Desalination and Water Treatment
www.deswater.com

doi: 10.5004/dwt.2023.29213

283 (2023) 299–307
January

Particle size obtained via pre-dispersion and its influence on sludge ultrasonic disintegration

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Received 12 January 2022; Accepted 9 December 2022

ABSTRACT

Wastewater treatment generates large amounts of sludge, requiring the implementation of techniques reducing the volume of excess sludge and its impact on the environment. Disintegration of the excess sludge is a pre-treatment process aimed at improving the anaerobic digestion of the sludge. Its main objective is the dispersion of sludge flocks and the lysis of microbial cells. Ultrasonic (US) preconditioning is one of the most widespread mechanical disintegration methods, and mechanical mixing of the sludge before ultrasonic treatment can effectively enhance the US effects. We examined the connection of the particle size of sludge (after homogenization) and the release of the intracellular material, monitored as cell lysis indicator kd_{SCOD}, after the application of ultrasound. Pre-homogenization of the excess sludge (at three different mixing times, 60, 120, and 180 s) was used to mix the sludge thoroughly and reduce the particle size of the sludge before ultrasonic treatment. Particle size measurement via light scattering allows for the precise determination of particle size distribution. Homogenization (pre-dispersion) before US at E_V 5.7 Wh·L^{-1} led to an increase in the kd_{FCOD} dispersion indicators from 1.89 (without mixing) to 3.33, 3.75, and 4.08 for three mentioned above mixing times, respectively, and an increase in the cell lysis indicator kd_{SCOD} from 1.33 to 1.65, 1.85, and 1.96, respectively. Our results confirm the connection between the size of the sludge flocs before US conditioning and the disintegration effects as well as the increase in the energy efficiency of the US disintegration.

Keywords: Ultrasonic disintegration; Volumetric energy; Excess sludge; Particle size; Laser diffraction

1. Introduction

Wastewater treatment constantly generates large amounts of sludge, including excess sludge produced in the activated sludge processes [1,2]. Such sludge frequently contains a wide variety of contaminants such as pathogens, complex organic substances, and heavy metals, among others [3], which, if not treated properly, can harm human and environmental health [3]. This requires the implementation of techniques reducing the amount of sewage sludge and its impact on the environment. Globally, sewage treatment plants implement various strategies of sludge disposal, of which the most widespread ones are sludge landfilling, composting, anaerobic and aerobic stabilization, drying, and application in agriculture [3]. The use of these specific strategies depends on the combination of technical, economical, and legal factors [3–5]. In large treatment plants, anaerobic stabilization is the most widely used sludge treatment process [6–8]. It not only stabilizes the sludge, improves its dewaterability, and greatly reduces its environmental and health hazard, but it provides also a source of renewable energy in the form of biogas. Since excess sewage sludge

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mainly consists of living bacterial material, it requires prolonged digestion, with long retention times in large digestion tanks [9]. Disintegration is a pre-treatment process aimed at improving the speed and effects of anaerobic sludge digestion; the main objectives of this approach are the dispersion of a complex sludge flock structure, the release of extracellular polymeric material, and the lysis of microbial cells, causing the release of easily digestible organic substances into the sludge liquid [6,9]. Ultrasonic (US) preconditioning is one of the most widespread mechanical disintegration methods [9–11].

Sludge sonication is based on cavitation; the passage of ultrasonic waves through sludge results in pressure variation and, subsequently, in the creation and collapse of micro-cavities, releasing large amounts of energy in a small volume of space [12]. Cavitation induced by ultrasonic waves is called "ultrasonic cavitation" [9,13], and the use of a low-frequency US field (20–40 kHz) is highly effective, both at laboratory and technical scale, for sewage sludge disintegration [13–15].

To characterize ultrasonic sludge conditioning, various energy and geometric parameters [12,16] are used:

$$I_{\mathrm{US}(E)} = P_{\mathrm{US}} A_E^{-1} \left[\mathrm{W} \cdot \mathrm{cm}^{-2}\right] \tag{1}$$

$$I_{\mathrm{US(CH)}} = P_{\mathrm{US}} A_{\mathrm{CH}}^{-1} \left[\mathrm{W} \cdot \mathrm{cm}^{-2}\right] \tag{2}$$

$$E_V = P_{\mathrm{US}} T_{\mathrm{US}} V_{\mathrm{CH}}^{-1} \left[\mathrm{kWh} \cdot \mathrm{m}^{-3}\right] \tag{3}$$

$$E_S = P_{\mathrm{US}} T_{\mathrm{US}} V_{\mathrm{CH}}^{-1}\ \mathrm{TS}^{-1} \left[\mathrm{kWh} \cdot \mathrm{kg}_{\mathrm{TS}}^{-1}\right] \tag{4}$$

$$\mathrm{PD}_{\mathrm{US}} = P_{\mathrm{US}} V_{\mathrm{CH}}^{-1} \left[\mathrm{kW} \cdot \mathrm{L}^{-1}\right] \tag{5}$$

