the MW output power across the evaluated range. As the MW output power increased from 1 to 6 kW, the maximum average sludge drying rates increased from 0.03 to 0.28 kg of water per 1 kg of dry solids⁻¹ min⁻¹. Comparable sludge drying rates were reported in the literature on laboratory/bench-scale MW systems; however, the literature showed much lower sludge drying rates for pilot-scale MW systems. Bennamoun et al. (2016) and Chen et al. (2014) reported sludge drying rates of between 0.17 and 0.40 kg of water per 1 kg of dry

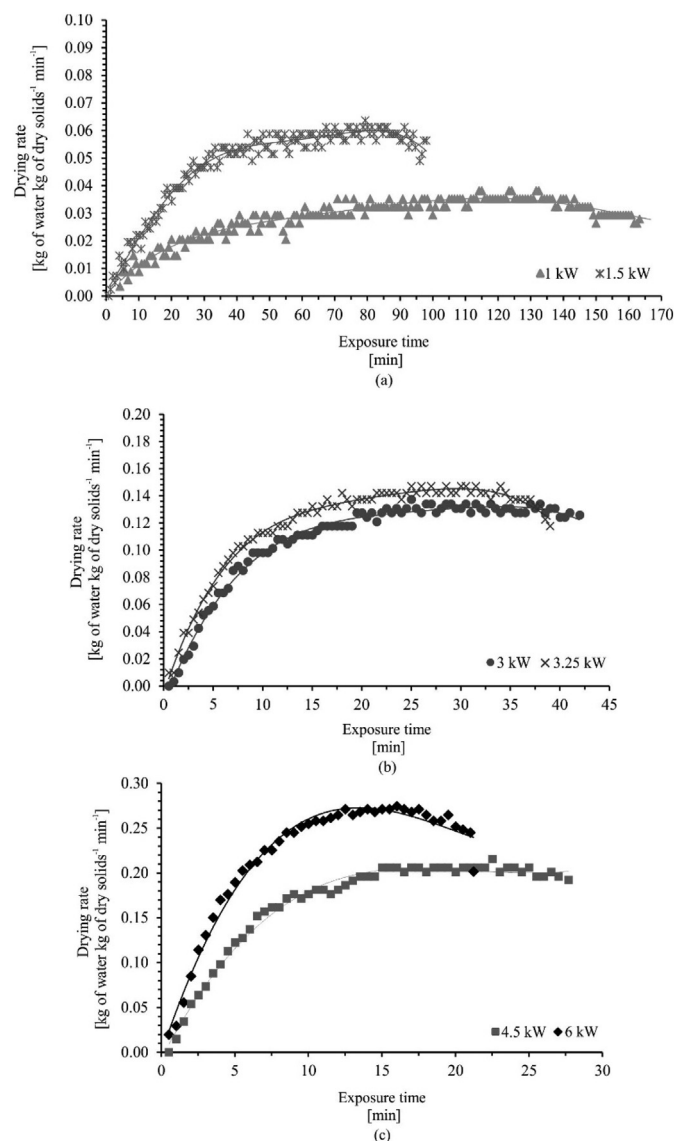


Fig. 3. Effect of MW output power on the drying rate as a function of exposure time at MW output power of (a) 1 and 1.5 kW (b) 3 and 3.25 kW and (c) 4.5 and 6 kW.

solids⁻¹ min⁻¹ for a laboratory-scale MW system, whereas Mawioo et al. (2017) reported sludge drying rates of between 0.01 and 0.04 kg of water per 1 kg of dry solids⁻¹ min⁻¹ for a pilot-scale MW system.

Further, the sludge drying rates can be presented as a function of the sludge moisture content, as shown in Fig. 4. Such plots (Krischer's plot) are commonly used to represent the drying process since they indicate the direct relation between the drying rates and the amount of water still present in the material. The abscissa in Fig. 4 follows the opposite direction to the abscissa in Fig. 3. That is, the higher the moisture content of the sludge, the lower the irradiation exposure time.

The changes in the sludge drying rates as a function of both the exposure time (Fig. 3) and sludge moisture content (Fig. 4) denote three main phases related to the drying process: (i) a drying rate adaptation period, (ii) a constant rate drying period, and (iii) a falling rate drying period. At the beginning of the adaptation period, the electromagnetic energy absorbed by the sludge resulted in a temperature increase with a subsequent increase of the sludge drying rate. The drying rate adaptation period is presented as a steep curve on the left-side and right-side of Figs. 3 and 4, respectively. The rapid increase in the sludge drying rate lasted for approximately $34 \pm 1\%$ of the exposure time at all the evaluated MW powers (Fig. 3) up to a sludge moisture content of approximately 3.8 kg of water per 1 kg of dry solids⁻¹ or 21% DS (Fig. 4). After the adaptation period, the sludge drying rate remained largely constant until almost the end of the drying process. The constant rate drying period is associated with the removal of water molecules from the surface of the sludge. This water fraction is commonly described as unbound water or free water (Kopp and Dichtl, 2000). As a result, the evaporation of the water molecules located at the surface of the sludge (free water) determines the drying mechanism (and drying rates) during the constant rate drying period. The constant rate drying period lasts for as long as the rate at which the water molecules continue to be transported from the inside of the sludge to the surface of the sludge equals the rate at which the water molecules are evaporated from the surface of the sludge (Mawioo et al., 2017). The MW radiation of sludge resulted in a prolonged constant rate drying period as a function of the moisture content, an observation that has previously been reported by Bennamoun et al. (2016) and Chen et al. (2014) on the MW drying of sludge. The third drying rate period (i.e., the falling rate drying period) can be observed in Figs. 3 and 4 and was most notable when the sludge was irradiated at the higher power outputs above 3 kW. The falling rate drying period was less evident at the lower power outputs of 1 and 1.5 kW. Similar falling rate drying periods during the MW irradiation of sludge have been reported by Bennamoun et al. (2016) and Chen et al. (2014). The authors observed that falling rate drying periods began when the sludge moisture content dropped to 0.7 kg of water per 1 kg of dry solids⁻¹ min⁻¹ and below. This falling rate drying period

