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SEWAGE SLUDGE THERMAL PRETREATMENT TECHNIQUES

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ABSTRACT: The development of world economy, consumption society, the need for environmental protection and sanitation in recent years has lead to increased demand for energy. An alternative to replacing the energy produced by fossil fuel consumption is renewable sources, including gaseous fuel from fermentation known as biogas One of the most popular methods is the biogas anaerobic digestion of biodegradable organic material in the sludge from wastewater treatment plants. This generating technology of renewable energy sources also solves environmental problems by reducing the quantity of sludge that must be stored and destroyed. The anaerobic digestion thus optimises WWTP costs, its environmental footprint and it is considered a major and essential part of a modern WWTP.The potential of using the biogas as energy source has long been widely recognised and current techniques are being developed to upgrade quality and to enhance the use of energy.

KEYWORDS: anaerobic digestion, energy, biogas, sewage sludge.

1. INTRODUCTION

The 21st century is characterized by a high growth of industrialization and urbanization. This leads to an increase in the needs of water consumption and therefore to increased flows of generated wastewater. The wastewater treatment leads in turn to generating important amounts of sludge. The sludge management is the major issue of wastewater treatment plants, as it costs 60% of the total plant capital cost and the laws for sludge disposal are becoming increasingly stringent, [1]. Over the years several methods of disposing of sludge such as incineration, ocean discharge, land application and composting have been used. These common sludge disposal methods are no longer reliable because of the economic constraints and the negative impacts on environment.

Although there are various possible ways of disposal of sludge, anaerobic digestion plays an important role for the abilities of transformation of organic matter into biogas (60-70% by volume of methane, CH_4), also in this type of treatment because it reduces the final solid amount of sludge for disposal, along with the destruction of the majority of pathogens present in the sludge and limiting the odor problems associated with residual putrescible matter. Anaerobic digestion thus optimises WWTP costs, its environmental footprint and is considered a major and essential part of a modern WWTP.

2. BASIC PRINCIPLES AND PARAMETERS OF ANAEROBIC DIGESTION

Sludge anaerobic digestion is a complex process that converts degradable organic compounds to methane (CH_4) and carbon dioxide (CO_2) in the absence of elemental oxygen on the basis of a series of microbiological processes. The way of conversion of the substrate into biogas (mainly CH_4 and CO_2) takes place in four steps, namely, hydrolysis, acidogenesis, acetogenesis and methanogenesis. The hydrolysis step degrades insoluble organic substances but also high molecular weight compounds such as lipids, polysaccharides, proteins and nucleic acids in soluble organic substances (e.g., amino acids and fatty acids). The components formed during hydrolysis are further split during acidogenesis, the second step. Volatile fatty acids are produced by acidogenic (or fermentative) bacteria along with ammonia (NH3), CO2, H2S and other by-products. The third stage is acetogenesis, where the higher organic acids and alcohols produced by acidogenesis are further digested by acetogens to produce mainly acetic acid as well as CO2 and H2. This conversion is controlled to a large extent by the partial pressure of H_2 in the mixture. The final stage of methanogenesis produces methane by two groups of methanogenic bacteria: the first group splits acetate into methane and carbon dioxide and the second group uses hydrogen as electron donor and carbon dioxide as acceptor to produce methane.

AD is performed with the participation of three different groups of bacteria:

-the first group involves the hydrolytic and acetogenic bacteria, which hydrolyze the complex substrates (carbohydrates, lipids, proteins, etc.) to dissolve the monomer (sugars, fatty acids, amino acids, etc.), and CO_2, H_2, organic acids and alcohols

-the second group is the metabolic hydrogen-producing bacteria, acetogens, which converts the simple monomers and fatty acids acetate, H_2 and CO_2.

-the third group of methanogenic bacteria use H_2, CO_2 and ethyl to produce CH_4 and CO_2. This complete process for the microbial digestion of the substrate is slow and requires a retention time. (Fig. 1).

Essentially all organic material can be digested, except for stable woody materials since the anaerobic micro-organisms are unable to degrade lignin.

