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Effect of hydrodynamic cavitation on flocs structure in sewage sludge to increase stabilisation for efficient and safe reuse in agriculture

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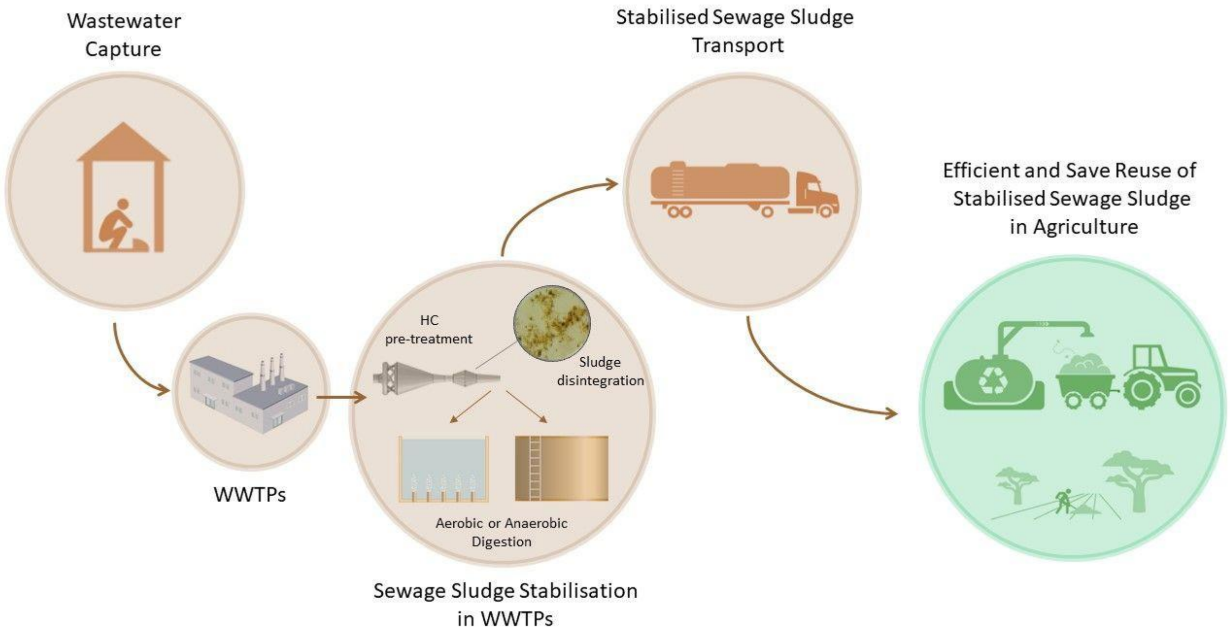
Abstract

Sewage sludge is the by-product of wastewater treatment processes. Its reuse is central to a circular economy approach and offers a sustainable alternative to its disposal. Treated sludge contains a wide range of nutrients (mainly nitrogen, phosphorus, and potassium), which favour its sustainable employment for agricultural purposes (i.e. land-spreading, compost production) and environmental requalification interventions (i.e. forestry, silviculture, land reclamation and revegetation). However, if not properly treated, sewage sludge can contain various contaminants such as heavy metals, organic pollutants, pathogens, and other emerging contaminants, which pose a threat for crops production and human health. Hydrodynamic cavitation (HC) is an eco-friendly and cost-efficient pre-treatment that can enhance sewage sludge stabilisation in both anaerobic and aerobic digestion units, thereby making safe its management and disposal. In this study, HC was used for the gradual disintegration of activated sludge (reaching a maximum disintegration degree (DD_{PCOD}) of 19.2% after 8 h of treatment), and the solubilisation of the dissolved organic matter (increasing the Soluble Chemical Oxygen Demand (SCOD) from 244 to 4,578 mg L^{-1} after 8 h of treatment). Then, both dynamic light scattering analysis and stereoscopic microscope observations proved that HC can also lead to a size reduction of sludge suspended particles. In addition to evaluate the HC treatment efficiency, in this work was also provided a brief discussion on the possible procedures to be followed for the safe and efficient sewage sludge disposal on land after it has been HC-treated.

Graphical Abstract



Keywords

Mechanical pre-treatment; Granulometric distribution; Particle size; Wastewater treatment.

Highlights

1. Hydrodynamic cavitation (HC) is an eco-friendly and cost-efficient pre-treatment method to enhance sewage sludge stabilisation
2. HC is an energy-saving method that increases the efficiency of wastewater treatment plants
3. HC favours the safe and efficient reuse of sewage sludge in agriculture

1. Introduction

Nowadays, preserving water quality is essential to cope with current water scarcity issues and to ensure sanitation to all the population. If, on the one hand, the development of many domestic and industrial wastewater facilities may be able to treat higher volumes of wastewater, on the other hand, it follows a higher quantity of sewage sludge to be disposed of (Prabu et al., 2020). According to the latest available data, in Europe (EU) approximatively 10 million tons of dry mass of sewage sludge are produced on an annual basis (Eurostat, 2020). It is also estimated that one person can generate almost 20 kg of dry mass of sewage sludge per year (Eurostat, 2020).

In the EU, the most common disposal methods for sewage sludge from wastewater treatment plants (WWTPs) includes incineration (18%), landfilling (13%), agricultural use (23%), composting (19%) and others (long-term storage and land reclamation) (Eurostat, 2020). In particular, the direct reuse of sewage sludge in agriculture (Dichtl et al., 2007) or the production of compost (Song and Lee, 2010) are sustainable alternatives to the costly incineration process (Lundin et al., 2004) and the low environmental-friendly landfilling operations (Lewis and Gattie, 2002).