where $I_{\mathrm{US(E)}}$ – intensity of the ultrasound field in relation to the surface area of the emitter; W·cm^{-2}, P_{US} – power of the emitter; W, A_E – surface area of the emitter; cm^2, $I_{\mathrm{US(CH)}}$ – intensity of the ultrasound field in relation to the surface area of the chamber; W·cm^{-2}, A_{CH} – surface area of the disintegration vessel; cm^2, T_{US} – sonication time; s, TS – total solids; kg·m^{-3}, V_{CH} – sludge volume; m^3, E_V – consumption of energy per unit volume (volumetric energy) corresponding numerically to the energy density W_{UP}, kWh·m^{-3}, E_S – consumption of energy per unit dry weight (total solids) of sludge, so-called "specific energy"; kWh·kg$_{\mathrm{TS}}^{-1}$, PD$_{\mathrm{US}}$ – power density; kW·L^{-1}.

The amount of energy required for effective sludge disintegration depends on the sludge characteristics, the design of the device, and its operation parameters [6]. According to Hogan et al. [16], the volumetric energy E_V of 80 kJ·L^{-1} is necessary for deagglomeration, whereas Carrère et al. [17] stated that the specific energy E_S required for cell lysis ranges from 1,000–16,000 kJ·kg$_{\mathrm{TS}}^{-1}$. Gogate and Patil [12], Hogan [16] and Zielewicz [18] reported that disintegration occurs for the volumetric energy 10–100 kWh·m^{-3}; however, for industrial application, energy levels closer to the lower threshold are more economically feasible.

The use of mechanical mixing before US sludge conditioning has been reported by Zielewicz et al. [18] and Skórkowski et al. [19] as a viable way of improving the effectiveness of US conditioning. The first stage of the sludge conditioning is mainly used for the destruction of aggregated sludge flocks, whereas in the second-stage, via ultrasonic disintegration, cell lysis and acidification occur. In a previous study, the use of a two-stage disintegration process (adding homogenization at a volumetric energy E_V = 62.50 Wh·L^{-1} before US at values of E_V = 20 Wh·L^{-1}) led to an increase in dispersion and cell lysis [19].

To assess the effects of sludge pre-treatment, indicators of the direct effects of disintegration are used. The disintegration degree proposed by Tiehm et al. [14] is calculated as a ratio of soluble chemical oxygen demand (SCOD) increase caused by the disintegration method in relation to the SCOD increase caused by chemical disintegration [14]. The degree of the disintegration indicator kd$_{\mathrm{DD}}$ is calculated using the following equation:

$$\mathrm{kd}_{\mathrm{DD}} = \frac{\left(\mathrm{SCOD}_{\mathrm{UT}} - \mathrm{SCOD}_{\mathrm{NT}}\right)}{\left(\mathrm{SCOD}_{\mathrm{NaOH}} - \mathrm{SCOD}_{\mathrm{NT}}\right)} \times 100\% \tag{6}$$

where kd$_{\mathrm{DD}}$ – disintegration degree, SCOD$_{\mathrm{UT}}$ – SCOD of disintegrated sludge supernatant; mg·L^{-1}, SCOD$_{\mathrm{NT}}$ – SCOD of untreated sludge supernatant; mg·L^{-1}, SCOD$_{\mathrm{NaOH}}$ – SCOD of chemically disintegrated sludge supernatant. Disintegration performed using 0.5 mol NaOH solution, 1:1 ratio, for 22 h; mg·L^{-1} [6,18].

The use of disintegration indicators (kd) as a mean of assessing the direct technological effects of sludge pre-treatment has been proposed by Zielewicz [6,9,18]. The effects of disintegration are evaluated based on the values of the following indicators (describing the ratio of substances after ($_{\mathrm{UT}}$) and before ($_{\mathrm{NT}}$) disintegration):

- Dispersion: kd$_{\mathrm{FCOD}}$ (indicating changes in FCOD – chemical oxygen demand of the filtered sludge supernatant (fraction below 3 µm); mg·L^{-1}), kd$_{\mathrm{CST}}$ (indicating changes in CST – capillary suction time; s);
- lysis: kd$_{\mathrm{SCOD}}$ (indicating changes in SCOD – chemical oxygen demand of soluble substances in supernatant (fraction below 0.45 µm); mg·L^{-1}), kd$_{\mathrm{TOC}}$ (indicating changes in TOC – total organic carbon of soluble substances in supernatant (fraction below 0.45 µm) caused by the release of cell content into the aqueous phase; mg·L^{-1});
- Acidification: kd$_{\mathrm{VFA}}$ (which describes the changes of VFAs – volatile fatty acids, such as CH_3COOH, of disintegrated sludge supernatant; mg$_{\mathrm{CH3COOH}}$·L^{-1}).