indicates that the surface of the sludge is no longer completely wet in that the rate at which the water molecules were being transported from the inside of the sludge to the surface of the sludge decreased to below the rate at which the water molecules were being evaporated from the surface of the sludge (Berk, 2018). Therefore, the sludge drying rate decreased at the end of the exposure time. Removing water during the falling rate drying period thus consumes more energy than removing water during the constant rate drying period.

In conventional thermal drying systems involving the use of heated air, steam, or flue gas, the heat transfer mechanism occurs by means of convection and conduction. Thus, the drying process is mostly determined by the water transport mechanisms inside the material to be dried (Léonard et al., 2005; Li et al., 2016; Tao et al., 2005). Léonard et al. (2005) examined the convective thermal drying (hot air at 120 °C) of dewatered municipal sludge. The authors reported the presence of a drying rate adaptation period, a constant rate drying period, and a falling rate drying period, yet, the duration of the constant rate drying period was so short that it was indistinguishable during the overall drying process. Tao et al. (2005) and Li et al. (2016) reported similar findings when drying dewatered sludge by means of thermal convective dryers. The authors observed only two phases: the drying rate adaptation period followed by a falling rate drying period. Therefore, it can be inferred that the removal of water during thermal convective drying is governed by an internal water diffusion mechanism (i.e., the mechanism involved in the transport of water molecules from the inside of the material to the surface of the material). External heat needs to penetrate the material (which usually exhibits a low thermal conductivity) to reach the drying front; then, the evaporated water needs to move to the surface of the material through the pores that have been reduced in size due to the same drying effect. Such drying mechanisms are characterised by low drying rates and, thus, long drying exposure times. As reported here and by Bennamoun et al. (2016), MW irradiation extends the constant rate drying period with the falling rate drying period only noticeable at the very end of the drying exposure time.

According to studies by Ni et al. (1999) and Fu et al. (2017) on the MW drying of various materials, the removal of surface water (free water) in the constant rate drying period is attributed to an inverted drying temperature profile with a corresponding increase in the internal pressure gradient. That is, when the material is subjected to MW radiation, the MWs penetrate the material and generate heat from inside the material thereby creating a temperature gradient between the inside of the material (high temperature) and the surrounding environment (low temperature) (i.e., an inverted temperature profile as described by Shepherd et al. (2018)). The high temperature at the core of the irradiated material leads to water evaporation at the core of the material. This, in turn, generates a pressure gradient within the material, driving the water molecules towards the surface of the material (Fu et al., 2017; Ni et al., 1999). Having more of this free water available at the surface of the material results in more free water being evaporated from the surface of the material, suggesting higher sludge drying rates with shorter exposure times and lower energy consumption compared with conventional thermal dryers. These findings are supported by research carried out by Kumar et al. (2016) on the effects of MW irradiation on sliced apples. The authors determined that the vapour pressure was highest in the core of the material and gradually decreased towards the surface of the material. Due to the presence of this vapour pressure gradient, the water molecules can flow from the inside of the material to the surface of the material at a rate approximately 10 times higher than that reported when drying the same material using a thermal convective dryer. Moreover, such penetrative features of the MW radiation and the molecular excitation caused by MWs could contribute to release water retained both in the complex network of extra cellular polymeric substances and inside of the cell's internal structure and cell membrane (Khan et al., 2018; Pino-Jelcic et al., 2006; Rao et al., 2019; Yu et al., 2010). Therefore, MW radiation increases the amount of surface (free) water available for evaporation thus promoting the occurrence of

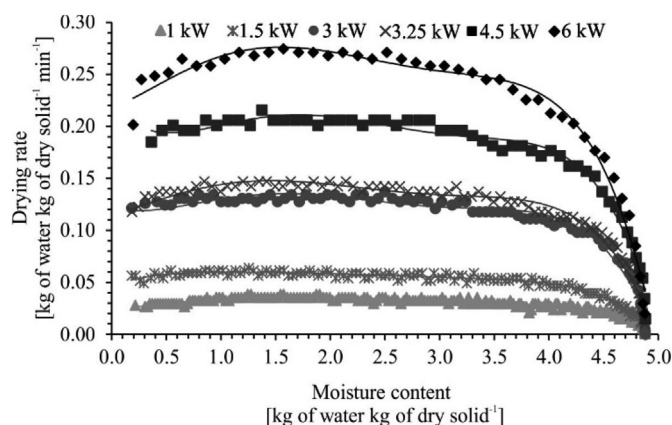


Fig. 4. Effect of MW output power on the drying rate as a function of sludge moisture content.