The beneficial effects associated with the land-spreading practice are various: (i) the organic matter in sewage sludge can promote a significant improvement of the soil structure (i.e. water holding capability and cation exchange capability), especially in sandy soils in both arid and semi-arid areas (Graber et al., 2014); (ii) the presence of nutrients (nitrogen, phosphorus, and other micronutrients) in sewage sludge can enhance soil fertility and thus crops production (Usman et al., 2012), also limiting pollution issues related to the supplemental application of mineral fertilizers to soils (Kumar et al., 2017); (iii) the costs associated with the implementation of the land-spreading practice are moderate if compared with those required by the other methods mentioned above (Lundin et al., 2004). With similar benefits, treated sewage sludge is also used in forestry, silviculture, land reclamation and revegetation.

However, the unsustainable production of sewage sludge, in addition to more stringent regulations due to the presence of pathogenic bacteria/viruses (Pourcher et al., 2007), heavy metals (Wang et al., 2008), hydrocarbons (Cai et al., 2008), microplastics (Van den Berg et al., 2020), and other toxic materials from industry in the sludge, have forbidden the use of sewage sludge, if not properly treated, for land applications in many regions in the EU (Hudcová et al., 2019).

The importance of suitable treatment methods and the definition of safe practices for sewage sludge reuse is also remarked by United Nations within the definition of the Sustainable Development Goal 6 (SDG 6) “Clean Water and Sanitation”, which aims to ensure availability and sustainable management of water and sanitation for all the population by 2030 (United-Nations, 2018).

Hence, the need to remove these contaminants from sewage sludge through stabilisation processes and specific treatment methods in WWTPs, before it can be reused again in agriculture. The most traditional and widely employed biological wastewater treatment processes to stabilise sewage sludge in WWTPs are aerobic and anaerobic digestion. Aerobic digestion is characterized by higher operating costs due to the administration of air to the system; in contrast, anaerobic digestion shows as main advantages the recovery of energy in the form of biogas, the mass reduction of sewage sludge, and the improved dewatering properties of the digested sludge (Cao and Pawłowski, 2012).

There is a rising motivation to explore and develop novel technologies to apply as pre-treatments before the aerobic or anaerobic digestion units, aiming to enhance their efficiency in terms of sludge stabilisation along with reduction of emerging contaminants, excess sludge production, and energy consumption during the sludge treatment and disposal phases.

With this purpose, different pre-treatments such as thermal (Pilli et al., 2014), chemical (Hai et al., 2014), mechanical (Houtmeyers et al., 2014; Mancuso et al., 2017), and a combination thereof (Tyagi et al., 2014) are proposed in the literature. The limits associated with the implementation of thermal and chemical pre-treatments mainly concern their high energy (Ruffino et al., 2015) and reagents (Tanaka et al., 1997) consumption. In contrast, mechanical pre-treatments are getting an increasingly attention, and among them HC is gradually taking a prominent role in the field of wastewater treatment, mainly due to the ease of operation, moderate energy consumption, flexibility and capability to vary the required intensities of cavitational conditions (Gogate and Kabadi, 2009; Mancuso et al., 2020, 2019). The HC process exploits the pressure difference within a fluid, due to the presence of a constriction in the flow, for the generation of free radicals, namely $^{\bullet}$H and $^{\bullet}$OH, which are very strong and non-specific oxidizing species. If the HC process is applied to sludge, the free radicals can be responsible of cell or microbial flocs disintegration (Mancuso et al., 2017).

Although the effectiveness of HC as pre-treatment is evident, in the literature there is a lack of studies showing its effect on sludge structural composition and rheology. A deeper knowledge of those aspects might not only improve the operating conditions for the treatment of wastewater, but also reduce the costs associated with the operations of sludge pumping, transport and storage in WWTPs (Eftekharzadeh et al., 2007). Also in agricultural practises, sludge characteristics could influence the selection of the most suitable equipment for the sludge application on land (Prasad et al., 2019). Therefore, the main aim of this work was to investigate the effect of HC on sewage sludge flocs structure. For this purpose, a modified swirling jet-induced reactor, named Ecowirl reactor (Mancuso, 2018; Puiseau et al., 2013), was used to generate HC. Sludge characteristics were analysed by investigating the granulometric distribution of sewage sludge suspended particles of HC-treated samples and observing visual changes in sewage sludge by means of a stereoscopic microscope. During the HC test, the investigation aimed also to find a correlation between sludge characteristics and sludge disintegration/solubilisation, to evaluate the energy consumption, and to analyse the influence of flocs structure variation during sewage sludge treatment and disposal.

2. Materials and methods

Source and characteristic of WAS

For investigations, excess activated sludge of a nitrification/denitrification process was obtained from the municipal WWTP of Trento, Italy. It was collected downstream the dynamic thickening unit, in order to get a sludge with a high total solids (TS) content (in the order of 30 g L^{-1}). Thickened sludge was further concentrated by sedimentation in order to obtain the desired TS content in the experiment (in the order of 50 g L^{-1}). Physical and chemical characteristics of the used thickened sludge were as following: pH 6.8 ± 0.2; TS = 33.4 ± 0.5 g L^{-1}; volatile solids (VS) = 27.9 ± 0.4 g L^{-1}; total chemical oxygen demand (TCOD) = 38,015 ± 321 mg L^{-1}; SCOD = 319 ± 5 mg L^{-1}; total Kjeldahl nitrogen (TKN) = 2,856 ± 3 mg L^{-1}; ammonia nitrogen (NH_4^+ -N) = 33.7 ± 1 mg L^{-1}; total phosphate (P_{TOT}) = 1,062 ± 56 mg L^{-1}.