For calculation, the following equations were applied [12,16,19]:

$$\mathrm{kd}_{\mathrm{FCOD}} = \frac{\mathrm{FCOD}_{\mathrm{UT}}}{\mathrm{FCOD}_{\mathrm{NT}}} \tag{7}$$

$$\mathrm{kd}_{\mathrm{CST}} = \frac{\mathrm{CST}_{\mathrm{UT}}}{\mathrm{CST}_{\mathrm{NT}}} \tag{8}$$

$$kd_{SCOD} = \frac{SCOD_{UT}}{SCOD_{NT}} \quad (9)$$

$$kd_{TOC} = \frac{TOC_{UT}}{TOC_{NT}} \quad (10)$$

$$kd_{VFAs} = \frac{VFAs_{UT}}{VFAs_{NT}} \quad (11)$$

The efficiency of the process, defined as the increase in the disintegration product, FCOD yield, per unit of energy (indicator of efficiency kde_{FCOD}), was calculated as follows [19]:

$$kde_{FCOD} = \frac{\Delta FCOD}{E_V} \quad (12)$$

where kde_{FCOD} is the indicator of efficiency of the ΔFCOD yield; $mg \cdot L^{-1} \cdot Wh^{-1}$.

The effect of sludge pre-conditioning can also be evaluated by particle size analysis using different methods such as sedimentation [20,21], microscopic observation [22], scanning electron microscopy (SEM) [23], and laser diffraction [24,25].

Laser diffraction is commonly used in soil science and sedimentology [21,26], and its application in the assessment of the sludge flocks has been gaining momentum [25,27,28] in recent years, although it is still not widely used. Houghton et al. [27] used laser scattering to analyze different types of digested sludge, whereas Chaignon et al. [28] applied laser diffraction to evaluate the changes in the size distribution and transfer of mineral particles between activated sludge flocks. Simonetti et al. [22], Bieganowski et al. [25], Zhu et al. [29], and Skórkowski & Zielewicz [30] used laser diffraction to assess the effects of different sludge pre-treatment techniques. Measurement of the particle size using the laser diffraction method is based on the analysis of the angle and amount of laser light scattered on the measured particles. In the case of the Mastersizer 3000, two light sources are used, red light (He-Ne, wavelength 632.8 nm) and blue light (LED, wavelength 470 nm). The beam passes through a measuring cell, and the particles diffract the light [24]. The energy of scattered light, recorded by the detectors (for 100 size classes), is then calculated by the analyzer's software, using the Fraunhofer or Mie theory to calculate the particle size distribution of the measured samples [25,30,31].

The aim of the presented study was to assess the influence of the particle size reduction (obtained by premixing) on the effects of ultrasonic sludge disintegration, and the energy efficiency of the process.

2. Materials and methods

The excess sludge used in this study was procured from a WWTP (wastewater treatment plant) in the east of Poland and stored at 4°C. All analyses were completed within 48 h after sampling.

The characteristics of the thickened sludge before and after disintegration were described by selected disintegration indicators (defined in the Introduction section), which are based on the changes in FCOD, SCOD, VFAs, and TOC in the liquid phase. Analysis of these values was performed after centrifugation (20,000 rpm, 30 min, 18°C) and filtration: for FCOD analysis through filter paper with a pore size of 3 μm and for SCOD, VFA, and TOC through a 0.45-μm membrane [6,9,19]. The TCOD (total chemical oxygen demand of sludge), FCOD, SCOD, and VFA were measured using the spectrophotometric method (Hach Lange DR5000), and chemical oxygen demand was determined via the dichromate method. For VFA, the esterification method was applied, and TOC was determined using a Shimadzu TOC-L total organic carbon analyzer equipped with an auto-sampler unit, applying the Shimadzu 680°C combustion catalytic oxidation method. The TS and total volatile solids (TVS) were determined according to Standard Methods (APHA) [32]. Table 1 shows the characteristics of the excess sludge and its supernatant before disintegration.

2.1. Disintegration of the thickened excess sludge

We used three methods of sludge pre-conditioning: chemical disintegration using 0.5 mol NaOH [6,9,18], which allows for the calculation of the disintegration degree (k_{DD}), mechanical premixing, as the first stage of disintegration, ultrasonic disintegration of premixed sludge, as well as ultrasonic disintegration only (for comparison with other methods).

Table 1
Characteristics of the thickened excess sludge and its supernatant

Sludge	Total solids (TS)	$g \cdot L^{-1}$	56.80
	Total volatile solids (TVS)	$g \cdot L^{-1}$	43.50
	TVS to TS ratio	–	0.77
	Water content	%	94.30
	Total chemical oxygen demand (TCOD)	$mg \cdot L^{-1}$	88,830.00
	Capillary suction time (CST)	s	103.00
Supernatant	Filtrated chemical oxygen demand ($FCOD_{NT}$)	$mg \cdot L^{-1}$	264.00
	Soluble chemical oxygen demand ($SCOD_{NT}$)	$mg \cdot L^{-1}$	207.00
	Volatile fatty acids (VFA_{NT}) as CH_3COOH	$mg_{CH3COOH} \cdot L^{-1}$	30.80
	Total organic carbon (TOC)	$mg \cdot L^{-1}$	95.25

2.2. Premixing of sludge

Sludge premixing was conducted in a semi-technical sludge disintegrating mixer (Fig. 1) equipped with a 2200w motor, a vertical shaft with a rotor (rotor diameter – D_M = 80 mm), and a steel tank (D_M = 265 mm, operating capacity of 15 L). The sludge mixer was attached to a digital control and frequency converter, which allows for the disintegration parameters to be set as necessary. Three different premixing times (T_M) were used: T_M = 60, 120, and 180 s, at a speed of 2,000 rpm, corresponding to a volumetric energy E_V = 3.49, 6.98, and 10.47 kWh·m^{-3}, respectively. This allowed us to determine the influences of the premixing time and energy on the dispersion effects (Table 2). The energy parameters of the mixing process were monitored using a LUMEL N12 programmable digital panel meter [19].

