Research Progress in Anaerobic Digestion of High Moisture Organic Solid Waste

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ABSTRACT

High moisture organic waste constitutes a large fraction of municipal solid waste and caused a nuisance. Anaerobic digestion of this high degradable fraction has been developed during the past 20 years. Parameters such as characteristic of substrates, temperature, organic loading rate and hydraulic retention time were studied. The most important conversion of intermediate of volatile fatty acid was observed as a indicator of digestion efficiency. One stage and two stage system are based on the stage separated into acidogenic phase and methnogenis phase. Two stage digestion of this kind of wastes were proved a better efficiency than single stage digestion. Batch system and continuous system are conducted in single stage and two-stage system. One stage system are split between wet system(Total solid less than 15%) and dry system(total solid higher than 15%) according to the characteristics of feedstock. Two-stage solid bed system are observed more and more popular in the digestion of solid state VFW and food waste experimental studies, however the large majority of industrial application use single stage systems. Two stage digestion of HMOW will be applied to industrial scale due to its larger resistance to high loading rate, high and stable gas production.

Keywords: Anaerobic digestion, high moisture, organic solid waste, biogas

1. INTRODUCTION

MSW are produced in large quantities in the world which compounded by many different opponents such as paper, plastic, metal, glass, wood and other high-moisture organic waste represented as green waste(GW), food waste(FW), fruit and vegetable waste(FVW) contributed by households, restaurants and markets. There are 12% food waste and 12% yard trimming of the total MSW in America in 2002 (EPA, 2003). In India, there are 5.6 million FVW was produced annually and currently are dumped on the outskirt of cities (Bouallagui et al., 2005), which constitute a source of nuisance. The proportion of food waste component in MSW is gradually increasing from 27% in 1991 to 50% in 1995(IEA and OECD, 1998). Considering the characteristics of this kind of waste is solid-shaped, high-moisture, high-organic and high bio-degradability, Landfill has great limitation due to it's environmental impact and resource waste and result in being restricted in some counties(Alvarez et al., 2000). Such as Swedish regulate that no biodegradable waste should be landfilled after 2005 (Murto et al., 2004) and a tax of 25 Euro per ton of biodegradable material deposited in landfills was introduced in 2000(Murto et al., 2004). Anaerobic digestion is the most promising alternative to disposal this kind of waste, due to high energy recovery. Matthias et al. (2006) researched the anaerobic digestion situation in Europe and developing countries. From the first original anaerobic digester was introduced in 1896 in England, there are series anaerobic digesters with different designs, Such as CSTR (Continuous Stirred Tank reactor), ABR(Anaerobic Baffled Reactor), ASBR(Anaerobic Sequencing Batch Reactor), UASB (Up-flow Anaerobic Sludge Blanket), AF(Anaerobic filters), UAF(Up-flow Anaerobic Filter), EGSB（Expand Granule Sludge Bed）, and APS(Anaerobic Phased Solid Bed). All this high rate reactors are based on different way of mixing, feeding, decanting and phase separating. Aiming to different high-moisture organic wastes, comparisons of substrate conversion efficiency between phased system and single system were observed in different temperature, organic loading rate (OLR) and hydraulic retention time (HRT).

2. SUBSTRATES AND INTERMEDIATE PRODUCT CONVERSION

2.1 Studied Substrates and Reactors

Variety high moisture organic waste was studied use different anaerobic system. Table 1 shows the overall research of the substrates and its reactors in the past years. The involved kinds of food, fruit, and vegetable waste including potato peelings, salad waste green beans and carrots, garlic, grass, apple, asparagus, tomato, etc., which the total solid concentration is from 8% (Verrier et al., 1987) to 29.54% (Zhang and Zhang, 2002), VS is around 90%, TKN is from 2.0 to 5.4, PH value is from 4.2 to 4.8. The substrates were shredded to small particles and homogenized to liquid state for facility of feeding and digestion (Bouallagui et al., 2004) or just chopped into small size to keep its solid state in the solid bed reactor (Vieitez and Ghosh, 1999). Prochnow et al.(2005) studied the relationship between Seasonal patterns and biogas production on landscape grass digestion, and found that the optimum cutting period of landscape management grassland is late summer.