HC system and HC pre-treatment test

Fig. 1 shows the experimental setup that has been used to perform the HC test (Mancuso et al., 2017). It consisted of a swirling jet device (Ecowirl reactor), a 50.0 L thermo-regulated feed tank, a Mohno pump (3.0 kW, nominal power, Netzsch Pumps & Systems GmbH, Germany), an inverter (Bonfiglioli Vectron - Active) used to control the pump flow rate, a sampling port, a system of control valves at appropriate places, pressure and vacuum gauges. The feed tank was filled with 50.0 L of excess activated sludge (50 gTS L^{-1}) collected from the dynamic thickening unit. The concentrated sludge was recirculated in the loop by using the by-pass line (V_6, V_7 opened – V_4, V_5

closed) for about 15 min to homogenise its TS content (50.0 gTS L^{-1}). Since the Ecowirl reactor was by-passed, HC did not occur. In the meantime, the temperature of the sludge was adjusted to 35.0°C by means of the heating/cooling system (immersion resistances / external cold-water bath) and kept constant throughout the HC test (with a variation of ± 3.0°C). Then, the by-pass line was closed (V_6, V_7 closed), and the flow was conveyed to the Ecowirl reactor (V_4, V_5 opened). Thereafter HC was detected. The inlet pressure upstream to the Ecowirl reactor was set to 4.0 bar by adjusting the frequency of the pump inverter. These operating conditions and the duration of the HC test (8 h) were selected on the basis of the optimal values observed in previous experimental campaigns (Mancuso et al., 2017), in which the HC efficiency was evaluated as function of the specific supplied energy. Table 1 summarizes the parameters and the operating conditions for the 8h-HC test.

Analytical methods and calculations

Sludge samples were collected by means of the sampling port located at the bottom of the feed tank (Fig. 1) at 0h, 1h, 2h, 4h and 8h of the HC test, respectively, and stored at 4.0 °C for subsequent analysis. VS, TCOD, SCOD, TKN, NH_4^+-N and P_{TOT} were calculated according to standard methods (APHA, 2005). Prior to SCOD and NH_4^+-N determinations, sludge samples were centrifugated at 5000 x g. The obtained supernatant was filtered by means of cellulose nitrate membrane with pore size of 0.45 µm by compression. pH was monitored by means of a Crison 25 portable pH-meter. All the analyses were performed in duplicates and the results were expressed as average of the obtained values. A reference sample was identified as the SCOD obtained by chemical sludge disintegration in a 1.0 mol L^{-1} sodium hydroxide solution for 24 h at 20.0°C (Salsabil et al., 2009).

The improvement of sludge solubilisation was evaluated in terms of SCOD increase (Eq. 1) (Zhang et al., 2008), and taking into account the ratio of change in SCOD after cavitation to particulate chemical oxygen demand ($PCOD_0 = TCOD - SCOD_0$) (Eq. 2) (Bougrier et al., 2006).

$$\Delta SCOD\left(mg\ L^{-1}\right) = SCOD_t - SCOD_0 \qquad \text{Eq. 1}$$

$$DD_{PCOD}\left(\%\right) = \frac{\left(SCOD_t - SCOD_0\right) \times 100}{PCOD_0} = \frac{\left(SCOD_t - SCOD_0\right) \times 100}{\left(TCOD - SCOD_0\right)} \qquad \text{Eq. 2}$$

where:

- $SCOD_t$ = soluble COD of the treated sludge by using HC [mg L^{-1}] at the time t.
- $SCOD_0$ = soluble COD of the untreated sludge [mg L^{-1}].
- TCOD = total COD of the untreated sludge [mg L^{-1}].

Dynamic light scattering analyses and microscopic observations

The sludge particles diameters, considered as spherical, were monitored at 1h, 2h, 4h and 8h during the HC test by using a dynamic light scattering analyser (Beckman Coulter, Delsa Nano C Particle Analyser, measuring range of 0.6 nm - 7 μm). For each analysed sample, a plastic disposable cuvette was filled with 0.2 ml of sludge diluted with distilled water within a 1:10 ratio (the total volume of samples was 2.0 ml). During the dynamic light scattering analyses, a beam of laser light incident on cuvette was scattered by the sludge particles and diffused within the sample cell due to Brownian motion, producing fluctuations in the scattering intensity as a function of time. Since the diffusion rate of particles was due to their size, it was possible to correlate it to the fluctuation rate of the scattered light, thereby allowing the determination of the particle size distribution within the sludge sample. The scattered light was measured by a highly sensitive detector.

Dynamic light scattering measurements were then coupled with visual changes (by using a stereoscopic microscope Micro-Combi-Tester, NIKON, Japan) on sludge flocs before (raw sludge sample) and after the HC pre-treatment (8h-HC treaded sludge sample). For the microscopic analysis, samples were prepared by dropping a 3times-diluted water on a glass plate.

3. Results

In this section, the outcomes of the investigation of HC effects on sludge solubilisation and sludge flocs structure were analysed, and considerations on sludge treatment and land disposal were reported.

SCOD measurements

Chemical analysis on sludge samples showed that higher HC pre-treatment times were associated with an increase of the dissolved organic matter. The SCOD increased from the initial value of 244 mg L^{-1} to 4,798 mg L^{-1}, after 8h of HC pre-treatment; the other values of SCOD for the intermediate pre-treatment times (1h, 2h and 4h) are reported in Table 2. Therefore, the sludge DD_{PCOD} increased during the HC test, varying from 1.7% to 6.5%, 10.8% and 19.2% after 1h, 2h, 4h and 8h of HC pre-treatment, respectively (Table 2).