2.3. Ultrasonic disintegration

The premixed and non-mixed sludge was subjected to ultrasonic disintegration, conducted using a high-power disintegrator setup, a WK-2010 ultrasonic generator, and a mosaic head with a short conical emitter with a diameter d_E = 120 mm. Fig. 1 shows the geometric parameters of the vessel and the placement of the emitter.

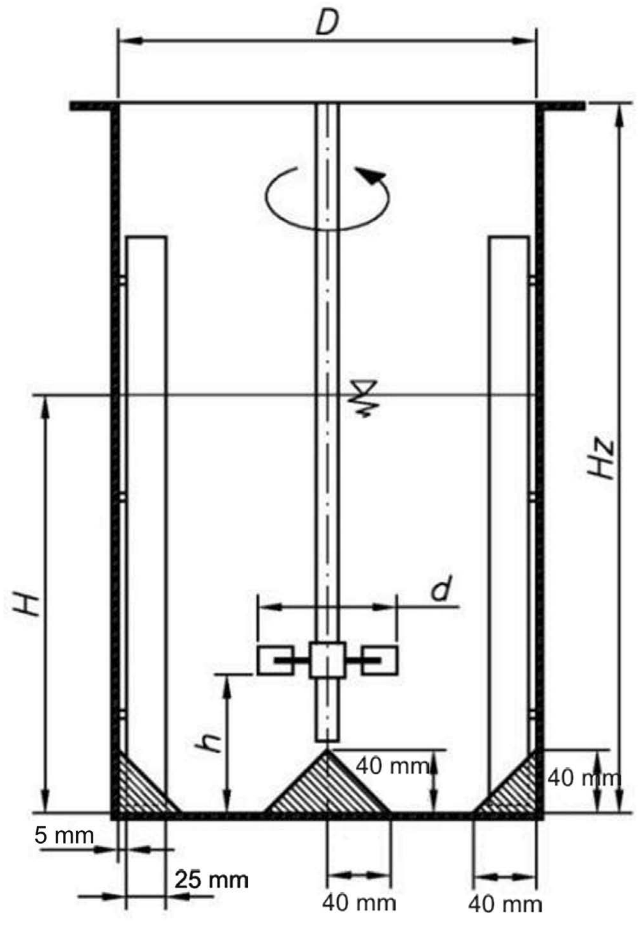


Fig. 1. Semi-technical sludge disintegrating mixer set-up (sludge disintegration vessel).

Sonication was conducted under static conditions at a frequency of 21 kHz, the generator power was P_G = 950 W, and the head power was P_{UT} = 483 W. The energy parameters of the ultrasonic disintegration were monitored using a LUMEL N12 programmable digital panel and calculated according to Eqs. (1)–(5).

The sludge was sonicated for T_{US} = 32 s, which corresponds to a volumetric energy E_V of 5.72 kWh·m^{-3}.

2.4. Particle size analysis

To assess the destruction of flocs and the particle size distribution after disintegration, the Malvern Mastersizer 3000 laser diffraction particle size analyzer (measuring range 0.01–3,500 μm) was used, which was equipped with a Hydro EV flexible volume wet dispersion unit. The analyzer uses the full Mie theory, which completely solves the equations for the interaction of light with matter [31]. The sludge volume used in the measurements was dependent on the obscurance (10% in this study) (Malvern [31]). To achieve optimal background values (low obscurance), deionized and degassed water was used. The parameters of the pump and stirrer were experimentally established to provide stable results during measuring; measurements were performed in four repetitions. The results were expressed as follows: d_1–d_{90} = cut diameters, D[4,3] = diameter (mean diameter – sphere equivalent in respect of volume or mass [31]), and the volume of the smallest fraction (below 99.9 μm). Table 2 shows the particle size of the pre-mixed sludge, and Table 3 represents the particle size of the ultrasonically disintegrated sludge.

3. Results and discussion

The ratio of TVS to TS [33] of the excess sludge used in the research was 76.58%, indicating a moderate content of organic substances. The parameters of the thickened excess sludge are shown in Table 1. The results of the disintegration using NaOH were as follows: FCOD = 8,690.00 mg·L^{-1} and SCOD = 8,525.00 mg·L^{-1}. The results of chemical disintegration, using NaOH solution, were applied to calculate the disintegration degree k_{DD} (Table 3) [14,19].