2.2 Intermediate Products Conversion

VFA is the most important and main intermediates produced during the anaerobic digestion which was converted from organic waste in the process of hydrolysis and acidification and then will be the main source for producing biogas by methogenies bacteria (Buyukkamaci and Filibeli, 2004). But high concentration of VFA will result in Decrease of PH, inhibit acidification, destroy methogenies bacteria activity and leading to failure of digester ultimately. Many studies have been conducted to observe the VFA conversion. VFA also can

Table 1 Overview of characteristic of the high-moisture solid state substrates studied in anaerobic digestion

Waste	TS (%)	VS (%)	TS/ VS(%)	TCOD/(g/kg)	TKN/(g/kg)	TOC/(g/kg)	Cellulose/(g/kg)	reference
Solid potato waste	19	18	95	ND	ND	ND	ND	Parawira et al.,2005
Mixed FVW	11.0	9.6	87	ND	2.3	59	ND	Bouallagui et al., 2004
Mixed FVW	10.0	8.8	88	120	3.8	ND	ND	Bouallagui et al., 2004
A dining hall	20.0	19.0	95	ND	ND	ND	ND	Kim et al., 2004
University's cafeteria	20.0	18.8	94	ND	ND	ND	ND	Kwon et al., 2004
A dining hall	7.0	6.6	94	ND	ND	ND	ND	Shin et al., 2004
A dining hall	16.0	15.4	96	ND	ND	ND	ND	Kim et al., 2004
Emanating from fruit and vegetable markets, household and juices centers	15.0	13.4	89	ND	ND	ND	ND	Rao & Singh, 2004
Garlic Waste	29.5	24.4	81.8	ND	0.93	39.4	ND	Zhang & Zhang., 2002
SMSW	16.0	14.5	90.7	15.2	ND	ND	ND	Vieitez & Ghosh, 1999
Potato peelings	11.9	10.6	89.0	126	ND	ND	12.9	Raynal et al., 1998
Salad leaves	7.9	7.2	91.0	57.8	ND	ND	13.5	Raynal et al., 1998
Peas-carrots	17.9	17.1	96.0	185.0	ND	ND	16.1	Raynal et al., 1998
Apple pomace	38.4	36.5	95.0	370.0	ND	ND	ND	Raynal et al., 1998
Mixed FVW	6.4	5.7	89.1	ND	1.12	ND	ND	Viturtia et al., 1995
Red beet peeling waste	7.9	6.1	77.2	71.0	1.4	20.4	ND	Verrier et al., 1987
Carrot peeling waste	9.0	8.3	92.2	104.5	2.0	41	ND	Verrier et al., 1987
Bean cutting waste	10.4	9.4	90.4	ND	5.4	45	19.2	Verrier et al., 1987

be used to calculate the acidification yield to show what the reaction degree is of converted the products coming from hydrolysis stage to VFA production (Bouallagui et al.,, 2004; Vieitez and Ghosh, 1999). VFA and its individual opponents were studied in both single anaerobic digestion and phased anaerobic fermentation. Table 2 is the list of researches VFA was studied.

The concentration of total VFA and individual VFA can be considered as the best control parameters in the liquid phase and indicators to the failure of anaerobic digestion. The highest VFA concentration can reach to the range from 13,000 to 21,000, and then the acidogenic activity was inhibited (Bouallagui et al., 2004; Vieitez and Gosh; 1999; Raynal et al., 1998; Cho and Park, 1995). Butyric is the main VFA products in the anaerobic digestion of FVW and MSW which reached to around 4000mg/L or more (Bouallagui et al., 2004, Vieitez and Ghosh, 1999) which higher than 2000mg/L studied as the factor to cause end-product inhibition of acidogenic activity (Zoetemeyer et al., 1982). It has been suggested that the concentration of acetic and propionic acid to acetic acid ration can be used an indicator of digester activity (Norstedt and Thomas, 1985; Marchaim et al., 1993; Hill et al., 1987). Acetic acid lever in excess of 800mg/L or the ration of propionic to acetic acid greater than 1.4 were studied to be as the indicator of digester failure (Hill et al., 1987).