Comparing these results with those of other studies reported in the literature where HC was used as pre-treatment, it has emerged that different sludge DD_{PCOD} have been reported. This discrepancy was mainly related to the different applied energies, the dissimilar operating conditions (sludge temperature and pH, flow inlet pressure), and the cavitating devise typology (Venturi (Hirooka et al., 2009), orifice plates (Lee and Han, 2013), high-pressure jets (Suenaga et al., 2015), swirling jet-induced cavitation (Mancuso et al., 2017), high-pressure homogenizers (Nabi et al., 2019), and rotor-stator type (Kim et al., 2020).

Dynamic light scattering measurements and optical microscope observations

In order to confirm the capability of HC to disintegrate sludge flocs into smaller particles, it was used the dynamic light scattering analysis on sludge samples collected at 1h, 2h, 4h and 8h of the HC test. The measurement range for the particles size was set from 0.6 nm to 7 µm. In Fig. 2 are reported the recorded maximum diameters of suspended sludge particles, considered as spherical, in function of the treatment times: the longer the HC pre-treatment the smaller the particles size. Similar results have been reported in other studies on ultrasonic cavitation (Le et al., 2013). The highest particle diameters have, in fact, more than halved after 8h as consequence of the HC pre-treatment if compared with the HC pre-treated sample at 1h (6,25 µm and 3,6 µm, respectively). Although both cavitation and shear stress can lead to a sludge particles reduction, however, it is has been reported that, for higher cavitation intensities, cavitation contributes more than shear stress (Kim et al., 2020). HC pre-treatment has influenced not only the highest dimensions of suspended particles, but also those intermediate, with a decrease in suspended particles size for increasing HC treatment times (Fig. 3). This suggests that the sludge could be initially constituted of aggregates of very small particles, which can separate due to cavitation, acting on the interfacial surfaces. In particular, for all the HC treatment times (1h, 2h, 4h, and 8h), the granulometric distributions showed a Gaussian trend, with the maximum of each curve in the range of (0.3 - 0.4 µm) (Fig. 4). Furthermore, higher HC treatment times involved a progressive narrowing of the curves with a remarkable increase in percentage of the smallest particles corresponding to the maximum (Fig. 4).

A strong breakdown and dispersion of the flocs aspect in the sludge samples were observed by stereoscopic microscope in untreated (Fig. 5a) and 8h-HC treated sludge (Fig 5b), confirming that HC has a direct effect on sludge disintegration. The untreated sludge was characterized by dark coloured flocs with different sizes, most with size higher than 100 µm. Due to the HC pre-treatment, sludge flocs were disintegrated, turning their colour in pale yellow, and reduced to an average value of about 10 µm. These outcomes are in agreement with those of previous studies in which acoustic cavitation has been used as disintegration method (Feng et al., 2009; Tytła and Zielewicz, 2018; Zielewicz, 2016).

Energetic measurements

Sludge temperature, flow inlet pressure and flow rate were kept constant throughout the 8h-HC test (Table 1). Under these conditions, it was observed a gradual reduction in the frequency of the pump inverter over time (from the initial value of 61 Hz to 53 Hz after 8h of HC pre-treatment) (Fig. 6). Further, he absorbed power by the pump decreased (Fig. 6), indicating that the same flow inlet pressure to the cavitating system was ensured with a gradual reduction of the resistance of the treated sludge to the flow. These outcomes confirmed the progressive alteration of sludge structure, which then changed its characteristics. This is in accordance with results of the dynamic light scattering analysis and microscopic observations (see previous section).

4. Discussions

Sewage sludge flocs disintegration

Sludge disintegration caused by HC is certainly a reason why this technique, if applied as a pre-treatment to the anaerobic or aerobic digestion, can enhance their treatment efficiency. In sludge digestion, hydrolysis is considered as the rate limiting step because of the presence in the sludge flocs of numerous constituents such as bacteria, particulate organic matter (polymeric substrates such as proteins, lipids and carbohydrates) and complex macromolecules, such as EPS (extracellular polymeric substances), which are excreted by microorganisms during biological treatment of wastewater (Gianico et al., 2013). Hydrolysis step can be enhanced by sludge pre-treatment methods, which imply the disintegration of macro-molecular organic compounds into low molecular-weight compounds that can be further used by the following either methanogens phase in the anaerobic digestion process or oxidation process in the aerobic process. Indeed, these low molecular-weight compounds are in turn assimilated by the bacteria and used as a source of energy and carbon or nutrients, improving sludge stabilisation and, eventually, biogas production.

The results obtained in this study showed that the HC pre-treatment has led to a gradual disintegration of sludge flocs, resulting in both a progressive reduction of the particles size and a gradual increase in the dissolved organic matter. In accordance with the chemical analyses and laser diffraction measurements, visual observations by optical microscope have confirmed the flocs disintegration mechanism. Variation in EPS may also contribute to the rheology evolution of sludge

(Liu et al., 2016). Outcomes of this study are in accordance with the literature data; HC acts by destroying bacterial cell walls and membranes, resulting in a modification of the particles size distribution and rheological properties (i.e. viscosity) of the sludge (Garuti et al., 2018; Langone et al., 2017). Furthermore, a linear correlation between the maximum diameter measured in the investigated range and the sludge DD_{PCOD} has been observed (R^2 = 0,9332), suggesting that the variation of sludge particle sizes may provide a valuable monitoring method for the evaluation of the HC effectiveness, in terms of sludge disintegration and solubilisation (Fig. 7).