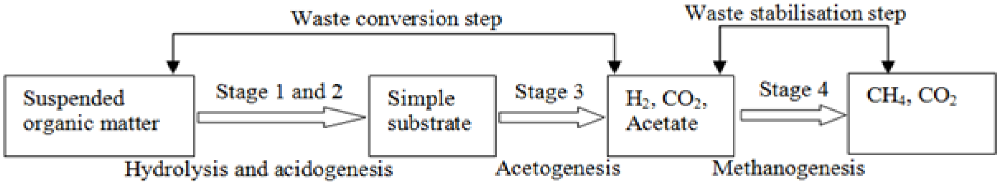

Fig.1. Stages of anaerobic digestion

The formed biogas has a high calorific value and is considered as a renewable energy source. Clearly, it is beneficial to produce as much biogas as possible, [2].

Despite these advantages of AD, some limitations are inevitable:

- only a partial decomposition of the organic fraction;
- the rather slow reaction rate , associated large volumes and high costs of the digesters;
- the vulnerability of the process to various inhibitors;
- the rather poor supernatant quality produced;
- the presence of other biogas constituents such as carbon dioxide (CO_2), hydrogen sulphide (H_2S) and excess moisture;
- the possible presence of volatile siloxanes in the biogas that can cause serious damage in the energy users (generator, boiler) due to the formation of microcrystalline silica;
- the increased concentration of heavy metals and various industrial ‘‘organics’’ in the residual sludge due to the significant reduction of the organic fraction during digestion, leaving the mineral and non-degradable fraction untouched.

Therefore, microbiology anaerobic digestion is complex and delicate, each of the groups of bacteria with their own optimal working conditions. These groups are sensitive and may optionally be inhibited by a number of waste and environmental factors.

3. WASTE AND ENVIRONMENTAL FACTORS ON METHANE PRODUCTION

3.1. Waste factors impacting methane production

Various factors associated with the waste impact both the quantity and rate of methane production:

-waste composition/degradable organic content;

-particle size;

-organic loading rate (kg/(m^3*d)).

The quantity of methane that can be produced depends on **waste composition** and in particular the degradable organic content. The theoretical maximum methane yield can be estimated from Eq. 1, [3]:

$$C_cH_hO_oN_nS_s + y\,H_2O \rightarrow x\,CH_4 + (c-x)CO_2 + n\,NH_3 + s\,H_2S \tag{1}$$

where:

x = 1/8 * (4c + h -20 – 3n – 2s);

y = 1/4* (4c – h – 20 + 3n + 3s).

However, all of the organic content may not actually be able to be degraded by the bacteria. Degradability of the substrate decreases as lignin content increases.

Biodegradable particles must come in close contact with bacteria as they attack and therefore should be provided a larger area between bacteria and particles. This can be achieved by a process of crushing the particles and creating a more homogeneous mixture of fine particles as well as bacteria. As the grain size is smaller, methane will be produced faster, because by increasing the exposed surface area bacterial attack intensity increases. The yield for substrates can be increased by up to 20% by shredding [5].

Mixing methods include:

- daily feeding of the digester (semicontinuous operation);
- installing a mixing device;
- creating a flushing action of the slurry through a flush nozzle;
- creating mixing action by flushing the slurry tangentially to the digester content;

3.2. Environmental factors impacting methane production

Environmental factors impacting the rate of methane generation include:

- temperature;
- pH;
- moisture content;
- nutrient content;
- concentration of toxic substances.

Recommended *temperatures* are: for mesophilic bacteria 30-40 °C and for thermophilic bacteria 50-60 °C. Thermophilic systems thus produce methane 25-50% faster, depending on the substrate, [6]. The digestion rate temperature dependence can be expressed using the Arrhenius equation:

$$r_t = r_{30}(1.11)^{(t-30)} \qquad (2)$$

where:

- t = temperature in °C;
- r_t, r_{30} are digestion rates at temperature t and 30°C, respectively.

Operating systems in the thermophilic range improves pathogen destruction.

Acidogenic bacteria prefer *pH* 5.5-6.5 and methanogenic prefers 7.8-8.2. When both cultures coexist, the optimal pH range is 6.8-7.5 [7]. Normally, alkalinity in anaerobic systems ranges from 1000 to 5000 mg / l, which ensures a sufficient buffer to avoid large drops of pH, [8].

Many landfill studies have confirmed that methane generation rate increases as waste *moisture content* increases. In many anaerobic systems, the digester is fed a water/waste mixture called slurry. As long as typical rules of thubfor water addition are followed, moisture content does not limit methane production, [9], [10].