Table 2 Overview of co-digestion substrates and efficiency in the past 6 year

Co-substrates	*Reactor type*	*Substrates ratio*	*reference*
primary sludge and the fruit and vegetable fraction	Batch reactor	PS/FVWMSW: 78%/22%	Gomez et al., 2005
organic fraction of municipal solid wastes and fats of animal and vegetable origin	CSTR	AF/VF/OFMSW:62%/28%	Fernandez et al., 2005
Manure and organic fraction of municipal solid waste	CSTR	Manure/OFMSW:50%/50%	Hartmann & Ahring, 2005
Sewage sludge and potato processing industry waste	CSTR	SS/PPIW: 72%:28%	Murto et al., 2004
solid potato waste and sugar beet leaves	Batch reactors	Variety	Parawira et al., 2004
WAS with OFMSW	CSTR+ UASB	WAS/OFMSW: 75%/25%	Sosnowski, 2003
sewage sludge and organic fraction of municipal solid wastes	CSTR	CS/FVW: 50%/50%	Callaghan et al., 2002
WAS with FVW	CSTR+ ITD	WAS/FVW: 75%/25%	Dinsdale et al., 2000
CS+FVW	Batch reactor	CS/FVW: 70%/20%	Callaghan et al., 1999

Acetic and butyric were the main VFA products at the high OLR when anaerobic digestion of FVW (Bouallagui et al., 2004; Hill et al., 1987; Buyukkamaci and Filibeli, 2001; Cho and Park, 1995; Noike et al, 1985). Production of acetic acid will be accompanied by accumulation of hydrogen gas and the conversion of VFA to acetic will be inhibited by hydrogen partial pressures (Vieitez and Ghosh, 1999).

PH will fluctuate accompany with VFA conversion. PH value will drop as the total VFA concentration is increasing, and some litter bit of increase will happen can be explained by the production of ammonia (Vieitez and Ghosh, 1999).

3. PROCESS PARAMETERS

There are many factors effect the conversion efficacy in anaerobic digestion process, such as temperature, organic loading rate, types and pretreatment of substrates.

3.1 Temperature

Ambient, mesophilic and thermophilic are the most applied temperature in AD system(T. Philip and I.Itodo.2007). All the digestion plants in Europe operated at Mosophilic temperatures before 1992 and some suppliers are starting to provide thermophilic digestion (Baere, 2000).

Thermophilic digestion was proved to accelerate reaction time. As to single anaerobic reactor, it is observed that thermophilic process has higher on average biogas production than those in psychrophilic and mosophilic temperature by 144% and 41% respectively, which result in the net energy production in the former was 195.7 and 49.07 kJ per day higher than that of the latter two. In the solid-bed two phase anaerobic system, 0.27m^3 biogas/g VS was achieved both during 300 days with solid bed was maintaining at ambient temperature and methanization reactor was maintained at mosophilic temperature and during 20 days with the whole system maintained at mosophilic temperature. (Vieitez and Ghosh, 1999; Raynal et al., 1998). 38% of the substrates in solid bed were hydrolyzed in 60 days maintained at ambient temperature, compared with 65.9%-91.7% hydrolysis yield at mosophilic temperature (Vieitez and Ghosh, 1999; Raynal et al., 1998). Philip and Itodo(2007) studied the Nomograph for Determining Temperatures in Anaerobic Digesters from ambient Temperatures, which provides an easy and direct method for the immediate determination of temperatures inside anaerobic digesters irrespective of temperature control methods on the digesters if the ambient temperature is known.

3.2 Loading Rate

Loading rate and retention time is the most important parameters for evaluating the digestion efficiency. Different digesters and systems have its limitation based on the substrates and reactor's sustainability.

Batch system is simply operated but has low loading rate and fluctuate gas production because it isn't fed in continuously. Even two-stage batch solid bed system was studied below the loading of 3gVS $L^{-1}.d^{-1}$. One stage continuous system can reach to it's maximum loading rate around 4gVS/d/L and will be inhibited due to VFA accumulation and PH dropping. Higher loading rate and more stable reaction was observed in two stage continuous system. The system loading rate can reached above 5.5gVS $L^{-1}.d^{-1}$ (Verrier, et al., 1987; Dinsdale et al., 2000; Bouallagui et al., 2004). Best hydrolysis and acidification yields between 80% and 90% were obtained with the highest loading rate at the range of 6gCOD$L^{-1}.d^{-1}$ and 9gCOD $L^{-1}.d^{-1}$at the digestion of fruit and vegetable waste (Bouallagui et al, 2004; Raynal et al, 1998).

