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Enhancement of high pressure homogenization pretreatment on biogas production from sewage sludge: a review

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ABSTRACT

Different kinds of pretreatments have been practiced to disrupt sewage sludge and release extracellular polymeric substances of sludge flocs and inner constituents of bacteria cells for efficient biochemical conversion and biogas production. Among them high pressure homogenization (HPH) is a promising unconventional mechanical pretreatment method. HPH pretreatment works on the principles of turbulence, cavitation and shearing, solubilizing the sludge or enlarging its surface area for enzymatic attack, so that enzymatic hydrolysis can be efficiently enhanced and subsequently biogas production can be significantly improved. HPH pretreatment of sewage sludge is not only investigated in research work (theoretically), but also it has been integrated into sewage sludge treatment in wastewater treatment plants, presenting positive results. However, there is still research gaps in terms of efficiency improvement and cost minimization. This review paper outlines promising aspects of sludge HPH pretreatment for biogas production enhancement and presents directions for future researches to fulfill the research gaps.

Keywords: High pressure homogenization; Pretreatment; Sewage sludge; Disintegration; Enzymatic hydrolysis; Biogas production

1. Introduction

Researchers have proposed an alternative energy sources in order to reduce the rapid utilization of fossil fuels, to reduce the dependency on petroleum producing countries and minimize environmental degradation. One of the alternative energy sources, having the potential to compete with oil, is the bioenergy produced from sewage sludge. With the increase of wastewater treatment plans (WWTPs), an increase of sludge production has been witnessed, for example, wet sludge of approximately 36 million tons was produced in China in 2018 [1], which is a great source for biogas production. And similarly the dry sludge production in USA was 7 million tons in 2005 and in European countries was 13 million tons in 2007 [2,3]. Therefore, the anaerobic sludge digestion for methane production has become one of the most important and widest applied technologies for sewage sludge treatment [4].

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Generally, the sewage sludge goes through four steps, that is, hydrolysis, acidogenesis, acetogenesis and methanogenesis during anaerobic digestion process and finally organic carbon of the sewage sludge is biochemically transferred to methane [4,5]. However, sewage sludge is resistant to biodegradation because it contains extracellular polymeric substance (EPS) and microbial cells [6]. Enzymatic activity during hydrolysis step is limited by microbial cell walls [7].

Different kinds of sewage sludge pretreatment, such as chemical, biological, hydrothermal and mechanical, have been executed to accelerate the hydrolysis step of anaerobic digestion and subsequently to improve biogas production [8,9]. In term of chemical pretreatment the solubilization of sludge organics is accomplished by the use of strong mineral acids or alkali and oxidants [10]. However, using strong chemicals (NaOH, KOH) can inhibit anaerobic digestion due to the generation of secondary products and also produce further environmental consequences [11]. Disadvantages of biological pretreatment are time intensive and difficult to maintain hydrolysis performance [12]. Generation of inert organic compounds and odor generation are the main drawbacks associated with sludge hydrothermal pretreatment [13]. High pressure homogenization (HPH) is one of mechanical pretreatments, which avoided or minimized these drawbacks, and has gained strong attention due to its various successful industrial scale applications [14]. Mosier et al. [15] stated that sludge pretreatment caused a physical and chemical alteration in sludge structure, as a result, the organics in sewage sludge became available to biogas production. For such chemical reaction and/or physical alteration due to pretreatment, the development of effective models is needed, which can be used for the rational design of pretreatment procedure. One of the main objectives of sludge pretreatment is to disintegrate the sewage sludge and release the organic matters into liquid, which is beneficial to accelerating the microbial reactions and subsequently improving the bioenergy production.

To enhance bioenergy production, pretreatment of sewage sludge has caught greater importance in the recent years. Only 17 research articles on sludge pretreatment were published in 2001, while 167 research articles were published in 2018 (Fig. 1) (https://www.engineeringvillage.com).

This review paper assesses and analyzes the present state of knowledge regarding to HPH pretreatment of sludge to improve bioenergy production and give directions for future researches. Moreover, this report give the explanation of HPH pretreatment mechanisms, factors influencing the performances of HPH pretreatment, and practical implementation of this technology. To enhance the efficiency of HPH pretreatment for qualitative and quantitative production of bioenergy, suggestions for future research are pointed out. This review tries to emphasize the importance of HPH pretreatment of sludge for better bioenergy production and waste management in WWTPs.

2. Principle and disintegration mechanisms of HPH pretreatment

HPH is totally a mechanical pretreatment, which works on the principle of passing a fluidic substrate by forcing through a narrow nozzle [16]. A standard homogenizer mainly consists of impact ring, homogenizer valve, valve seat and positive displacement pump [17]. The fluid is forced into the homogenizing valve by pump, where the work is done as shown in Fig. 2.