Based on the results of the sludge mechanical disintegration (premixing) presented in Table 2 the particle size

Table 2
Cut diameters of sludge for specific premixing time

Particle cut diameter	Size	Mixing time T_M (s)			
		0	60	120	180
Dx (1)	μm	13.4	5.98	5.23	4.94
Dx (10)	μm	75.1	21.5	17.6	16.6
Dx (25)	μm	155	40.4	31.5	31.5
Dx (50)	μm	339	69.8	57.6	57.5
Dx (75)	μm	622	113	97.4	98.3
Dx (90)	μm	965	172	155	160
$D[4,3]_M$	μm	449	90.4	80.3	77.4
Volume below 99.9 μm	%	14.78	69.07	75.96	75.62

Table 3
Characteristics of excess sludge and its supernatant after disintegration – kd indicators, particle size, particle fraction volume

Disintegration effect	Parameter		Effects				
		Unit	T_M[s]/T_{US}[s]				
			0/0	0/32	60/32	120/32	180/32
	E_S – specific energy	kWh·kg_{TS}^{-1}	0.00	0.09	0.15	0.21	0.27
Dispersion indicators	kd_{FCOD}	–	1	1.75	3.33	3.75	4.08
	kd_{CST}	–	1	1.05	8.68	8.93	12.52
	kd_{SCOD}	–	1	1.30	1.65	1.85	1.96
Cell lysis indicators	kd_{TOC}	–	1	1.51	1.65	1.67	1.71
	k_{DD}	%	0	0.75	1.62	2.10	2.38
Acidification indicator	kd_{VFA}	–	1	1.27	1.74	1.90	2.13
Particle size	Dx (1)	μm	13.4	12.9	5.45	4.91	4.74
	Dx (10)	μm	75.1	72.4	18.8	16.5	15.5
	Dx (25)	μm	155	145	36.1	33.1	29.7
	Dx (50)	μm	339	312	64.7	59	55
	Dx (75)	μm	622	586	107	97.7	94.3
	Dx (90)	μm	965	913	168	151	151
	$D[4,3]_{M+US}$	μm	449	419	86.6	75.6	74.8
Particle fraction volume	Volume below 99.9 μm	%	14.78	15.96	71.74	76.22	77.36

M – mixing; US – sonication

diameter evaluated as $D[4,3]_M$, decreased by 79.87% for T_M = 60 s. The increase in the mixing time to 180 s only led to a 3.29% further reduction in $D[4,3]_M$.

The particle size distribution presented in Table 2 corresponds with the results reported by Kampas et al. [34] for mechanical sludge pre-treatment using a spider deflaker. This approach (P = 5.7 kW for 5 L of sludge) for short conditioning times led to the destruction of large aggregates, and with the elongation of the conditioning time up to 15 min, the median size of raw sludge particles was reduced from 65.5 to 9.3 μm (85.80% reduction); the authors also reported the destruction of porous flocks (~100 μm) [34].

To show the influence of the particle size (obtained as a result of premixing) on the ultrasonic disintegration, the results of sludge disintegration, namely the indicators of the direct results of the disintegration and particle size diameter measurements of the sludge subjected to sonication (T_{US} = 32 s), are summarized in Table 3 and presented in Figs. 2–4.

A 6.70% reduction of the $D[4,3]_{US}$ diameter (from 449 to 419 μm) was noted for disintegration using US only. The sonication of pre-mixed sludge led to a decrease in the $D[4,3]_{M+US}$ diameter with an increase in premixing time, reaching 83.30% for T_M = 180 s, which indicates that the ultrasonic disintegration of the pre-mixed sludge resulted in the decrease in $D[4,3]_{M+US}$ diameter by 332.4–344.2 μm when compared to the sonicated only sludge (Table 3). Sonication of the pre-mixed sludge led to a further reduction in the $D[4,3]_M$ diameter, as shown in Fig. 3a–c. The $D[4,3]_M$ diameter decreased from 90.4 to $D[4,3]_{M+US}$ 86.6 μm for T_M 60 s, from 80.3 to 75.6 μm for T_M = 120, and from 77.4 to $D[4,3]_{M+US}$ 74.8 μm for T_M 180 s. The dispersion effects mentioned above correspond to the energy used in the disintegration processes. Chu et al. [10] reported a reduction in the Dx (50) of sludge flocks from 87.37 to 52.63 μm for an ultrasonication density 0.3 W·mL^{-1}. A particle size reduction with increasing energy density has been shown by Simonetti et al. [22] (68.01% d_{50} reduction for E_S = 50 kJ·g^{-1} and 80.89% for 200 kJ·g^{-1} for the US process alone), Skórkowski & Zielewicz [30], and Kampas et al. [34]. However, the energy used to achieve similar results was considerably higher.