extended constant rate drying periods, as illustrated in Figs. 3 and 4. Noticeably, the MW treatment enhances the rate at which the water leaves the material to be dried exceeding by far the amount of water that can be transferred to the air by just conventional air drying. In case the air flowrate provided by either an axial ventilator or by any other auxiliary equipment is not large enough (or not provided at all) condensation may occur in the dried material leading to a rewetting of the surface; thus, leading to an increase in the SEC (Fennell and Boldor, 2014; Fennell et al., 2015; Mawoo et al., 2017). Effective removal of water/vapour may be incorporated into such systems by providing a stream of air over the surface of the material under drying as it was the case in this study (Fennell and Boldor, 2014; Fennell et al., 2015). The presence of extended constant rate drying periods has a positive effect on sludge drying since the exposure time (energy) required to remove free water from the material is much lower than the exposure time (energy) required to remove internal water. This unique feature of the MW drying process thus has the potential to provide a remarkable competitive advantage with respect to thermal drying systems given that thermal drying systems require long and energy-intensive exposure times to remove internal water (Mujumdar, 2014; Ohm et al., 2009).

3.3. Specific energy output

To evaluate the specific effects of the different MW output powers on the drying rate of the sludge, the sludge drying rates were reported at the same specific energy output (i.e., the energy delivered by the system per mass of sludge sample) as illustrated in Eq. (2) for all the evaluated output powers. That is, the sludge drying rates were calculated at a specific energy output (SEO) of 2 MJ kg^{-1} of sludge for all the evaluated output powers (from 1 to 6 kW). The results are described in Fig. 5. The sludge drying rates at each evaluated power output were calculated as in the following example. When working at an output power of 1 kW, after an exposure time of 100 min (1.21 h), an energy output of 1.66 kWh (6 MJ) was delivered. The initial mass of the sludge was 3 kg. Dividing the energy output by the initial mass of sludge, a SEO of 2 MJ kg^{-1} of sludge was obtained. At an output power of 1 kW and after 100 min of drying, moisture content of 2.4 kg of water per 1 kg of dry solids⁻¹ (29% DS) and a sludge drying rate of 0.03 kg of water per 1 kg of dry solids⁻¹ min⁻¹ were obtained, as illustrated in Figs. 2 and 3, respectively. The same calculations were conducted for all the evaluated MW output powers and the results are presented in Fig. 5. The sludge drying rate increased linearly with the increase of the MW output power. Further, the higher the output power, the higher the DS content. Hence, the MW sludge drying process is governed by the rate at which energy is delivered to the sludge rather than by the SEO. The

treatment of the sludge at higher MW output powers (at the same energy output) resulted in faster drying (lower exposure time), increasing the throughput potential capacity of the system. The faster drying is a result of both the MW system delivering more energy per unit of time (higher MW output power) and the sludge absorbing more energy per unit of time and unit of volume (higher sludge power absorption density).

The sludge power absorption density is described by Eq. (8). According to Eq. (8), the power absorption density depends on the dielectric properties of the irradiated material, the electric field intensity (i.e., MW power output), the frequency of the MW, and the sample volume. The MW frequency, the initial volume/mass of the sludge, the type of material (sludge), the initial sludge moisture content, and the dielectric properties at the beginning of the experiment were constant throughout the six experimental conditions evaluated. However, the MW output power was increased from 1 to 6 kW with a resulting increase of the electric field intensity, as indicated in the empirical formula described in Eq. (9). The increase in the electric field intensity resulted in an increase in the sludge power absorption density, as described by Eq. (8). Therefore, increasing the rate at which energy is delivered to the sludge (i.e., increasing the MW output power) resulted in an increase in the capacity of the sludge sample to absorb more energy per unit of time and per unit of volume (i.e., a higher power absorption density), resulting in higher sludge drying rates, as reported in Fig. 5. The higher the rate at which the energy is absorbed by the sludge (i.e., the higher the power absorption density), the lower the likelihood that the MW radiation (MW energy) will be reflected towards the dummy water load or absorbed somewhere else in the system. Similar findings have been reported by Robinson et al. (2007) who found a relation between the energy efficiency of the MW drying system and the rate at which the energy was delivered to the irradiated material (biodegradable wastes) rather than the SEO.

Similar findings can be observed when looking at the SEO as a function of the moisture content, as described in Fig. 6a. Lower SEO values were reported at the higher MW output powers. In other words, less energy was demanded by the MW system to achieve the same drying results when working at the higher output powers. This lower energy demand could be explained by the higher power absorption density experienced by the sludge at the higher output powers minimising the opportunities for the MW energy to be reflected towards the dummy water load or absorbed somewhere else in the system.

Additionally, similar drying phases as those presented in Fig. 4 can be identified when observing the changes in the SEO as a function of the moisture content. A drying rate adaptation period is observed at the right-side of Fig. 6a and corresponds to the start of the drying process. The pronounced slope at the beginning of the drying process represents a high SEO per unit of evaporated water. In this drying rate adaptation period, most of the energy was utilised to raise the temperature of the sludge resulting in severely limited water evaporation. After reaching a moisture content of 3.8 kg of water per 1 kg of dry solids⁻¹ (21% DS), a constant rate drying period was observed, as reflected by the consistent slope in Fig. 6a. This slope indicates a constant SEO per unit of evaporated water lower than that observed in the drying rate adaptation period. As explained in Section 3.2, the constant rate drying period is related to the removal of the sludge's free (unbound) water, which requires relatively little energy to be removed from the sludge. This low energy demand explains the lower slope in Fig. 6a, representing lower energy consumption per unit of evaporated water compared with the drying rate adaptation period. Finally, the falling rate drying period, as described in Fig. 4, was not noticeable in Fig. 6a. This is likely due to the short duration of this phase, as observed in Fig. 4, and the fact that it is only noticeable at evaluated output powers.