During HPH, mainly three kinds of mechanisms are involved for the disintegration of biomass, eddies in turbulence flow, impingement and cavitation. Liquefied homogenate is formed during HPH process because of turbulence, cavitation and deformation of droplets and collision, resulting in recoalescence of droplets [18].

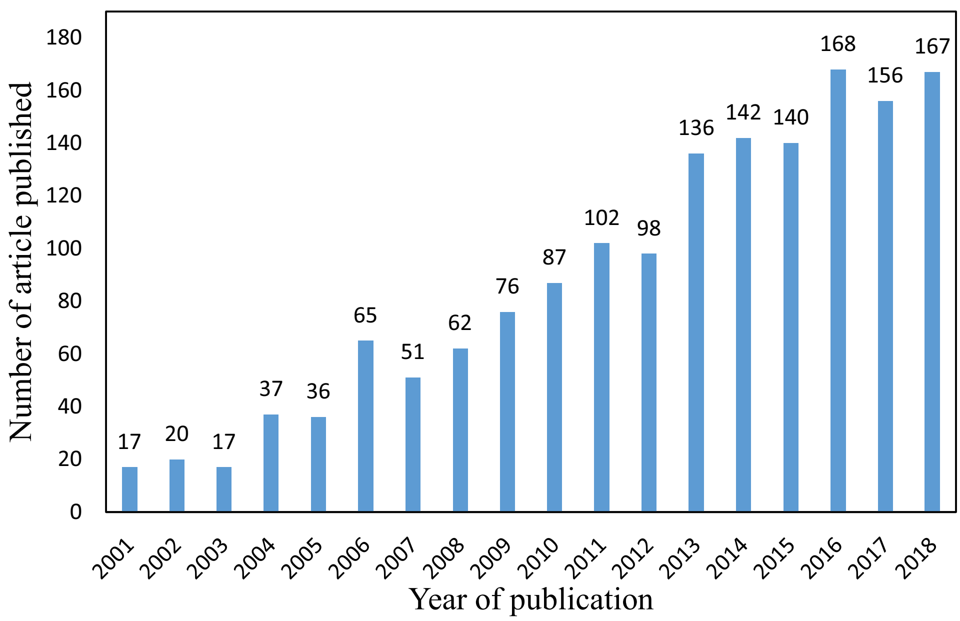

Fig. 1. Research articles published annually on sludge pretreatment.

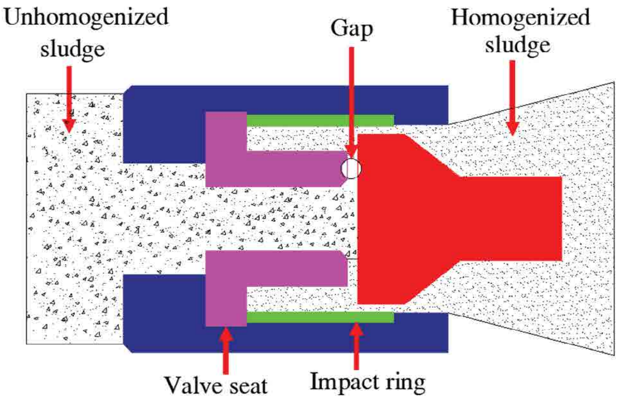

Fig. 2. Disruption valve of high pressure homogenizer.

2.1. Eddies in turbulence flow

The energy applied to homogenizer valve is converted to kinetic energy, which disperses into the liquid. Huge number of eddies then form in the turbulence flow, and microorganism cells in sewage sludge suffer shearing force in different scales and intensities. Such disperse energy produces turbulence in the liquid, resulting in formation of large and small eddies. The small eddies are responsible for the disruption of cells [19].

2.2. Impingement

In high pressure flow devices, it is necessary to impinge high velocity jet of suspended cells on a stationary surface, for effective cell disruption. Impingement stresses are produced when the high velocity jet strikes on impact plate positioned near the orifice discharge, due to the applied pressure [20], resulting in a high liquefied homogenate [21]. And a huge shearing and cavitation is produced because of sudden pressure drop in the fluid.

2.3. Cavitation

Thermodynamics cavitation is formed in orifice and gap between the valve and valve seat of homogenizer, where the fluid pressure drops below the vapor pressure [22]. Actual measurement of cavitation noise in homogenization valve suggests that the greater the intensity of cavitation, the greater the effect of homogenization [23]. Rai and Rao [24] reported that when HPH pretreatment was executed for sewage sludge, microbial cells were ruptured by means of cavitation and turbulence, which resulted in the increase in soluble chemical oxygen demand (SCOD) and the decrease of the microbial growth.