Metanogenic bacteria require *macronutrients* P and N as well as *micronutrients*. The amount of P and N required can be estimated using COD/N/P ratios, with a minimum ratio of 350:7:1 COD/N/P needed for highly loaded systems (0.8-1.2 kg COD/(kg VSS*day), and a minimum ratio of 1000:7:1 COD/N/P needed for lightly loaded systems (<0.5 kg COD/(kg VSS*day) [6].

High levels of ammonia, soluble sulfides, soluble salts of metals, and alkali and alkalineearth metal salts in solution (e.g. those of sodium, potassium, calcium, or magnesium) can be *toxic* to methanogens, [11]. In addition, the methanogens are strict anaerobes; thus, their growth is inhibited by even small amounts of oxygen, or highly oxidized material, like nitrates.

4. SLUDGE THERMAL PRETREATMENT

In order to accelerate the digestion and to enhance the production of biogas, various treatments can be used to improve digestion rate-limiting hydrolysis. These treatments include biological interventions, mechanical, thermal, chemical of raw materials. All pre-treatments result in a lysis or disintegration of sludge cells, thus releasing and solubilising intracellular material into the water phase and transforming refractory organic material into biodegradable species.

Anaerobic digestion can be improved *by thermal pretreatment* of active sludge. The sludge is subjected to temperature in the range 150-200 °C and some pressures adjacent to these temperatures in the range 600-2500 kPa. The heat introduced during heat treatment affects the chemical bonds of the cell wall and membrane, thus solubilizing the cellular components. Table 1 shows the results obtained by different researchers in the use of thermal pretreatment to improve anaerobic digestion.

Table 1. Overview of thermal pre-treatment studies

Reference	Treatment conditions	Comments
Hiraoka et al. [12]	60–100 ^{O}C	-Maximum increase in gas production at 60 ^{O}C -Maximum VS reduction at 100 ^{O}C (only 5–10%)
Pinnekamp [13]	120–220 ^{O}C	-ODS reduction of 10–55% for WAS -ODS reduction from 7% to 34% for primary sludge -Maximum gas yield for treatment temperature of 170 ^{O}C -Positive correlation between gas yield and treatment temperature
Li and Noike [14]	62–175 ^{O}C 30–60 min	-Increase of sludge solubilisation ratio by 25–45% (optimum at 90 ^{O}C) for WAS -Increase of 30% VSS degradation and of 100% methane production (optimum at 170 ^{O}C and 60 min) -No further improvement for longer treatment times -Reduction of retention time in digester by 5 days
Tanaka et al. [15]	180 ^{O}C 60 min	-90% increase of methane production -VSS solubilisation of 30%
Zheng et al. [16]	220 ^{O}C 30 s	-55% VS reduction during digestion -Increase in gas production of 200% during first 2 days -Total increase in gas production of 80%
Kim et al. [17] _	121 ^{O}C 30 min	-Increase of VS reduction by 30%
Valo et al. [18]	170 ^{O}C	-59% increase of TS reduction -92% higher gas production
Ferrer et al. [19]	70 ^{O}C 9–72 h	-Positive effect on gas production -Higher temperature (110–134 ^{O}C) did not have any effect
Climent et al. [20]	70–134 ^{o}C 90 min–9 h	-Studied thermophilic digestion -50% increase of biogas production at 70 ^{O}C (9 h)

Although all studies reported a positive impact on pre-treatment of anaerobic digestion, optimal and effective conditions vary considerably. This is due to the fact that the temperature and duration of the pre-treatment depends largely on the nature and composition of the sludge; the more complex it makes it more difficult to improve the process of hydrolysis [22].

Some commercial processes have been developed based on thermal pre-treatments. The most well-known processes developed on the basis of pre-thermal and industrial treatments are Cambi and Exelys. The Norwegian company Cambi Inc. Has developed a system based on thermal hydrolysis. A soluble solubility of approximately 30% (depending on the type of sludge being processed) has been reported for a 30-minute treatment at 180 ° C and an associated increase of 150% biogas production.

The Cambi process serves as an effective pre-treatment technique to the anaerobic digestion of sludge [23]. As illustrated in Figure 2, the Cambi process consists of three basic units: the Pulper, the Reactor and the Flash Tank.