Considerations on sludge treatment and land disposal

The design and management of sludge treatment processes in WWTPs and further operations, such as sludge transport and disposal, require an accurate prediction of the hydrodynamic sludge behaviour, and thus a deep knowledge of its rheology (Prasad et al., 2019). Sludge rheology might indeed influence different sludge operations, namely pumping, mixing, mass transfer rates, and sludge-water separation (settling and filtration) (Ratkovich et al., 2013; Verma et al., 2007). A rheological characterization of sludge is useful for the selection of the best equipment to be used for its treatment, transport and final disposal, particularly when sludge is reused for agricultural purposes (i.e. land-spreading) (Prasad et al., 2019).

Rheological properties of sewage sludge are mainly described by viscosity, which depends on solid concentration, temperature, particle size (distribution), shape and surface charge. In general, sludge with a solid concentration higher than 2% shows a non-Newtonian behaviour (Ratkovich et al., 2013; Sanin, 2002), and the sludge apparent viscosity generally changes with the shear rate (flow velocity). Viscosity tends to increase as the solid concentration becomes higher, while a decrease in sludge viscosity can be detected as the temperature increases (Prasad et al., 2019). Furthermore, the variation of particle size distribution, which occurs after disintegration pre-treatments, also impacts on rheological behaviour of sewage sludge (Ruiz-Hernando et al., 2013). As consequence, sludge with different rheological characteristics can require different amount of energy for its treatment in WWTPs and for its transport and disposal.

The results obtained in this study prove that HC is an effective and energy-saving treatment. It can be potentially used at different stages of the sludge treatment in WWTPs (Fig. 8a): as pre-treatment to anaerobic digestion (Elalami et al., 2019), to aerobic digestion (Mancuso et al., 2017), or as treatment of the activated sludge in the sludge recycle line. This involves an increase of the efficiency of sludge treatment processes, due to both an increase in sludge solubilisation and biodegradability that allow the reduction of volumes to treat as well as of retention times in sludge treatment units, thereby optimizing the energy balance in WWTPs. Indeed, HC implies low levels of supplied energy, part of which can also be recovered through the production of biogas in anaerobic digestion, resulting in a reduction of the sludge treatment costs.

Furthermore, sludge disintegration treatments can also have a positive effect in the optimization of sludge management, transporting, storing, dewatering, landfilling, composting and land-spreading operations (Fig. 8b). (Landry et al., 2006) showed that sludge viscosity influenced the performances of handling and land application equipment, and following costs.

In addition to those considerations, disintegration sludge treatments can contribute to maximize pathogens and micropollutants removal prior to land application. As reviewed by (Tyagy et al., 2014), acoustic cavitation has been applied to remove hazardous pollutants from sludge. HC treatment has been successfully applied for the removal of toxic carcinogens dyes (Mancuso et al., 2016), pharmaceutical products, toxic cyanobacteria, bacteria and viruses (Dular et al., 2016) from polluted aqueous solutions. Further research, however, is needed to establish the efficiency of HC on pathogens and micropollutants in sludge treatment, which currently are limiting factors for the reuse of sewage sludge for land applications. In the present context of COVID-19 emergency, the role of HC for SARS-CoV-2 inactivation and removal from sludge could be of interest and needs to be examined in depth.

5. Conclusions

Excess sludge treatment and disposal currently represent a very important challenge for WWTPs due to economic, environmental and regulation factors. Operations such as land-spreading, production of compost, land reclamation and revegetation would seem to provide a sustainable and environmental-friendly solution to the problem. However, sewage sludge from WWTPs needs to be properly treated before its employment for the mentioned applications. In WWTPs, aerobic and anaerobic digestion are used for the sludge stabilisation process. However, this process can be optimized through the application of novel pre- and post-treatment methods, which further contribute to increase remove conventional contaminants, pathogens and other emerging micropollutants from sludge in order to ensure sludge safe disposal. Not by chance, the 2030 Agenda for Sustainable Development Goals has proposed target calls for reducing water pollution, minimizing release of hazardous chemical and increasing treatment and reuse.

In this context, it has been already proved that HC is an effective and energy saving technique, which favours an increase of sludge solubilisation. Further, in this study, it was observed that the HC pre-treatment has led to a gradual disintegration of sludge suspended particles, which were characterized by ever smaller dimensions as the HC pre-treatment time increased, contributing to reduce the volume and the time in the following treatment units as well as the energy required by operations such as sludge mixing, pumping, and disposal.

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HC time (h)	T (°C)	P_{inlet} (bar)	Q ($m^3\ h^{-1}$)	TS ($g\ L^{-1}$)
0, 1, 2, 4, 8	35.0	4.0	4.1	50.0

Table 1 - Parameters and operating conditions for the 8h-HC pre-treatment test.

HC time (h)	TCOD (mg L^{-1})	SCOD (mg L^{-1})	Δ SCOD (mg L^{-1})	DD_{PCOD} (%)
0	46,423	244	0	0.0
1	45,392	992	748	1.7
2	44,371	1,719	1,475	6.5
4	43,200	2,693	2,449	10.8
8	41,327	4,578	4,334	19.2

Table 2 – Results of chemical analysis and HC efficiencies.