3. Main influencing factors for HPH pretreatment performance

3.1. Substrate compatibility

The main purpose of HPH technology in cosmetic, pharmaceutical and food industries, is to make the feeding substrate stabilized, emulsified and mold into the desired shape [25]. HPH has been used in juice producing industries and the shelf life of juice was successfully prolonged. Carbonell et al. [26] passed orange juice through HPH at 150 MPa and claimed that the juice could be stored for 3 months at 3°C. Maresca et al. [27] pretreated apple juice with HPH using 150 MPa and three homogenization cycles, and the microbial inactivation achieved, so that the apple juice can be stored for 28 d under refrigerated condition. Furthermore, the particle size decreased up to ten times with a mean diameter from 567.1 to 51.2 μm with HPH treatment, and such small particles contributed to the cloudiness of juice. Milk was treated with HPH by Ciron et al. [25], and yoghurt with low fat was prepared from the treated milk, the significant modification was observed in its microstructure, such as, porous structure, fat globules and interconnected protein network. Such kind of microstructure is responsible for modification of gel particle size, sensory properties and rheological behavior, producing products with high gel strength, uniform particle size distribution and high viscosity.

Furthermore, some researchers studied HPH in sewage sludge pretreatment. With the HPH pretreatment of sludge, the particle size reduces, forming a fine emulsion, and the highly proper order structure changed to distorted and poly porous structure [28]. Hence, HPH pretreatment can enlarge the surface area of sewage sludge for better enzymatic activities [29]. When HPH pretreatment was executed prior to the anaerobic process, sludge was disintegrated and anaerobic digestion was accelerated, significantly. Meanwhile, the total suspended solid (TSS) and volatile suspended solid decreased by 30.52% and 37.04%, respectively, with the HPH pretreatment at 80 MPa [30]. Energy consumption during HPH pretreatment is higher than hydrothermal pretreatment [31], but lower than ultrasonic pretreatment [32].

The types of biomass to be pretreated, greatly affect the performances of HPH, because different microbial cells have relative resistance to HPH pretreatment for disintegration [33]. The DD_{COD} is attributed to the different cell wall and cell membrane composition, e.g. cell wall of gram-positive bacteria is made of 40 layers of peptidoglycan chain, so that gram-positive bacteria show more resistant to HPH pretreatment. In contrast, cell wall of gram-negative bacteria is made of about 1–5 layers of peptidoglycan chain, which is sensitive to HPH pretreatment [34]. Homogenization pressure of 250 MPa was applied to three different microbial strains i.e. *E. coli*, *S. cerevisae* and *L. delbrueckii*, and the inactivation of *E. coli*, *S. cerevisae*, and *L. delbrueckii* achieved 6, 5 and 1 log-cycles, respectively [35]. Therefore, it is necessary to consider the compositional characteristics of feeding substrate. Furthermore, when the biomass contains lignocellulose with compact structure, they are more resistant to HPH disintegration, and the mechanisms are also different. Chen et al. [29] pretreated sugarcane bagasse with HPH at 100 MPa and found that the enzymatic digestibility increased from 29.5% to 59.4%. The increase of enzymatic digestibility was attributed to the significant decrease of particle size and the disruption of bagasse microstructure, which changed from a rigid and highly ordered fibril to a distorted, poly-porous and empty-inside structure.

3.2. Total solid (TS)

TS of feeding sewage sludge significantly affect the performances of HPH pretreatment. When the same homogenization pressure was applied to sewage sludge, a TS content of 9.58 and 24.60 g/L resulted in the highest and lowest DD_{COD}, respectively [32]. The higher the TS of feeding substrate, the lower the DD_{COD} is at the same homogenization pressure. Zhang et al. [30] pretreated sewage sludge with different TS contents using HPH to optimize energy efficiency, and obtained energy efficiency of 46.92, 55.31 and 77.18 g/MJ for maximum SCOD solubilization with the sludge TS of 1.00%, 1.49% and 2.48% at a homogenization pressure of 30 MPa, respectively. HPH pretreatment of sewage sludge with the higher TS is more energy-efficient under the same operating parameters, that is, homogenization cycle number and homogenization pressure, because more organic matters are released. These results are consistent with the research work from Onyeche et al. [36], being executed for the improvement of bioenergy production through HPH pretreatment of sewage sludge. Biogas production of three sludge samples were compared by Onyeche et al. [36], the first sample was raw sludge as a reference, the second was disrupted at 50 MPa, and the third was concentrated and disrupted at 50 MPa. The results indicated that the total biogas production after anaerobic digestion of 20 d for the concentrated and disrupted sludge was higher than the rest two. For the optimization of HPH pretreatment performance, it is necessary to select specific homogenization conditions for specific TS, which is still a research gap needed to be filled.

3.3. Homogenization pressure and cycles

Homogenization pressure and cycles are the key influencing factors, which affect the performances of HPH pretreatment. With the increase of homogenization pressure, the DD_{COD} of substrate increases. Zhang et al. [32] demonstrated that the increase of homogenization pressure from 20 to 80 MPa resulted in a significant increase of DD_{COD}. Although the increase in pressure resulted in efficient sludge disintegration, the HPH pretreatment is energy-intensive.