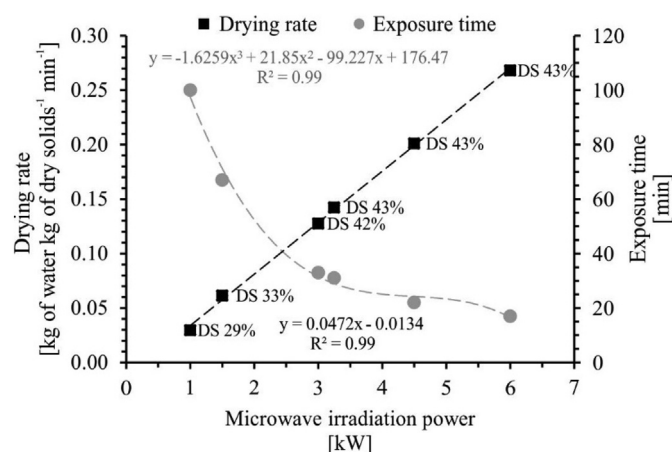


Fig. 5. Drying rate and exposure time as a function of the MW output power at a specific energy output of 2 MJ.

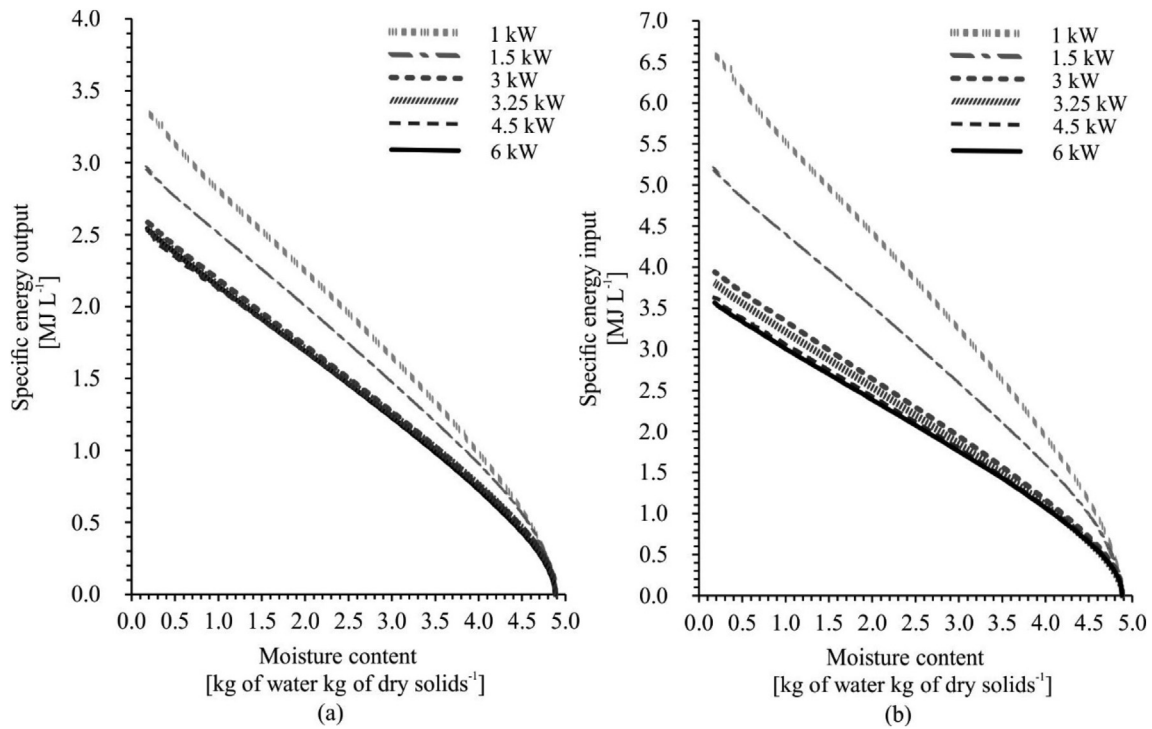


Fig. 6. (a) SEO and (b) SEI as a function of the moisture content.

3.4. MW generation efficiency, energy efficiency, and specific energy consumption

The energy performance of the novel pilot-scale MW system was also evaluated by determining several indicators including MW generation efficiency, energy efficiency, and specific energy consumption.

3.4.1. MW generation efficiency

The energy consumed by the novel pilot-scale MW system was measured by a power analyser. The specific energy input (i.e., the energy consumed by the MW system per mass of sludge sample) as a function of the moisture content is presented in Fig. 6b. Fig. 6a also shows the energy delivered by the MW system as a function of the moisture content (i.e., the MW power output based on the manufacturer's information). Furthermore, Fig. 6b shows the energy consumed by the system (both by the MW power supply and the MW generator) as a function of the moisture content measured using a power network analyser. That is, the ratios between the energy delivered by the MW system (Fig. 6a) and the energy consumed by the MW system (Fig. 6b) at each of the evaluated powers represent the efficiency of the MW generator (μ_{gen}). These ratios remained constant throughout the drying period and are presented in Fig. 7 as MW generation efficiency as a function of the output power. In other words, the efficiency of the electrical energy conversion into electromagnetic energy was evaluated for each output power tested (Eq. (5)).