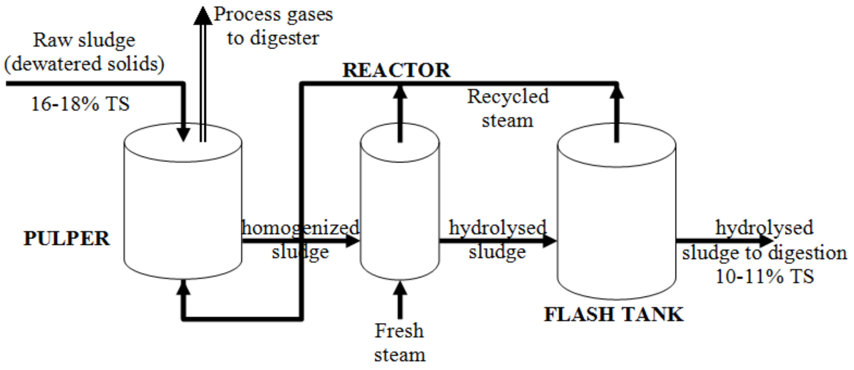

Fig. 2. Schematic Cambi Process Overview

The thermal hydrolysis treatment hydrolyzes the cell walls and releases soluble COD for digestion. Cambi process is better than the conventional thermal hydrolysis process because it operates at comparatively lower temperatures (160°C-180°C) and utilizes steam instead of heat exchangers for primary heating of sludge.

The process offers the following advantages over conventional systems:
- high volatile solids destruction (~60-70%);
- low digester volume;
- high biogas yield (~150%);
- well dewatered cake (~35%);
- pasteurized product(Class “A” biosoilds) with low transportation cost.

In addition, the dewatered cake solids also increase substantially. All these advantages can be explained by the bioavailability of organic material to fermentative organisms after thermal hydrolysis. The process takes place in 4 steps:

Thickening: The sludge is dewatered to 16-17% dry solids using a centrifuge, belt and filter press or other dewatering devices.

Pulper: The dewatered sludge is fed into the pulper to be mixed and heated by recycled steam from the reactor(s) and the flash tank. Process gases are compressed and broken down biologically in the digesters (minimal odor).

Reactor: The sludge is batchwise pumped into the reactor. Thermal hydrolysis takes place in reactor(s) at 165ºC for 20-30 minutes. The steam is gradually released and sent back to the pulper. The batch reactor is maintained at these conditions for approximately 30 minutes to produce a product that meets Class A biosolids standards and causes no filamentous bulking problems in the digester. The sludge is homogenized using a recycle loop and a macerator.

Flash Tank: The sterilized sludge is then passed rapidly into the flash tank, resulting in cell destruction from the pressure drop. The sludge temperature is decreased to approximately 102º C by flashing steam back to the pulper.

By relieving the kinetic limitations of biological hydrolysis, higher solids loading rates can be applied such that a significantly smaller digester volume is required. Hydrolysis temperature is more important than the contact time and seems to govern the extent to which sludge disintegration occurs [24]. It was reported that a temperature higher than the optimum range leads to a sharp reduction in biodegradability of sludge hydrolysate [25].

In reality there are more components in the system than these three main units. The residuals need to pass through some type of screening facility ahead of the THP to remove materials from the residuals stream that could potentially damage downstream equipment. The residuals must also be pre-dewatered to slightly higher than 16% TS before being transferred to a silo or bin that is large enough to provide equalization of inflow variations allowing the THP to operate at a uniform flow rate. When the residuals are introduced to the THP system, they are first transferred to the Pulper Tank via augers in the bottom of the storage bin and pumps. The concentration of solids to the pulper is diluted to a concentration between 14.5 and 16.5% TS using dilution water, typically plant effluent.