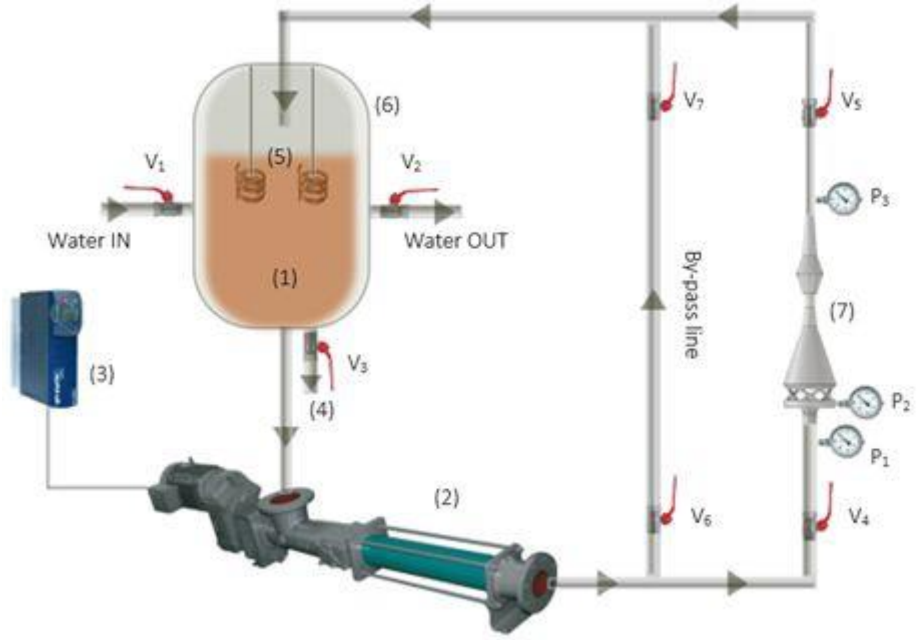

Fig. 1 – Schematic representation of the HC experimental setup: (1) Feed Tank; (2) Screw pump; (3) Inverter; (4) Sampling port; (5) Immersion resistances; (6) External cold-water bath; (7) Ecowirl reactor; P_n pressure and vacuum gauges; V_n Control valves.

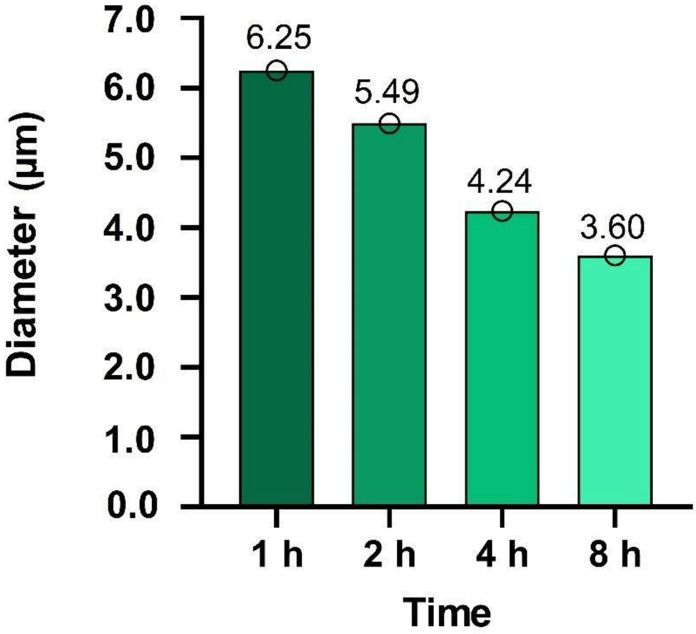

Fig. 2 – Maximum diameter of suspended particles, considered as spherical and recorded by dynamic light scattering analyzer, of HC pre-treated samples at 1h, 2h, 4h and 8h.

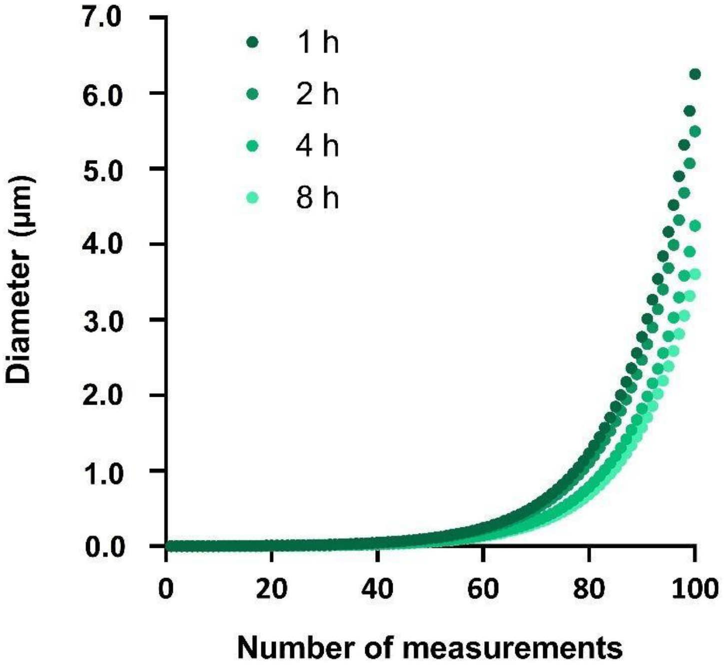

Fig. 3 – Overall size of suspended particles of HC pre-treated samples at 1h, 2h, 4h and 8h vs. number of measurements.