For instance, at a MW output power of 1 kW, MW input power of 2 kW was drawn from the power source resulting in MW generation efficiency of 50%. However, as the MW power output increased to 3 kW, MW generation efficiency rose to 70%. Notably, at MW power outputs of above 3 kW, the increase in MW generation efficiency was less pronounced, averaging approximately $70 \pm 1.8\%$. Operating the MW system at the maximum MW output power resulted in the highest MW energy efficiency. Therefore, the optimal performance of the MW generator was obtained when operating the system at the maximum MW power output of 6 kW.

3.4.2. Energy efficiency

Energy efficiency (μ_{en}) is represented as the ratio between the theoretical energy demand for the evaporation of the water and the actual energy consumed by the MW unit (Eq. (4)). Fig. 8 shows the energy efficiency for the sludge drying as a function of the moisture content at the evaluated output powers. Overall, energy efficiency increased as the output power increased. Moreover, the same drying phases as described in Figs. 4 and 6 were observed. At the beginning of the drying process (right-side of Fig. 8) and up to a moisture content of $3.8 \text{ kg of water per } 1 \text{ kg of dry solids}^{-1}$ (i.e., 21% DS), a drying rate adaptation period can be seen. This phase represents a high energy demand per unit of evaporated water since most of the energy was utilised to increase the temperature of the sludge with limited water removal. Thus, the lowest energy efficiency of the evaluated drying process was reported during this period. At the end of the drying rate adaptation period, the energy efficiencies ranged between 36 and 66% for output powers of 1 and

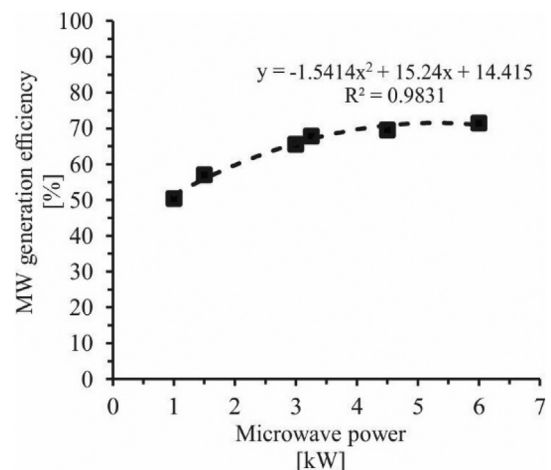


Fig. 7. MW generation efficiency as a function of the MW output power.

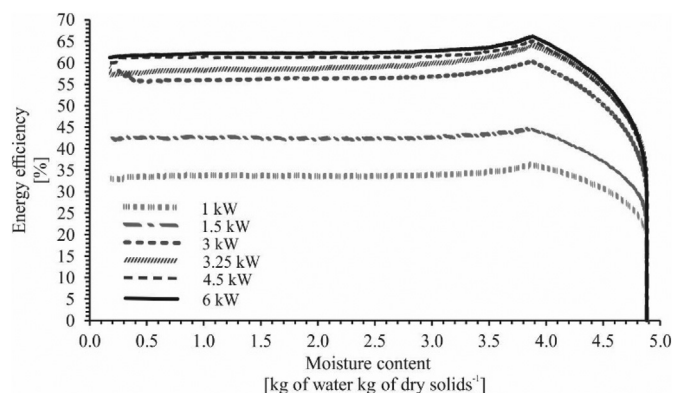


Fig. 8. Effect of MW output power on the energy efficiency as a function of sludge moisture content.

6 kW, respectively. After reaching 3.8 kg of water per 1 kg of dry solids⁻¹ moisture content, a constant rate drying period was observed. This period was characterised by a constant energy consumption per unit of evaporated water of the drying process. Therefore, a negligible change in energy efficiency was observed in this phase at all the evaluated output powers with energy efficiencies ranging from 33 and 62% found at output powers of 1 and 6 kW, respectively. That is, removing the sludge's free (unbound) water demanded less energy per unit of evaporated water, as reflected in the energy efficiency. The final falling

rate drying period, as illustrated in Fig. 4, was not noticeable when reporting the energy efficiency as a function of the moisture content.

The energy efficiencies were determined considering the amount of energy drawn from the power source and not the actual energy delivered when irradiating the sludge. Therefore, the energy efficiencies reported in Fig. 8 were directly affected by the MW generation efficiency (or inefficiency), as described in Fig. 7. Taking a MW generation efficiency of 100%, the maximum energy efficiencies previously reported at the constant rate drying periods would increase to 66 to 89% (from 33 to 62%, respectively) at the evaluated output powers of 1 and 6 kW, respectively. Even at 100% MW energy generation efficiency, a considerable amount of energy is still dissipated in the MW system. Eliminating the energy inefficiencies introduced by MW energy generation contributed significantly to the increase of the energy efficiency of the overall MW system. Nonetheless, there are still other major elements that contribute considerably to energy losses in the MW system.