Kruger Inc., a subsidiary of Veolia Water, has developed a similar heat treatment marketed under the name of **Exelys**. Compared to conventional digestion, treatment provides 30-40% less sludge for disposal, 20-40% more biogas, up to 50% capacity uptake for existing digesters, and reduced carbon footprint

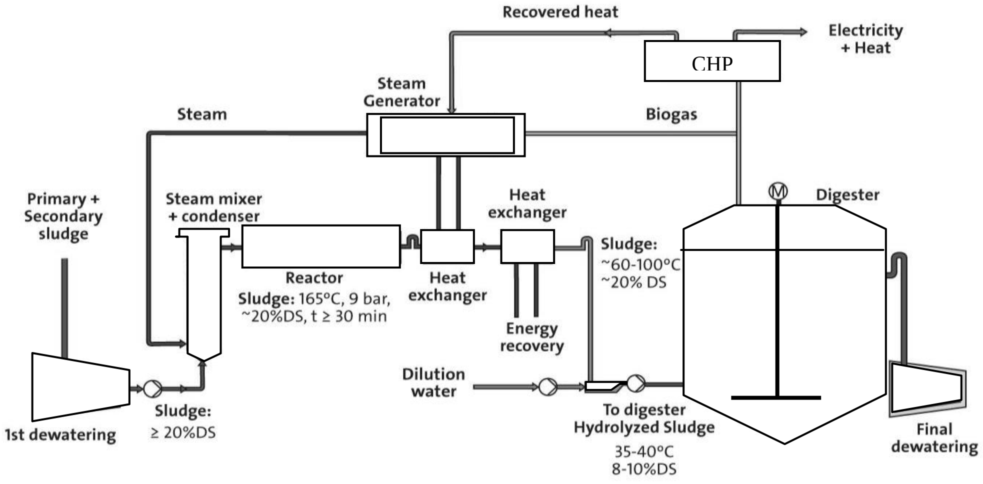

Fig.3. The EXELYS-DLD™ (Digestion – Lysis – Digestion) process configuration

EXELYS™ is an innovative technology that represents the next generation of thermal hydrolysis. Thermal hydrolysis has been recognized as one of the most effective ways to enhance biogas production and solids destruction when used as pretreatment for an anaerobic digestion system. Through its innovative design and continuous operational configuration, EXELYS is the most energy-efficient technology available for thermal hydrolysis. With the unique characteristics of the hydrolyzed sludge, EXELYS is the ideal solution for significantly increasing the capacity of existing digestion systems. EXELYS - the key to achieving the full potential of your renewable biosolids energy.

EXELYS offers special features:

- incoming sludge with high DS content results in more efficient energy utilization;
- continuous automated operation allows for optimal performance at all times;
- higher solids loading in the digester due to the hydrolysate’s characteristics, increasing existing digester capacity by up to 50%;
- cost-effective expansion of digester capacity;
- heat recovery and recycling further improves energy efficiency;
- simple and efficient maintenance and cleaning of all components;
- reduced operation and maintenance costs;
- increased biogas production over traditional digestion;
- decreasing plant’s energy costs.

The variant EXELYS-DLD™ (Digestion–Lysis–Digestion) process configuration, Fig. 3, is a patent pending design to become the powerhouse of your wastewater treatment plant. EXELYS-DLD™ optimizes the anaerobic digestion process, maximizing the production of renewable biogas energy while minimizing the volume of sludge for disposal. In a modern wastewater treatment plant where energy efficiency is vital, the increased biogas energy available from the EXELYS-DLD™ solution is enough to make the entire wastewater treatment process energy self-sufficient – decreasing costs and reducing the carbon footprint.[26].

At the core of the process EXELYS technology offers important advantages:

- increased biogas production when compared to thermal hydrolysis alone, energy self sufficiency possible;
- 20-30% higher solids destruction than conventional digestion, lowering disposal costs;
- energy-efficient thermal hydrolysis – less biogas consumed for hydrolysis;
- significantly decreased carbon footprint.

Special features

- optimized utilization of the biosolids resource’
- maximized solids destruction – maximized biogas production;
- less biogas consumed – more available for other applications;
- energy recovery and recycling is optimized;
- nothing is wasted

Blue Plains Advanced Wastewater Treatment Plant Process (hydromechanical screw-mill) operated by District of Columbia Water and Sewer Authority (DC Water), is the largest plant of this kind in the world, averaging 370 MGD, which provides advanced nutrient removal (i.e. nitrification and denitrification, multi-media filtration and chlorination / dechlorination) [26]. The plant used to generate Class B biosolids for land application by 100% lime-stabilizing and dewatering sludge (primary, secondary and nitrification / denitrification). Currently DC Water is implementing their new Biosolids Management Program (Fig. 4) that includes four CambiTM thermal hydrolysis process (THP) trains (6 reactors each train) for sludge pretreatment, four 3.75 MG (14,200 m^3) mesophilic anaerobic digesters for biogas production and three 4.6 MW gas turbines for power generation and heat recovery [27]. In each THP train, predewatered raw sludge (TS 16.5%) is preheated in the pulper tank to 97 °C for homogenization for 1.5 hours and then treated in THP reactors at 165° C and 6 bar for 20 min.