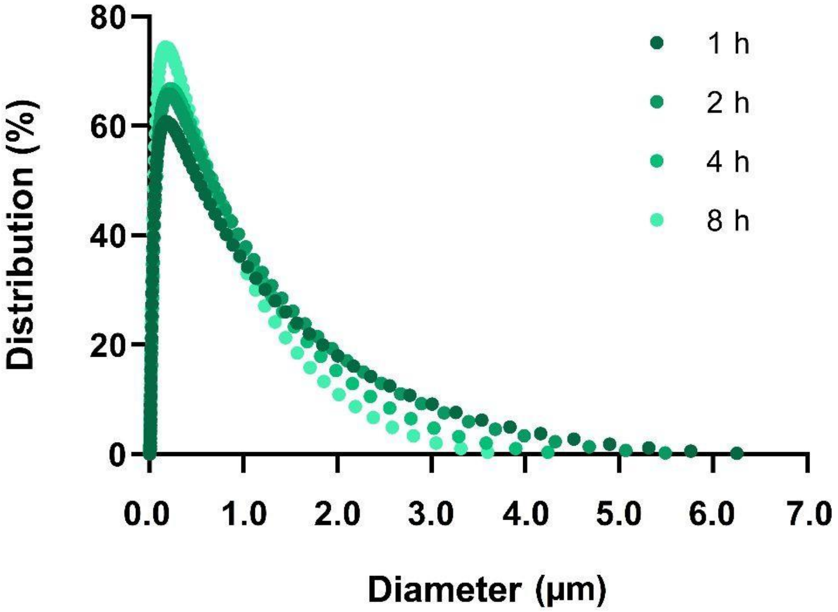

Fig. 4 – Granulometric distribution of suspended particles of HC pre-treated samples at 1h, 2h, 4h and 8h.

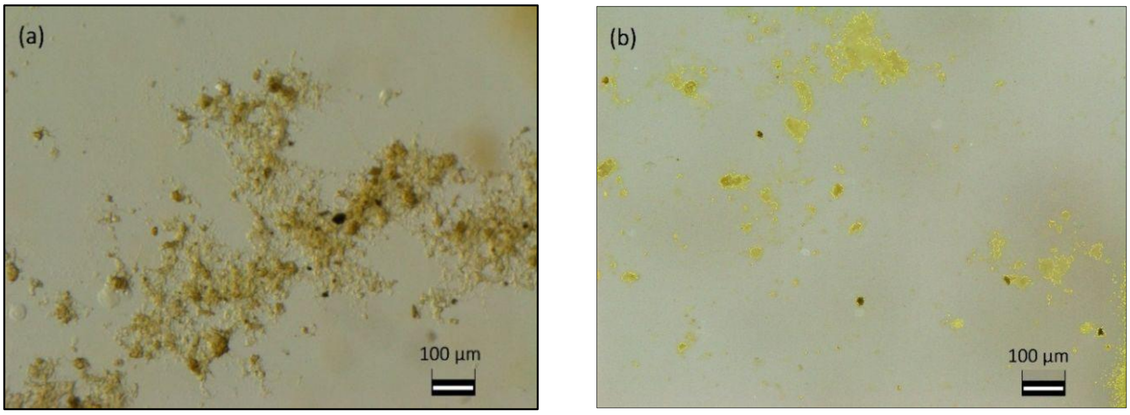

Fig. 5 – Observation by stereoscopic microscope of sludge flocs in a) raw sludge and b) 8h HC pre-treated sludge.

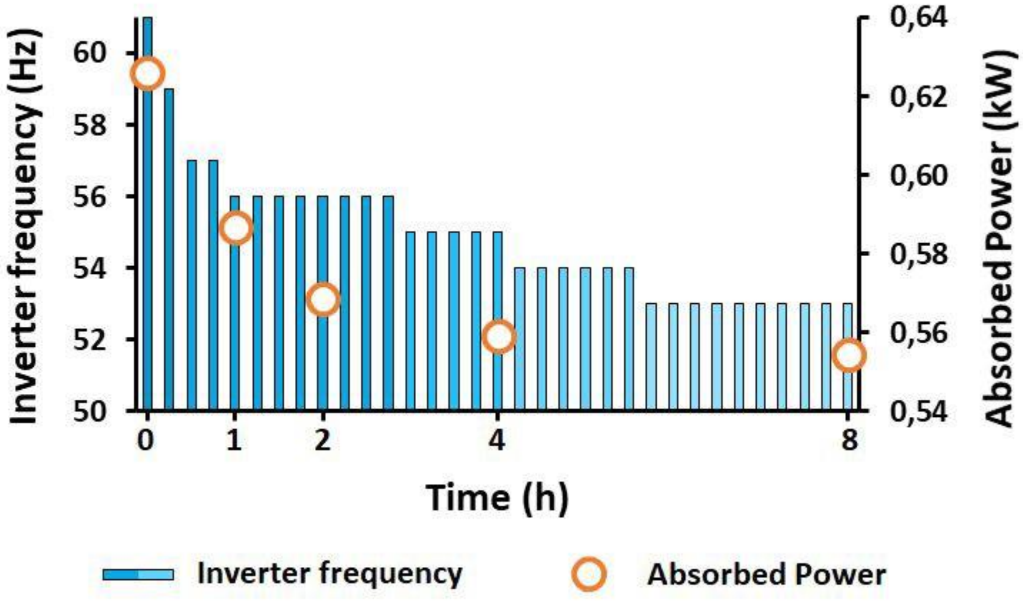

Fig. 6 – Pump inverter frequency and absorbed power at 1h, 2h, 4h and 8h.