The changes in FCOD, SCOD, VFAs, and TOC, as disintegration indicators, are shown in Table 3. Analysis of these indicators showed that the premixing process was effective, with significant results. The dispersion effects, monitored using the indicators kd_{CST} and kd_{FCOD}, for sonication alone was kd_{FCOD} 1.75, kd_{CST} 1.05. For the sonication of premixed sludge, the values of the dispersion indicators gradually increased with an increase in premixing time; kd_{FCOD} increased to 4.08 and kd_{CST} up to 12.52, indicating an increase in the dispersion indicators by 2.33 (kd_{FCOD}) and 12.47 (kd_{CST}) compared to the sludge conditioned with US only. The low kd_{CST} value for the use of US alone can be attributed to the low energy density and the heterogeneous nature of the thickened sludge. The thickening of excess sludge is also supported by the addition of polyelectrolyte, which makes the sludge, at 5% TS concentration and higher, more "resistant" to ultrasonic deagglomeration [19]. The results for the unmixed sludge were similar to those reported by Zielewicz [6,9,18], Skórkowski [19], Skórkowski & Zielewicz [30], and Zhu et al. [29]. The obtained conditioning results (monitored as disintegration indicators) of the pre-mixed sludge are in accordance with the results obtained by mechanical disintegration (hydrodynamic, mixing, etc.) presented by other researchers, such as Kampas et al. [34], Zubrowska-Sudol & Walczak [35], and Gladchenko et al. [36]. Among them,

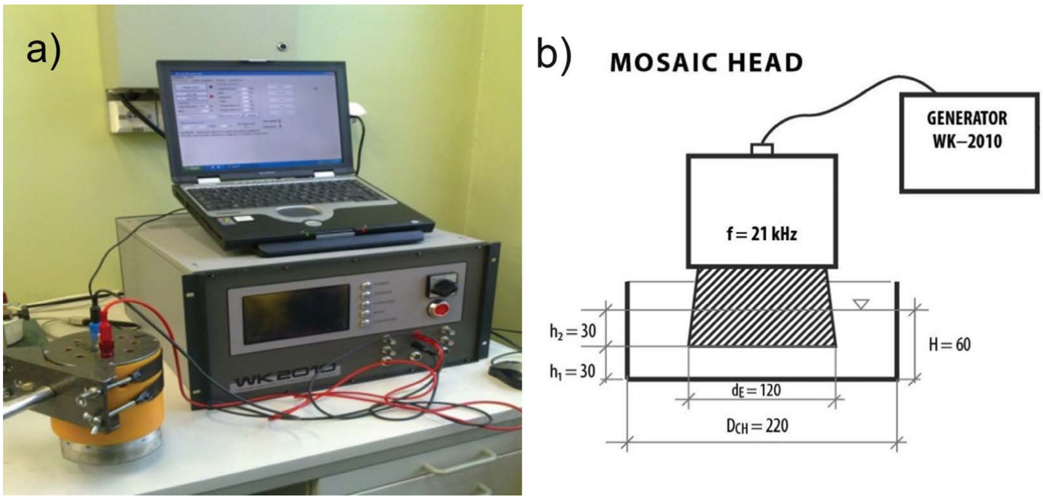
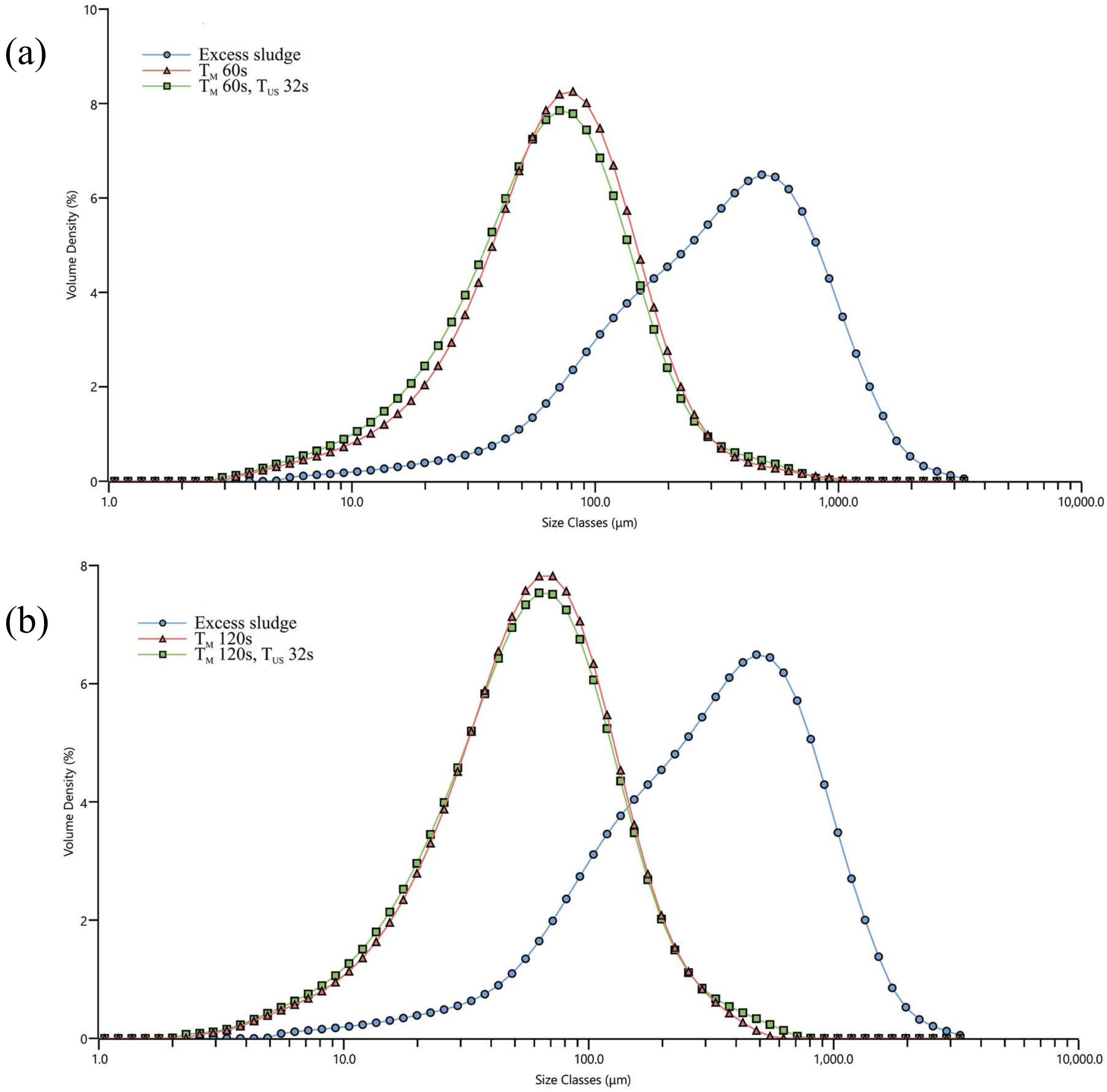