The pressurized sludge is subsequently transported to the flash tank, where cell destruction occurs resulting from pressure drop. The sludge temperature is decreased to approximately 102 °C by flashing steam back to the pulper tank. THP generates hydrolyzed sludge (TS 8–12%) with lower viscosity allowing mixing at higher solids concentration and more readily biodegradable materials for subsequent AD process, which results in remarkably higher biogas production compared to conventional digestion. Biogas will be utilized to fuel the CHP facility to generate 11.8 MW of power and supply steam for THP simultaneously, which will not only offset 33% of the power consumption but also reduce the plant’s GHG emissions by 40%. The THP pretreated sludge can be fed to digesters at higher organic loading rates with reduced digester volume, which further enhances the economy of the project [53]. This process will also generate pathogen-free Class A biosolids for soil amendment. Blue Plains AWWTP will be the first facility in North America that adopts full-scale THP technology for sludge pretreatment prior to AD. This practice will potentially reduce the plant’s carbon footprint by approximately 60,000 mt of CO_2 equivalent annually, resulting from biogas-based energy generation, elimination of lime for sludge stabilization and reduced truck use for biosolids disposal and transportation [27].

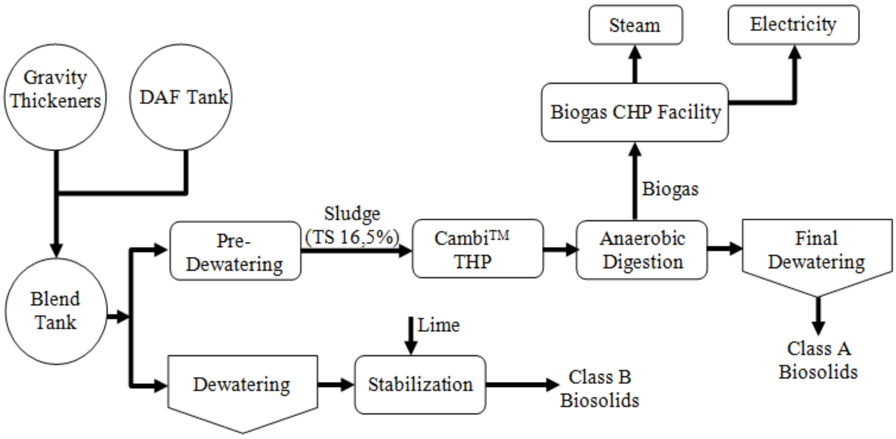

Fig.4. Blue Plains Advanced Wastewater Treatment Plant (AWTP), operated by District of Columbia Water and Sewer Authority

5. CONCLUSIONS

This review presents many different possibilities for the use of anaerobic digestion technology in WWTPs. While biogas production at WWTPs has less publicity than other renewable fuels such as solar or wind, provides reliable sustainable energy and low cost for WWTPs, and reduces the greenhouse gases emissions from wastewater treatment plant operations. Recent expansion in the definition of "cellulosic biofuel" is expected to greatly increase the demand for biogas production and utilization due to eligibility of biogas derived fuels to generate low greenhouse gases emissions. However, the wastewater industry may end up unable to increase the production of biogas from the level of demand. Although increasing biogas industry in the world is a complex process, the implementation of new practices will improve the technologies for the production of biogas, but also offering solutions to many technical challenges. Among the many efforts to improve digester performance at US WWTPs, co-digestion of sludge with other organics is very promising because of high methane yield, more efficient digester volume utilization and less biosolids production. Development of new strategies is important to maintain energy self-sufficiency at WWTPs. This is helpful not only for developing a viable and sustainable biogas industry, but also for providing valuable insight to state and local regulators, community officials and other stakeholders.

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