Single pass of substrate through homogenizer is not as effective as passing many times (multiple cycles), which is shown in Table 1. For cell disruption, using single HPH pass requires very high pressure, which increases the cost of energy, equipment and maintenance. Alternatively, the effectiveness of HPH pretreatment can be improved by multiple cycles [27,37]. Increase in cycle number favors the sludge disintegration; however, multiple cycles are also energy-intensive. So cycle number should be optimized. Fang et al. [38] found that after three homogenization cycles, the SCOD and DD_{COD} of sewage sludge increased by 39% and 11%, respectively, compared to the single homogenization cycle. The sewage sludge DD_{COD}, as a result of HPH pretreatment, is affected by two main parameters i.e. homogenization pressure (P) and cycle number (N) as shown in Eq. (1) [32].

$$DD_{COD} = kN^a P^b \tag{1}$$

where k is the rate constant of sludge disintegration, a is the homogenization cycle exponent and b is the homogenization pressure exponent. From Eq. (1), it can be inferred that sludge disintegration is directly proportional to homogenization pressure and number of homogenization cycle. For the energy conservation and sludge disintegration efficiency, it is important to determine the optimum homogenization pressure and cycle according to compositional characteristics of substrate for energy conservation and high efficiency of sludge disintegration.

3.4. Disruption valve of homogenizer

The cell wall disruption by HPH at a fixed pressure is significantly affected by the valve design, that is, height and shape of the valve gap and geometrical characteristic of the seat and valve (Fig. 2). The geometry of homogenization valve is of great importance because it affects the efficiency of energy transfer from the surrounding fluid to suspended cells through fluid dynamics, which establishes in the valve and downstream of it. To date, no studies were devoted to the modification of existing homogenization valve for sewage sludge disruption. The sludge composition is different from the traditional substrates (cosmetic, pharmaceutical and food industries), so the special design of disruption homogenization valve specific to sludge pretreatment is needed. And modelling studies in the design of homogenization valve will be actually beneficial to the investigation of sludge treatment and utilization.

3.5. Combination of HPH with other pretreatments

Single pretreatment, physical, chemical or biological has its own drawbacks in term of poor sanitization, more energy

Table 1
Effect of multiple homogenization cycles on HPH performances

Feeding substrate	Effecting parameters	Changes in parameters with increase in cycle number			References
Sludge	DD_{COD} (%)	11.75 (1 cycle)	32.15 (2 cycles)	40.07 (3 cycles)	[39]
Sludge	VS removal (%)	23.58 (1 cycle)	33.42 (2 cycles)		[14]
	TCOD removal (%)	24.37 (1 cycle)	44.85 (2 cycles)		
	Biogas production rate (mL/d)	885 (1 cycle)	1,634 (2 cycles)		
Orange juice	Microbial load	Decrease in microbial load with increase in cycle number (cycle number increased from 1 to 5)			[40]
Apple juice	Yeast	Inactivation of Yeast in fruit juices (3 cycles)			[27]

consumption and high operational and capital cost. To minimize these drawbacks, hybrid pretreatment techniques are advised to be executed. Many researchers have been investigated the improvement of bioenergy production through hybrid pretreatment methods [10,41,42]. To improve sludge disintegration efficiency and reduce operational cost, HPH should be combined with other pretreatment methods like chemical pretreatment. However, only a few studies have been conducted at the moment regarding the combination of HPH pretreatment with other pretreatment methods, which needs further exploration.

The combination of alkaline and HPH pretreatment increases the DD_{COD} of sewage sludge [39], because cell wall is firstly weakened by alkaline pretreatment, which enhances the efficiency of following HPH treatment. The sludge DD_{COD} of 59.25% achieved after alkaline + HPH pretreatment of sewage sludge, while the sum of DD_{COD} with the single alkaline treatment and single HPH treatment was 40.07%, under the same operational pretreatment conditions (pressure = 80 MPa, cycle number = 3 and NaOH dosage = 0.05 mol/L). Therefore, combination of other pretreatments with HPH pretreatment may result in a synergistic effect. Fang et al. [43] found that with a NaOH dosage of 0.04 mol/L, the DD_{COD} and SCOD increased by 26% and 93%, respectively, compared to HPH pretreatment alone (pressure of 60 MPa), and cumulative biogas production increased by 60% after 14 d anaerobic digestion. Energy efficiency can also be improved by the combination of NaOH and HPH pretreatment, compared to single HPH pretreatment [39]. After pretreatment at a pressure of 60 MPa with one homogenization cycle, combined with an alkaline dosage of 0.04 mol/L, the sludge total chemical oxygen demand (TCOD), VS removal and cumulative biogas production in a mesophilic anaerobic digestion system increased by 24.68%, 18.95% and 95.81%, respectively, in comparison with single alkaline pretreatment [44]. Jiang et al. [45] compared NaOH and NaOH + HPH pretreatments of lignocellulosic biomass in term of enzymatic hydrolyzability, and found that the enzymatic hydrolysis of NaOH + HPH pretreated biomass was significantly higher than that with single NaOH pretreatment. However, the high dosage of alkaline also inhibited the microbial activities. Therefore, strict supervision is required during the practical implementation of such hybrid pretreatment methods [46,47].