As discussed in Section 3.3, the higher the output power, the higher the rate at which the sludge absorbs the MW energy and thus the lower the amount of MW energy that will be dissipated into the system. The MW energy not absorbed by the irradiated material can be reflected to the MW generator and/or escape the system with the extracted vapour. Therefore, the power absorption density capacity of the material can be directly linked to the MW energy losses (and related energy inefficiencies). Such findings are in agreement with studies carried out on the MW drying of various types of materials (Alibas, 2007; Wang et al., 2009). The authors reported that an increase in the MW power output, and thus in the power absorption per unit of the sample, was

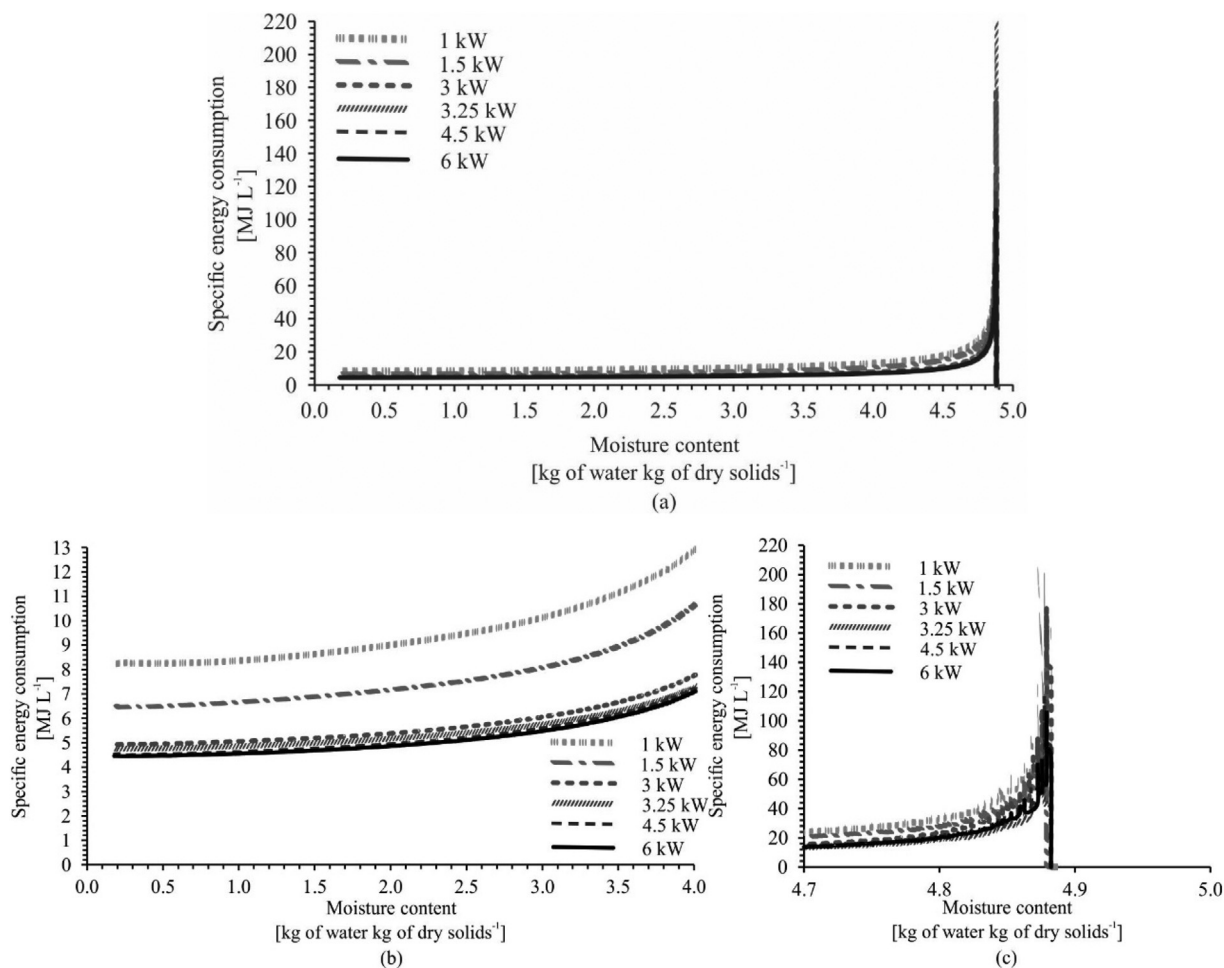


Fig. 9. Effect of MW output power on the specific energy consumption as a function of sludge moisture content (a) from 0 to 5 kg water kg dry solid⁻¹, (b) from 0 to 4 kg water kg dry solid⁻¹, and (c) from 4.7 to 5 kg water kg dry solid⁻¹.