3.3 Co-digestion

Co-digestion in most cases improves the efficiency due to positive synergisms established in the digestion medium and the supply of missing nutrients by the co-substrates (Alvarez et al., 2000). Sievers and Brune (1978) have reported that the C/N ratio in anaerobic digestion should be 16/1 for optimal operation. Considering lacking nitrogen and phosphorus in FVW, co-digestion is a reasonable way to balance the nutrient by adding others with high nitrogen or phosphorus (Gomez et al., 2005; Murto et al., 2004; Callaghan. F, 2002). Even thought experiments success in proving this merit, it was less applied because of complex operation and high additional cost. In Europe, there is only 6.7% of the organic solid waste treated by co-digestion mostly with liquid manure (Baere, 2000).

MSW, FW and VFW are studied in co-digestion mostly with sewage sludge as the co-substrate (Sosnowski, 2003; Stroot et al., 2001; Dinsdale et al., 2000). Others conducted co-digestion of FVW and animal slurry (Callaghan et al., 2002; Callaghan et al., 1999).High methane production can be obtained with the proportion of FVW of up to 50% in the co-digestion with cattle slurry, but chicken manure was observed not a successful co-substrates (Callaghan et al., 2002). Co-digestion was proved to obtain good balance in carbon and nitrogen nutrition (Sosnowski et al., 2003; Callaghan et al., 2002). Different ratio of so-substrate was applied in the co-digestion of sludge and MSW (or FVW). An optimal mixture was identified as 80:20 (Demirekler and Anderson, 1998) and 75:25(Sosnowski et al., 2003; Alvarez et al., 2000), which both are similar. High efficiency in the two stage anaerobic co-digestion of MSW and FVW was observed using sludge as co-substrate (Sosnowski et al., 2003; Dinsdale et al., 2000).

Co-digestion also increased load of biodegradable organic matter and better biogas yield (Gomez et al., 2005; Sosnowski et al., 2003). Whereas the performance of an anaerobic co-digestion process is much dependent on the types and the composition of the material to be digested. Co-digestion of starch-rich waste like potato waste with sludge was more sensitive to environment and has low buffer capacity but in contrast to those condigestion with N-rich substrates. (Murto et al., 2004). An Overview of co-digestion substrates and efficiency in the past 6 year was shown in table 2.

4. BIOREACTOR PERFORMANCE

Biogas production, methane production, VS (or COD) destruction and substrate conversion have been studied at the anaerobic digestion in different digesters.

4.1 One Stage System

Anaerobic digestion of organic waste is in the series process of three steps called hydrolysis, acidification and methonization. In one stage reactor, all the conversion and transformation take place simultaneously in the same single reactor. One stage system is the most popular design in large-scale waste treatment plant.

4.1.1 One Stage Batch System

In one stage batch system, digester are filled once with fresh FVW, with or without addition of seed materials, and allowed to go through all degradation steps in one stage. The system has, up to now, not succeed in taking a substantial market share (Bouallagui et al, 2005). Most of this system ate used for testing the methane production potential. The biochemical methane potential of 54 fruit and vegetable samples were determined. The ultimate yields and kinetics if fruit waste ranged from 0.18 to 0.732l/gVS added and 0.016 to 0.122/d, the conversion kinetics were higher at 35 ^{o}C than 28 ^{o}C (Gunaseelan, 2004). First-order kinetic constant around 4.1 10-3l (hg) VSS was estimated for the digestion of mixture of vegetable waste under mesophilic and thermophilic conditions (Converti et al., 1999). Cho and Park (1995) assessed the BMPs of different food wastes at 37^{o}C and 28 days of digestion time. The BMPs were 482, 294, 277, and 472 L/ kgVS for cooked meat, boiled rice, fresh cabbage and mixed food wastes, respectively., which were 82%, 72%, 73% and 86 % of the stoichiometric methane yield, respectively, based on elemental composition of raw materials. Anaerobic batch digestion of mixed vegetable waste was digested successfully at 5% total solid concentration and resulted in 0.16m3 biogas/kg TS added (Rajeshwari et al., 1998), but inhibited by the VFA accumulation and irreversible decreasing pH problems(Bouallagui et al., 2001; Marouani et al., 2002).