In another study, ethylenediaminetetraacitic acid (EDTA) was combined with HPH for the disruption of bacterial cells to release intercellular proteins; the maximum proteins were released at 13.8 MPa, whereas single HPH pretreatment needed 34.5 MPa to achieve the same release of proteins [48]. Using such a low pressure for the cell disintegration resulted in 60% decrease in energy requirements. To enhance intercellular protein release at lower pressure and with minimum protein denaturation due to chemical exposure, combination EDTA pretreatment with HPH is an efficient method [48].

The above examples clearly reflected that the combination of HPH pretreatment with other pretreatments has a positive effect on bioenergy production. During HPH pretreatment, the disintegration resistance of substrates either sewage sludge or other biomass (containing lignocelluloses) to the HPH pretreatment can be addressed through combination with other pretreatment. For the enhancement of bioenergy production and reduction of operating cost, it is a blank gap for further research to combine the HPH with other most suitable pretreatment methods either physical, biological or chemical methods.

4. Substrate change after HPH pretreatment

4.1. Organic release

When the sludge flocs are disrupted, the cell constituents (proteins and pectins) are released [49]. Physical disruption of sewage sludge and other biomass have been investigated by some researchers [38,50,51] through SEM studies, showing a distinct structure difference of substrates before and after HPH pretreatment.

The disintegration of sewage sludge by HPH results in the release of organic matters in supernatant. Zhang et al. [32] disintegrated sludge by HPH and found a positive increase in proteins and polysaccharides in the sewage sludge supernatant. The concentration of SCOD, proteins and polysaccharides of raw sludge were 99.20, 10.60 and 20.45 mg/L, which reached to 5,660.26, 614.12 and 372.17 mg/L, respectively, with HPH pretreatment at 80 MPa and four homogenization cycles. Furthermore, the increase in operating pressure (from 20 to 80 MPa) increased the concentration of proteins and polysaccharides by about 140%. In another study [52] for the spectroscopic analysis of dissolve organic matters of the sewage sludge after HPH pretreatment, it was observed that besides the release of proteins and polysaccharides, lipids were also released into the homogenate. The VS, SCOD and TCOD removal after anaerobic digestion are successfully improved by the HPH pretreatment, because the disrupted sewage sludge becomes more easily available for microorganisms [14,53]. The higher the removal of these materials, the higher the biogas production, demonstrating a strong correlation of the HPH pretreatment with biogas production. Biomass with compact structure does not release a lot of organic matters after HPH pretreatment, however, HPH pretreatment accelerates enzymatic hydrolysis because the compact structure is ruptured and larger biomass surface is exposed to enzymatic attack [53]. It can be concluded that the increase of soluble organic matters from pretreated substrates effectively improves the anaerobic sludge digestion [14].

4.2. Particle size change

The HPH pretreatment of sewage sludge increases the volume of small size particles because of the shearing and disruption [38,54]. Different researchers studied the particle size before and after HPH pretreatment and found huge decrease (Table 2). After the HPH pretreatment, the amount of small particles increases and the amount of large particles decreases enormously, because the large particles are susceptible to HPH and are easily broken into fragments. In addition, sludge particles can be reaggregated due to the increase of particle-particle interaction [38,55,56].

4.3. Viscosity change

HPH is a mechanical pretreatment, which changes the physical structure of substrates to a great extent. After HPH

Table 2
Effect of HPH pretreatment on particle size of different substrates

Substrate	HPH (MPa)	Before HPH pretreatment (μm)	After HPH pretreatment (μm)	References
Sewage sludge	20	48.26	15.54	[38]
	40	48.26	13.70	
	60	48.26	11.80	
Ortanique juice	20	346.3	130.3	[57]
	30	346.3	123.2	
Salustiana juice	15	340.3	150.1	
	30	340.3	107.7	
Soy protein isolate	137	3.3313	0.1467	[58]

pretreatment the viscosity of homogenate increases. Sewage sludge viscosity is directly proportional to the loosely bound EPS. With the HPH pretreatment of sewage sludge, the EPS are disintegrated and cellular content are released due to that the viscosity of pretreated sludge increases [59]. The viscosity of sewage sludge changes with the stress application, therefore, the sewage sludge can be categorized as non-Newtonian fluid.