Fig. 2. Ultrasonic disintegrator set-up – WK-2010 ultrasonic generator with a mosaic head: (a) photo and (b) scheme.



(Fig. 3 Continued)

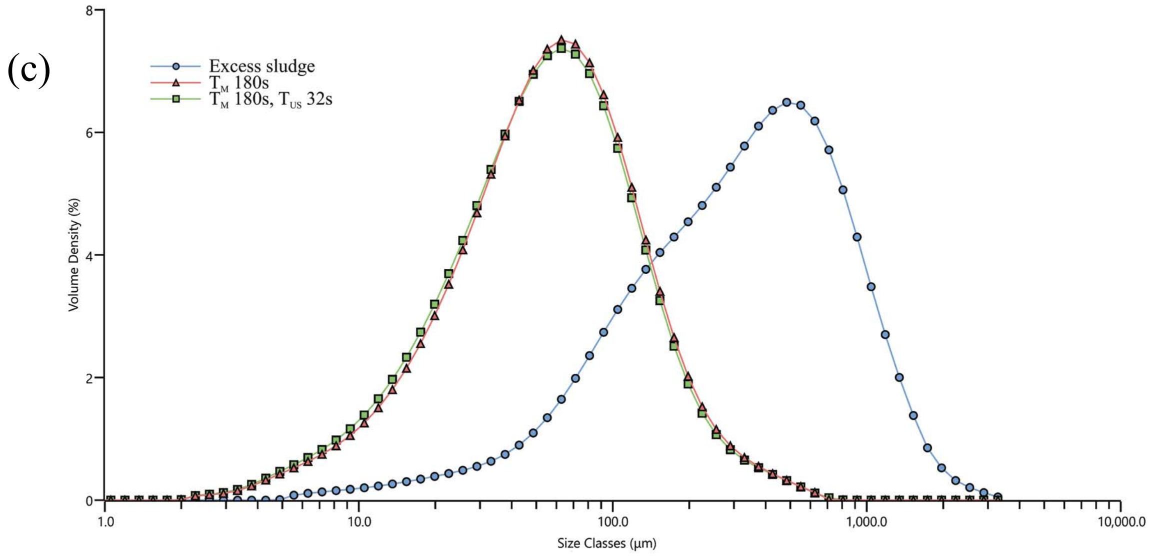


Fig. 3. Particle size distribution of sonicated (T_{US} = 32 s) premixed sludge: (a) T_M = 60 s, (b) T_M = 120 s and (c) T_M = 180 s.

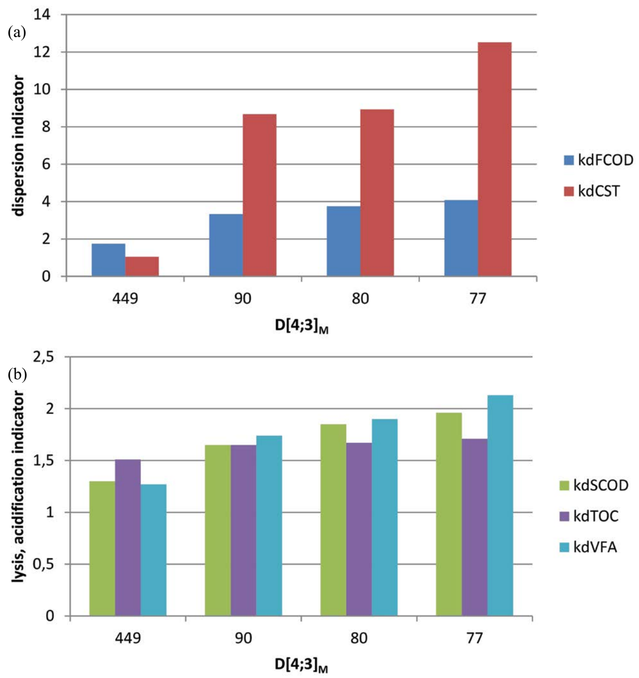


Fig. 4. Indicators of direct effects of disintegration (kd) in relation to D[4,3]$_M$ diameter: (a) dispersion indicators and (b) lysis and acidification indicators.