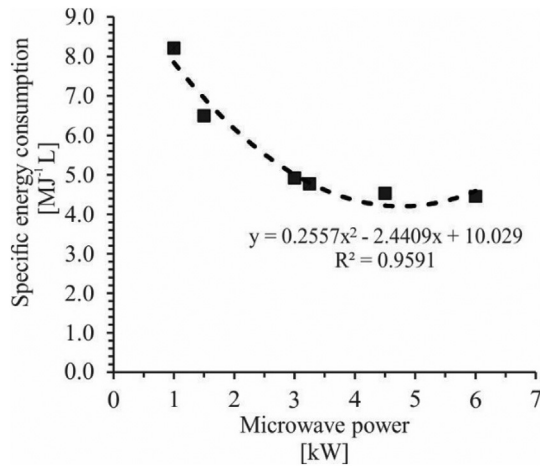


Fig. 10. Effect of MW output power on the SEC.

followed by an increase in energy efficiency (a reduction in MW energy reflection). Leiker and Adamska (2004), evaluated the energy efficiency of a MW system for drying wood. The evaluation was carried out by continuously measuring both the MW output power and the reflected power. The authors found that more than 80% of the MW energy was absorbed by the irradiated sample (beech wood), while the remaining 20% of the MW energy was reflected. Thus, energy efficiency as high as 80% was reported (Leiker and Adamska, 2004). These findings are consistent with Swain et al. (2006) who reported a 20% decrease in MW output power after operating a domestic MW appliance continuously for 5 min. In conclusion, the power (energy) supplied by the MW system can be: (i) absorbed by the irradiated material, (ii) returned to the MW generator as reflected power, or (iii) dissipated by being both partially absorbed into the MW cavity and lost with the vapour/condensate (Mawioo et al., 2017). Thus, MW energy losses in the form of reflected power and dissipation into the MW system can explain the energy inefficiencies observed in this research when reporting the MW system energy efficiency (μ_{en}). The higher the output power, the higher the sludge power absorption density, so the lower the chances for MW energy losses.

Moreover, in this research, the MW output powers were not quantified. Rather, these values were based on the manufacturer's ratings and settings. Accordingly, the MW power output could be lower than specified by the manufacturer, leading to an overestimation of the MW

output power, MW generation efficiency, and energy efficiency. Jang et al. (2011) reported a drop in MW generation efficiency of 20% when reducing the nominal MW output power from 30 to 10 kW.

3.4.3. Specific energy consumption

The energy performance of the MW unit was also evaluated by determining the specific energy consumption (SEC). The SEC, as described in Eq. (1), is defined as the energy consumed by the MW system (measured by the power network analyser at a particular period) to remove 1 L of water from the sludge. The SEC is commonly used to evaluate and compare the energy performance of different types of dryer systems (Kudra, 2012). This parameter (energy) provides an indication of the operational costs of the system. Fig. 9a presents the SEC as a function of the sludge moisture content for the entire sludge drying range at the evaluated output powers. At the beginning of the drying process (right-side of Fig. 9a and highlighted in Fig. 9c), very high SEC values were reported. This corresponds with the very beginning of the drying process during the adaptation drying period when almost no water is evaporated. Consequently, the denominator on the SEC equation (Eq. (1)) tends to zero, resulting in high SEC values (Fig. 9c). The lowest SEC values of approximately 4.5 to 8.5 MJ L⁻¹ of water (1.25 to 2.36 kWh L⁻¹) were reported at output powers of 1 to 6 kW, respectively (Fig. 9b). As previously discussed, the higher the output power, the higher the energy efficiency and thus the lower the SEC. Moreover, below the moisture content level of 3.8 kg of water per 1 kg of dry solids⁻¹, there is a transition from the adaptation drying period to the constant rate drying period. As previously explained, less energy is required during the constant rate drying period demand than the drying rate adaptation period. Therefore, lower SEC values were reported as the drying process progressed (and moisture content reduced).

Fig. 10 describes the overall SEC when drying the sludge with an initial moisture content of 4.88 to final moisture content of 0.18 kg of water per 1 kg of dry solids⁻¹ (i.e., from 17% to 85% DS) as a function of the output power. For instance, a SEC of 8.2 MJ L⁻¹ of water (2.3 kWh L⁻¹ of water) was obtained when operating the MW system at an output power of 1 kW. Above an output power of 3 kW, much lower SEC values were reported at 4.6 ± 0.16 MJ L⁻¹ of water (1.3 ± 0.05 kWh L⁻¹ of water). As previously explained, the higher the power output, the higher the energy efficiency of the system and thus the lower the SEC.

Fig. 11 shows the SEC for different types of thermal driers (convective and conductive) and MW drying systems. The SEC values reported for the MW drying system evaluated in this study were slightly higher