4.4. Change of other properties

Fang et al. [38] found that the pH of HPH pretreated sludge slightly decreased, due to the release of volatile fatty acids (VFAs) from sewage sludge. Normally, there is a negative charge on the sludge flocs, and the solubilization of the loosely bound EPS results in the increase of negative charge of substrates and the change in zeta potential [60].

5. Bioenergy product enhancement through HPH pretreatment

Recently a great effort has been devoted to the biochemical conversion of biomass to different energy value products [61,62]. From Table 3 it can be concluded that different biomass were efficiently converted to bioenergy products by applying HPH pretreatment. To accelerate the hydrolysis step of anaerobic sludge digestion, sewage sludge was disintegrated through HPH pre-treatment to release inter and intracellular organic contents [14,43,44]. Biochemical conversion of these substrates is a complex process, during which biomethane, bioethanole and biohydrogen can be produced through anaerobic digestion, anaerobic fermentation and photobiological hydrogen production.

As an end product, biogas is generated from the breakdown of organic matters during anaerobic digestion, which is an economical method for the conversion of biomass to bioenergy [63,64]. Zhang et al. [14] compared methane production from raw sludge with HPH pretreated sludge, and found that methane production for the pretreated sludge with HPH was higher than that without HPH pretreatment. This phenomenon can be attributed to the higher content of soluble organic matters for methanogens in the sludge pretreated with HPH [14,65]. HPH pretreatment enhances biodegradability of sludge in the anaerobic digestion system, so that more biogas is produced and the methane content in biogas is improved. Wahidunnabi and Eskicioglu [66] conducted a comparative study on anaerobic digestion to investigate the methane production from sludge in a two-phase anaerobic digestion (2PAD), pretreated with HPH. It was observed that under the mesophilic and thermophilic condition, 75%–81% and 45%–54% more methane

Table 3
Energy products obtained from different biomass pretreated by HPH

Feeding biomass	Homogenization pressure (MPa)	Combination with other pretreatment	Energy products	References
Sewage sludge	50	Single HPH	Methane	[14]
Sewage sludge	60	Alkaline (NaOH)	Methane	[44]
Sewage sludge	60	Alkaline (NaOH)	Methane	[43]
Bamboo	100	Alkaline (NaOH)	Ethanol	[45]
Grass clipping	10	Alkaline (NaOH)	Reduce sugar, Methane	[51]
Sugarcane bagasse	100	Alkaline (NaOH)	Reduce sugar	[29]
Corncob	100	Nil	Xylooligosaccharide	[82]
Wheat straw	150	Nil	Glucose, Xylose, Ethanol	[83]
Microalga	120	Folch method of lipid extraction	Lipid	[81]
Eucalyptus kraft pulp	300 to 400	Nil	Reducing sugar	[84]

was produced in HPH + 2PAD system relative to the control digester, respectively.

Recently, agricultural, food and muncipal wastes have been investigated for the biohydrogen production [67]. The main drawback regarding biohydrogen production from these biomass is the low yield [68,69], and researchers used differnent pretreatment methods to address this problem [70–72]. Up to date there is very limited research on the enhancement of biohydrogen production by HPH pretreatment, which can be taken into consideration for the future research. Conversion of organics to VFAs through acidogenic fermentation is one part of anaerobic digestion, and VFAs can further be converted to biohydrogen by photo-perfermentation. *Entrobacter* and *Clostridium* are the well known bacterial species responsible for biohydrogen production, which is expected to increase in abundance with HPH pretreatment [73–75].

The VFAs production from sewage sludge through anaerobic fermentation is a promising technology in resource recovery and sludge treatment [9]. When sewage sludge is pretreated with HPH, the concentration of soluble carbohydrates and proteins increases drastically, which are easily biodegraded to produce VFAs through fermentation process. Li et al. [76] pretreated sludge with HPH, and the results showed that the VFA production was improved and the production increased with the increase of pressure. Furthermore, the sludge liquor obtained from the hydrolytic acidification can be added to sequencing batch reactor as external carbon source for denitrification successfully.

Enzymes play a vital role during the biochemical conversion of substrate to bioethanol, and the process normally comprises of pretreatment, hydrolysis, fermentation and distillation [77,78]. HPH pretreatment changes the sewage sludge to liquefied homogenate for the purpose of better enzymatic reaction, and enlarges the surface area of sludge, which is directly proportional to the enzymatic reaction and bioethanol production [79]. Some by-products generated during the bioconversion of biomass should be also taken into account for further utilization. For example, Filiciotto et al. [80] reported the utilization of levulinic acid, furfural and humins, which were produced from acid catalyzed sugar conversion. Lipid extraction from *Scenedesmus* specie (suitable for biodiesel production) was enhanced through HPH pretreatment combined with Folch methods, and a good result was observed comparing with conventional Folch method for lipid extraction [81].