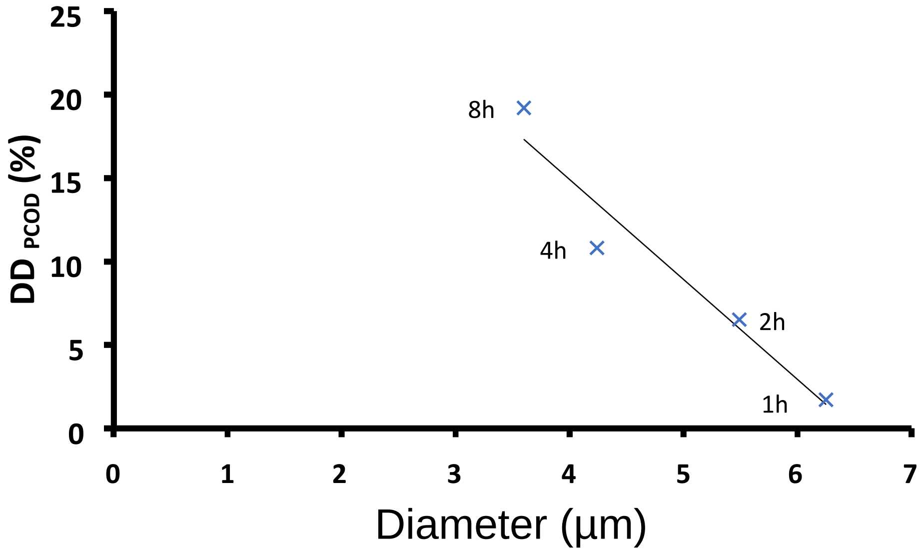

Fig. 7 – Correlation between the maximum diameter measured in the investigated range and the sludge disintegration degree. The width of the spheres depends on the applied HC pre-treatment time.

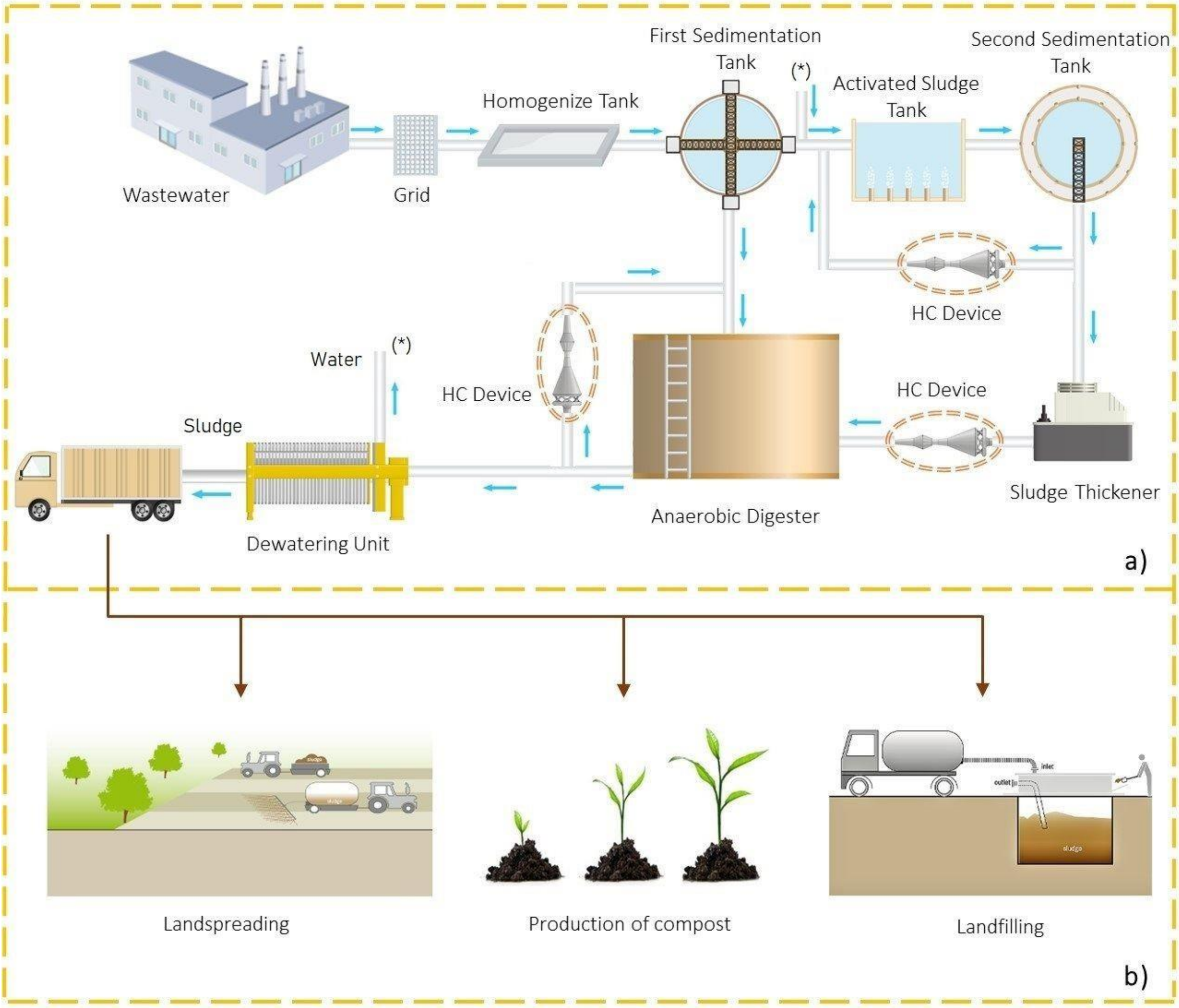

Fig. 8 – a) Application of HC for the improvement of rheological features in WWTPs; b) environmental-friendly solutions for the safe disposal of stabilised sludge.