Table 4
Statistical correlation between E_V, T_M, D[4,3]$_M$ parameters and effects of disintegration r – correlation coefficient, R^2 – coefficient of determination, p – significance level

Indicator of disintegrated sludge	E_V		T_M		D[4,3]$_M$	
	r	R^2	r	R^2	r	R^2
kd$_{FCOD}$	0.93	0.86	0.93	0.86	–0.96	0.93
kd$_{CST}$	0.93	0.86	0.93	0.86	–0.94	0.88
kd$_{SCOD}$	0.97	0.94	0.97	0.94	–0.91	0.83
kd$_{TOC}$	0.92	0.85	0.92	0.85	–0.96	0.93
kd$_{DD}$	0.97	0.94	0.97	0.94	–0.91	0.83
kd$_{VFA}$	0.97	0.95	0.97	0.95	–0.91	0.83
D[4,3]$_{M+US}$	–0.80	0.62	–0.80	0.62	1.00	1.00
fr < 99.9	0.82	0.67	0.82	0.67	–0.99	0.97
$p < 0.05$	M – Premixed; US – Sonicated					
$p < 0.10$						

Kampas et al. [34] observed an average increase in VFAs from 3 to 403 mg·L^{-1} and SCOD from 176 to 4,440 mg·L^{-1} (15 min disintegration time, P = 5.7 kW for 5 L of sludge). Gladchenko et al. [36] reported a 2–6-fold SCOD increase for mechanical sludge pre-treatment. For ultrasonic conditioning, the lysis indicators kd$_{SCOD}$ and kd$_{TOC}$ had values of 1.3 and 1.51, respectively, and the addition of premixing led to an increase in kd$_{SCOD}$ up to 1.96 and in kd$_{TOC}$ up to 1.71. The kd$_{SCOD}$ and kd$_{TOC}$ values were 0.66 and 0.20, respectively, higher compared to the values observed for sonicated only sludge. The acidification indicator changes were analogous to those observed for the lysis indicators.

The reduction in the D[4,3]$_M$ diameter resulted in a noticeable increase in the disintegration indicators (Fig. 4). Premixing greatly impacted the dispersion indicators (Fig. 4a), but the influences on lysis (kd$_{SCOD}$) and acidification (kd$_{VFAs}$) were lower (Fig. 4b). This can be attributed to the low specific energy used in this study (E_S < 2,500 kJ·kg$_{TS}^{-1}$) [34] and moderate TVS/TS ratio (the influence of premixing, for a high TVS/TS ratio, was noticeably greater [19]).

The statistical correlation between volumetric energy E_V, premixing time T_M, particle size of pre-mixed sludge D[3,4]$_M$, and the results of the disintegration, monitored as kd indicators and particle size measurements (D[4,3]$_M$), are shown in Table 2, illustrating the impact of reduced sludge particle size on the direct effects of disintegration. Because

Table 5
Indicator of efficiency of ΔFCOD yield (efficiency of dispersion process) for sonicated sludge (T_{US} = 30 s)

Increase of FCOD per unit of energy	T_{US} = 30 s			
	T_M (s)			
	0	60	120	180
$kde_{\Delta FCOD}$ (mg·Wh^{-1})	81.00	95.66	78.08	66.61

of the characteristics of this study (i.e., sample number), the correlation results were presented for p = 0.05 and 0.10 [28].

The introduction of premixing, resulting in a decreased particle size, also influenced the efficiency of the disintegration process. As shown in Table 5, sludge premixing for T_M = 60 s led to an 18.10% increase in the effectiveness of ultrasonic disintegration, monitored as $kde_{\Delta FCOD}$. A further lengthening of the mixing time (120 and 180 s) resulted in a decrease of $kde_{\Delta FCOD}$ by 3.60% and 18.77%, respectively.

4. Conclusions

We assessed the influence of sludge premixing, which goes along with a reduction in sludge particle size, on the effects of ultrasonic sludge disintegration. Our results demonstrate the correlation between premixing and ultrasonic sludge disintegration. The use of premixing, and the resulting reduction of the $D[4,3]_M$ diameter by up to 83.2%, led to the significant improvement of the disintegration dispersion indicators of sonicated sludge (kd_{CST} to 15.52 and kd_{FCOD} to 4.08) and a noticeable increase in the lysis and acidification indicators (kd_{SCOD} to 1.96, kd_{TOC} to 1.71, kd_{VFA} to 2.13). These findings lead us to infer that premixing mainly promotes deagglomeration, along with a positive influence on the final disintegration as well as on the energy effectiveness of the process.

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