6. Ground implementation and sustainability of HPH pretreatment for bioenergy production in WWTPs

6.1. Application of HPH pretreatment in WWTPs

The technology, combining HPH pretreatment and anazerobic digestion for bioenergy production, is available with the patent name of BIOGEST Crown disintegration system, CSO Technik, UK, and 11 installations have been set up. A study was conducted for the evaluation of BIOGEST Crown disintegration system, and reported that the sludge pretreatment with HPH prior to anaerobic digestion resulted in 20% reduction in sludge solid and 30% increase in biogas production [85]. Onyeche [86] reported that when the HPH was integrated into a WWTP for sludge pretreatment before anaerobic digestion, the produced energy was more than consumed in the pretreatment and digestion process. HPH can be combined with alkaline pretreatment for sludge disintegration, which has been patented under the trade name of MicroSludge™. The system has been implemented in the Chilliwack WWTP, British Columbia, Canada. In this system the sewage sludge was solubilized with the combined pretreatment of alkaline and HPH, and the hydraulic retention time reduced from 18 to 13 d. The MicroSludge™ has also been successfully installed in WWTP in Los Angeles County, California [87]. It can be inferred that the HPH is quite young technology for the biogas production, but has been implemented in the bioenergy plant and received positive results.

While considering the implementation HPH in WWTPs, energy consumption during the process cannot be ignored. The energy consumption of homogenizer for one homogenization cycle can be calculated according to Eq. (2) [48].

$$E_t = PQt \tag{2}$$

where P, Q and t are operating pressure, volumetric flow rate and time of operation, respectively. Total energy dissipated can be calculated for multiple cycles, by multiplication of E_t and number of homogenization cycle. To calculate total energy input, operational time was replaced by V/Q. Dividing by the total volume processed V, the energy dissipation per unit volume E is given by Eq. (3).

$$E = PN \tag{3}$$

where E is measured in terms of MJ/m^3, N is the number of homogenization cycle used and P is the operating pressure (MPa). From Eq. (3), it is clear that energy consumption of HPH is directly proportional to the input pressure [48]. Onyeche et al. [36] concluded that the energy consumed during the process (decanter, HPH, pumps and other accessories) was lower than that of the energy produced, i.e. energy balance is positive. The concentrated sludge attained positive energy of about 790 and 512 kJ/kg TS at a homogenization pressure of 10 and 20 MPa, while the non-concentrated sludge disrupted at same homogenization pressure were 291 and 189 kJ/kg TS, respectively.

6.2. Sustainability of HPH pretreatment

Facing the challenge resulted from huge volume of sludge produced in WWTPs and further possible serious environmental pollution [87], the sludge utilization with HPH pretreatment is proposed prior to biochemical conversion (Fig. 3). The waste sludge is subjected to HPH pretreatment to improve biochemical conversion. After the biochemical conversion of sludge, two kinds of products are produced: biogas and low load effluent. However, there are some constraints which need to take into consideration, such as homogenizer maintenance, combination with other chemicals, long term operation and energy balance. Direct application of the digestate in the agriculture land may cause environmental degradation. To address this problem, several methods are available for solid-liquid separation and nutrient recovery, after that the solid organic matters can be use in the agriculture land [88]. The liquid from digestate should return to the wastewater treatment system with different sources including communities and industries.

The sustainability of HPH pretreatment rests on environmental and economic dimension. Although HPH pretreatment process consumes energy, it reduces digester volume and sludge retention time, and increases biogas production [89]. Furthermore, HPH pretreatment does not need or minimizes the use of chemicals, presents simple operation, and there are no chemical changes in biomass composition [36,90]. HPH is a mature technology in the dairy, pharmaceutical, cosmetic and liquid food industries for emulsification, homogenization and pasteurization operation [16,91]. However, HPH is quite young technology for the pretreatment of sewage sludge to accelerate anaerobic digestion for bioenergy production. Researchers have used this technology as a pretreatment to improve biogas production from sewage sludge [89]. Based on the present knowledge about HPH pretreatment it is necessary to explore this technology and give some scientifically feasible guidelines for the pretreatment of sewage sludge to produce bioenergy.

HPH pretreatment combined with anaerobic digestion would be helpful for environmental sanitation and improve environmental health and public health because of the efficient sludge minimization and recycling [92]. HPH pretreatment consumes energy due to high input pressure; however, the sustainability of this process is potential. Stephenson et al. [21] calculated the cost of energy consumption by homogenization and the energy produced by the anaerobic digestion system (MicroSludge™) as electricity and heat for evaluating the efficiency of MicroSludge™ system. The unit power cost assumed 0.05 US$/kWh, and the total power cost of homogenization was about 38 US$ per dry ton of thickened waste sludge, while the total value of energy produced from MicroSludge™ system was about 128 US$ per dry ton of waste sludge processed.