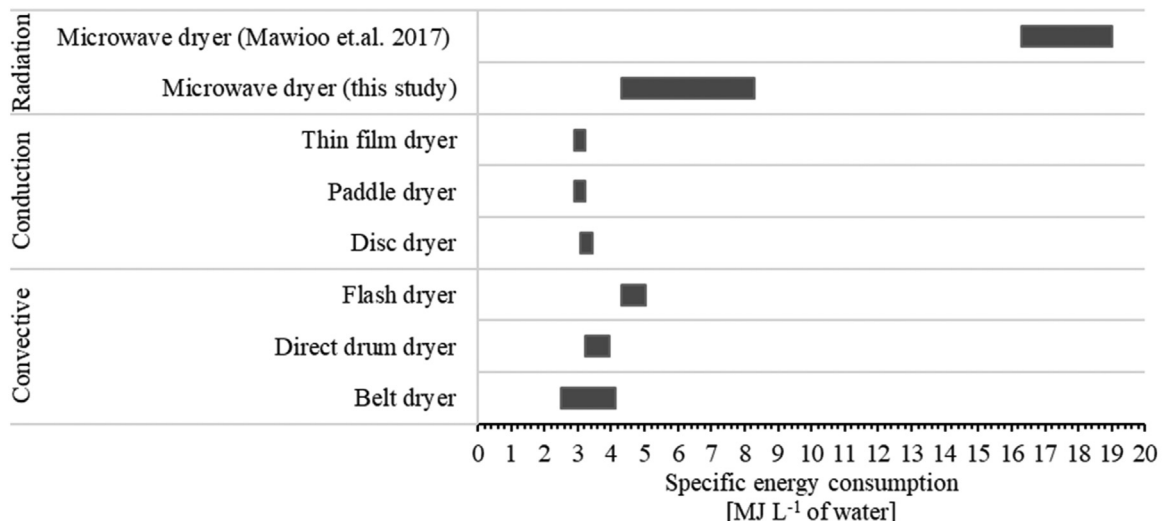


Fig. 11. Specific energy consumption (SEC) of different types of dryers (Léonard et al., 2011).

than for thermal driers; however, the SEC values reported in this study were much lower than those reported in the MW pilot-scale study carried out by Mawioo et al. (2017). Therefore, the modifications and innovations introduced in this research mitigated the design difficulties experienced by Mawioo et al. (2017) and can be summarised as follows. Firstly, the selective heating of the irradiated material could be one of the most effective ways of reducing the energy losses associated with the heating of the surface of the cavity and/or other components of the system. The irradiation cavity was constructed from stainless steel, which is characterised by both high conductivity and a high dielectric loss factor and thus does not absorb MW energy (Gupta and Leong, 2007; Saltiel and Datta, 1999). Secondly, the provision of a proper vapour extraction system eliminated the in-cavity condensation of the evaporated water during the irradiation process, avoiding the simultaneous evaporation of the water and re-absorption of the condensate. Finally, the provision of a MW generator with a higher quoted MW conversion (generation) efficiency directly improved the overall energy efficiency of the MW system.

The reported SEC values incorporated the energy expenditure required to heat the sludge to a temperature at which water evaporation would occur. Theoretical energy demand of 0.38 MJ (0.1 kWh) was required to increase the temperature of 1 L of water from room temperature (approximately 10 °C) to 100 °C. The MW drying process produces approximately 0.82 kg vapour per kg of raw sludge⁻¹. Such vapour production contains more than enough energy to heat the sludge to the desired temperature. Furthermore, assuming a MW generation efficiency of approximately 60%, heating the sludge with the condensate could represent SEC savings of approximately 0.63 MJ (0.17 kWh) per L of evaporated water, reducing the overall SEC to approximately 3.9 MJ L⁻¹ (1.1 kWh L⁻¹) of water. Additionally, by utilising full-scale industrial MW generators, MW generation efficiencies can be increased by up to approximately 90% (Fricke und Mallah Microwave Technology GmbH). Therefore, assuming an average MW generation efficiency of 60% in this research, the SEC can be reduced even further to approximately 2.6 MJ L⁻¹ (0.74 kWh L⁻¹). As such, the SEC of the MW drying process is similar to the lower range of SEC found in convective (e.g., belt, direct drum and flash dryer) and conductive (e.g., disc, paddle, thin-film dryers) driers, the energy consumption of which ranges from 2.5 to 5.0 MJ L⁻¹ of water and 2.9 to 3.4 MJ L⁻¹ of water, respectively. Moreover, the MW drying process produces a final product (dried sludge) that has a high energetic content (i.e., calorific value) of approximately 18.4 MJ kg⁻¹ of DS, as indicated in Table 2. The energy content embedded in the final product could produce more energy than the energy required to dry the sludge using MWs.

The results presented and discussed in this study considered the impact of the different MW power outputs on drying performance. As such, it would be desirable to further explore the performance of the MW drying system when other key MW drying features are modified such as the thickness of the sludge in the MW irradiation cavity and the mass to MW output power ratio.

4. Conclusions

- The MW sludge drying process extended the duration of the constant rate drying period with consequent high drying rates, short exposure times, lower energy consumption, and high throughput capacity.
- The MW drying performance is governed by the rate at which energy is absorbed by the sludge as heat rather than by the specific energy output. High MW output powers caused high sludge power absorption densities, resulting in increased drying rates and reduced exposure times, increasing the throughput capacity of the system. In other words, less energy was required by the MW system to achieve the same drying results when working at the higher output powers.
- Operating the MW system at the maximum MW output power resulted in the highest MW generation efficiency (i.e., the efficiency of the electrical energy conversion into electromagnetic energy).

- MW energy efficiency increased as the output power increased. Energy losses in the form of reflected power and power that dissipates into the MW system can explain the energy inefficiencies reported. The higher the output power, the higher the sludge power absorption density, so the lower the likelihood of such MW energy losses.
- Similar SEC values were obtained for the MW drying process as for conventional thermal convective and conductive dryers. These results indicate that MW technology is successful at efficiently reducing the sludge moisture content. In addition, MW drying technology may introduce logistic advantages lowering the costs related to sludge transport, handling, and storage.

CRediT authorship contribution statement

Eva Kocbek: Methodology, Validation, Formal analysis, Investigation, Visualization, Writing - original draft. **Hector A. Garcia:** Supervision, Visualization, Writing - review & editing, Project administration. **Christine M. Hooijmans:** Supervision, Writing - review & editing. **Ivan Mijatović:** Conceptualization, Supervision. **Branko Lah:** Investigation, Resources. **Damir Brdjanovic:** Conceptualization, Supervision, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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