4.1.2 One Stage Continuous System

One stage continuous system with feeding and decanting continuously in one reactor. The most popular systems were completely stirred tank reactor (CSTR), anaerobic sequencing batch reactor (ASBR), plug flow reactor, anaerobic filter (AF) and up-flow anaerobic sludge reactor (UASB). About 90% of the full scale plant, currently in use in Europe for the anaerobic digestion of organic fraction of municipal solid wastes bio-wastes, relies on this system (Bouallagui et al., 2005). In one-stage system, given the very large biodegradable organic content of FVW and food waste, a major limitation of anaerobic digestion of these wastes is a rapidly acidification decreasing the pH and a large volatile fatty acids production, which stressed and inhibited the activity of methanogenic bacteria. According to the total solid concentration feed in reactor, the system can be divided into wet system whose total solid is less than 15% and dry system whose total solid is much than 15% (Lissens, 2001). As to the dry system, due to high viscosity of the feed, transport and handling of the waste is more complex and expensive than the centrifuge pumps used in the wet system, but makes the pretreatment somewhat simpler. Dranco process, Kompogas process and Valorga system are the at least three designs have been demonstrated effective for the adequate mixing of solid waste at industrials scale. Different experiments on anaerobic digestion of VFW and food wastes were carried out using different one-stage system. Most of them reached to a agreement that this kind of waste will cause a larger and faster VFA production which stressed the validity of the OLR limit (Alvarez et al., 1990). Alvaretz et al. (1992) examined the performance of anaerobic mesophilic digestion of organic fraction of the wastes from food markets using CSTR and showed that the maximum OLR was below 3kg TVS/(m^3 day). Bouallagui et al. (2004) have the similar results in the digestion of FVW, which indicated that the best results were obtained by applying an HRT of 20 days with an OLR of 2.6kg TVS(m^3day). The overall average of biogas yield 360ml/gVS was obtained in the digestion of 4 kind of food processing waste at the average OLR of 2.34gVS/ ($L^{-1}d^{-1}$),using contact-type reactors(Shimi et al., 1992).

4.2 Two-stage Systems

Two stage concept was first introduced by pohland and Ghosh (1971) and by Ghosh (1975). This two-phase system was first used for soluble substrates and liquid waste (Cohen, 1983; Verrier et al., 1987). Then phase separation has been studied by digestion of solid vegetable waste at the 80's (Cohen, 1983, Cohen et al., 1983; Lane, 1984; Verrier et al., 1987; Viturtia and Alvarez, 1989).

Three mainly advantages compare with single anaerobic digestion, including less detention time, higher gas conversion efficiency and higher methane concentration were proved in some studies (Brummeler et al., 1992; Ghosh, 1995; Bae et al., 1998).

4.2.1 Two-stage Wet Digestion

All the substrates in two-stage wet system should be putrescibled and homogenised to liquid state. Two-stage wet digestion of FVW was studied using coupled ASBR (Bouallagui et al., 2004). High methane yield of 320ml/gCOD input was obtained at the loading rate of

10.1gCOD/L.d and 96%of total COD was reduced. Acidogenic CSTR and methanogenic inclined tubular digesters combined as the two stage system operated at 30 ^{o}C at an overall system loading rate of 5.7kgm^{-3}d^{-1} with 40% VS destruction and a system biogas yield of 370ml/gVS(Dinasdale et al., 2000). A another type of combined two-stage system is a CSTR connected with a up-flow anaerobic filter reactor was used to treat vegetable wastes and made possible overloading rates near 6g VS L^{-1}.d^{-1} (Verrier et al., 1987). All the two stage digestion of FVW was operated with a continuous feeding model except the digestion of FVW studied by Viturtia et al. (1989). The efficiency of some typical two stage wet system was shown in table 3.