7. Conclusion and future prospects

HPH is an emerging and promising technology for sewage sludge pretreatment because of its high efficiency and other advantages. HPH pretreatment significantly improves sludge particle reduction and organic solubilization, so the organics are more easily available for microorganisms and enzymatic attack during anaerobic digestion. HPH pretreatment disintegrate sludge on the principle of turbulence, cavitation, and shearing, and the sludge disruption mainly occurs at the homogenizer valve. This work presented outline of the HPH pretreatment to be executed for the sludge disintegration. However, there are some research gaps regarding HPH pretreatment, which needs to be fulfilled.

- The homogenization valve is the principal part of high pressure homogenizer, which is responsible for the substrates disruption. Up to date the homogenization valve of HPH designed for the normal product treatment does not fully meet the requirement for the pretreatment and is quite different from that of sewage sludge and other biomass (energy-rich substrates), therefore, future researches on the design of homogenization valve are needed to be investigated in depth to be fit for the pretreatment of sewage sludge and other different biomass.
- To accelerate enzymatic hydrolysis and to reduce operational cost, combination of HPH pretreatment with other pretreatment methods (for example alkaline + HPH

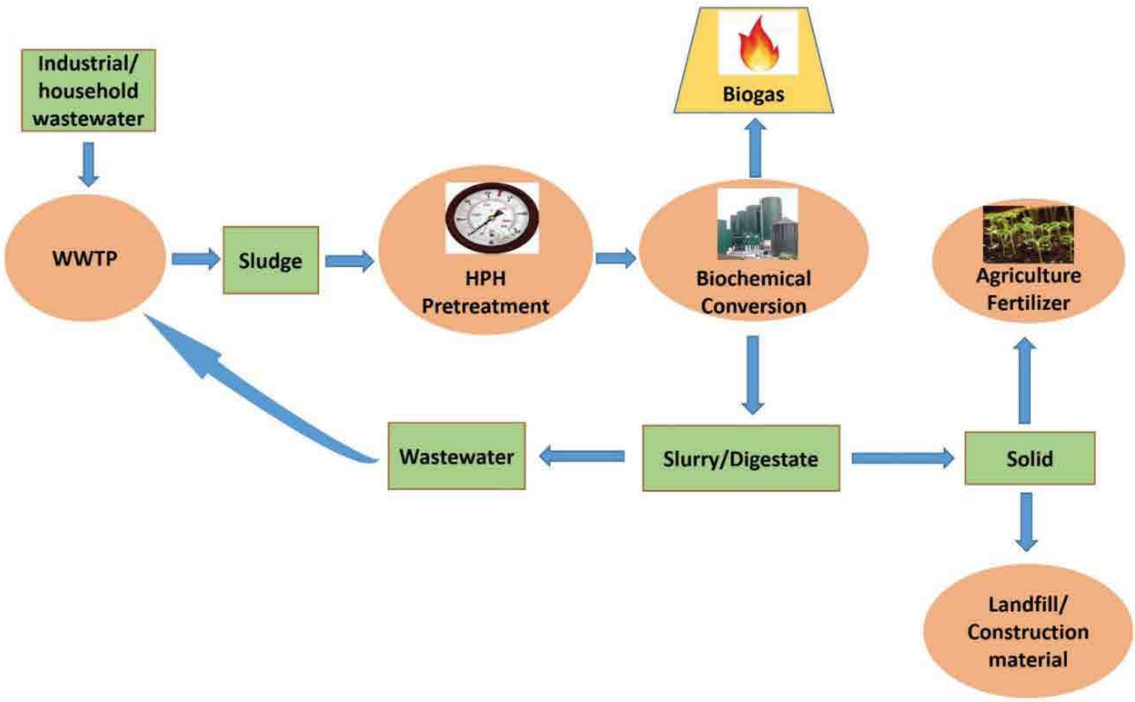

Fig. 3. Integration of HPH with bioenergy production in WWTP.

pretreatment) is a good option. The combination of HPH with other pretreatments is more effective than individual pretreatment method. However, there are further needs of researches on combining HPH pretreatment with other chemical pretreatments to achieve the proposed goals. It is suggested that HPH should be combined with some cheap and effective chemicals for the pretreatment of sludge.

- Specific energy input is inversely proportional to the influent TS and disruption pressure, which is lineally proportional to the energy consumption of HPH. To optimize the performances of HPH, it is necessary to select a specific homogenizing pressure for specific TS and specific substrates, which are still a research gap and needs further deep researches.
- Based upon the enhancement of bioenergy by HPH pretreatment, it is proposed to integrate HPH technology in the bioenergy production plant and investigate the comprehensive cost-effectiveness analysis in a very depth.

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