Table 3 Performance data of the lab-scale two stage continuous system digestions of high-moisture solid wastes

First stage /Volume(L)	*Second stage /Volume(L)*	*Feed stocks*	*Temperature (C^o)*	*HRT in first stage /second stage(d)*	*TS Removal /(%)*	*System Loading ($gVSd^{-1}L^{-1}$ or $gCOD\ d^{-1}L^{-1}$)*	*Methane Yield (m^3/gVS or COD)*	*Reference*
ASBR/1.5	ASBR/5.0	FVW	35	3.0/10.0	96.0	2.3	0.32	Bouallagui et al., 2004
CSTR/5.0	Tubular/8.0	FVW	30	3.0/10.0	40.0	5.7	0.25	Dinsdale et al.,2000
ASBR/2.5	UAF/10.0	VW	35	7.0/10.0	87.5	3.7	0.29	Rayanal, et al., 1998
CSTR/7.0	UAF/3.8	VW	35	2.0/2.3	96.0	5.65	0.42	Verrier, et al., 1987

Table 4 Performance data of the lab-scale two stage bed batch system digestions of high-moisture solid wastes

Solid bed/Volume(L)	*Second stage /Volume(L)*	*Feed stocks*	*Temperature (C^o)*	*Total VS (g)*	*Reaction days(d)*	*System Loading (gVS/L)*	*Methane Yield (m^3/gVS)*	*Reference*
2.0	UASB/1.0	Potato waste	37	180	50	60.0	0.39	Parawira, 2005
2.0	UAF/0.84	Potato waste	37	180	37	63.4	0.39	Parawira, 2005
5.4	UASB/3L	MFW	-	220	10	26.5	0.30	Wang, 2005
5.2	ASBR/4.0	Garlic waste	35	160	14	17.8	0.38	Zhang, 2002
12	UPBR/8.0	SIMSW	35	1227	295	61.4	0.135	Vieitez, 1999
4.0	UAF/7.3L	MFW	37	752	33	66.5	0.28	Cho et al., 1995
1.3	UASB-AF/0.5	MFVW	37	57	31	31.7	0.53	Viturtia&Alvarez, 1989

4.2.2 Two -stage Solid-bed Digestion

In order to reduce the inhabitation of methane fermentation by organic acid in the digestion of solid state masteries, Ghosh et al. (1983) proposed the concept of two-phase fermentation with high solid feeds using a solid-bed for acid fermentation and subsequent methane fermentation (Cho and park, 1995).

Two-stage solid bed batch system means one solid bed reactor combined with one methane reactor with feeding in a batch mode in the common reactor used in many studies (Wang et al., 2005; Yu et al., 2002; Zhang and Zhang, 1999; Vieitez & Ghosh, 1999; Cho and Park, 1995; Alvarez et al., 1993). These studies used food waste, grass, onion waste and simulated MSW as the substrates. Table 4 show the digestion performance in two stage solid bed batch system in digestion of high-moisture solid waste.

Two stage solid bed continuous system include Multi- hydrolysis reactors and one bio-gasification reactor. In order to make feeding in a continuous mode, several solid-bed reactors connect with one gasifier was introduced, which facilitate to feed individual solid-bed without effecting the whole system operation. The APS Digester system (US patent 6342378B1) was developed based on previous research of two phase digestion processes. This process would have a cyclic biogas production rate, which is not desirable for downstream utilization in engine-generators. Also, second phase of reactors require complicated flow distribution mechanism and are therefore e prone to operational and maintenance problems. The APS Digesters use four hydrolysis reactors coupled to one bio-gasification reactors. The solid feedstock is batched loaded into the hydrolysis reactor every regular days, to facilitate near continuous system, which will provides for a stable, relatively constant biogas production. Previous studies were reported that food wastes and green waste can be digested with constant and high biogas yield within 12 days (Liu. et al. 2006), also, the profiles of hydrolysis and acidification yield in the two stage were studied by Liu et al (2007).

5. CONCLUSIONS

Considering the characteristics of the high-moisture solid waste, anaerobic digestion represents a feasible and effective waste to convert it to biogas fuel. Different substrates were studied using different reactors and systems. Temperature, pretreatment, hydraulic retention time and organic loading rate are the main process parameters in the operation. Batch and continuous operation methods were conducted both in single stage and two-stage anaerobic digestion systems. Two stage system was indicated a possible way to increasing the organic loading rate and gas production of the digestion of high-biodegradable waste. Two stage wet system and solid bed system were the main types to conducted digestion based on the state of substrates. All of the two stage solid bed reactors studied before was conducted in batch system. Continuous system should be introduced into using multi-hydrolysis reactors combining with a gasification reactor, which will result in continuous operation, high organic loading, high biogas yield and stable system biogas production.

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