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PERFORMANCE EVALUATION OF AN ANAEROBIC BAFFLED REACTOR TREATING WHEAT FLOUR STARCH INDUSTRY WASTEWATER

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ABSTRACT

Feasibility of the anaerobic baffled reactor process was investigated for the treatment of wheat flour starch wastewater. After removal of suspended solids by simple gravity settling, starch wastewater was used as a feed. Start-up of a reactor (with a volume of 13.5 L and five compartments) with diluted feed of approximately 4500 mg/L chemical oxygen demand was accomplished in about 9 weeks using seed sludge from anaerobic digester of municipal wastewater treatment plant. The reactor with hydraulic retention time of 72h at 35°C and initial organic loading rate of 1.2 kgCOD/m^3.d showed 61% COD removal efficiency. The best performance of reactor was observed with an organic loading rate of 2.5 kgCOD/m^3.d or hydraulic retention time of 2.45 d and the COD conversion of 67% was achieved. The system also showed very high solids retention with effluent suspended solids concentration of about 50 mg/L for most organic and hydraulic loadings studied. Based on these observations, the ABR process has potential to treat food industrial wastewater as a pretreatment and is applicable for extreme environmental conditions.

Key words: Anaerobic baffled reactor, starch wastewater, COD removal, organic loading

INTRODUCTION

During the last 30 years, there has been an increasing demand for more efficient systems for the treatment of wastewater due to increasingly stringent discharge standards now widely adopted by various national and international agencies (Akunna and Clark, 2000). The treatment of both domestic and industrial wastewater is usually carried out using biological methods due to their lower costs compared to chemical methods (Langenhoff *et al*., 2000). Great advances have been made over the last 20 years in anaerobic reactor design and in understanding the complex processes that occur in anaerobic digestion (Langenhoff and Stucky, 2000). The successful application of anaerobic systems to the treatment of industrial wastewater is critically dependent on the development and use of high rate anaerobic bioreactors. These reactors achieve a high reaction rate per unit reactor volumes in terms of kgCOD/m^3.d by retaining the biomass Solid Retention Time, (SRT) in the reactor independently of the incoming wastewater Hydraulic Retention Time, (HRT), (Barber and Stucky, 1999). Such separation allows the slow growing anaerobic bacteria remain within the reactor independent of the wastewater flow. This allows higher volumetric loads and produces significantly enhanced removal efficiencies (Akunna and Clark, 2000). In contrast to domestic wastewater, industrial effluents pose many problems for treatment and such effluents are subject to daily and sometimes seasonal fluctuations with respect to both their flow and strength (Nachaiyasit and Stucky, 1997a). The characteristics of food-processing wastes show high variation in Biological Oxygen Demand (BOD), Total Suspended Solids (TSS) and flow rate. The wastes may be highly alkaline or highly acidic. Mineral materials (N and P) may be absent or may be present in excess of the ratio necessary to promote good environmental conditions for biological treatment (Nemerow and Dusgopta, 1991). Wheat starch is an important agro-based

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product found in many parts of the world. The starch extraction process includes preprocessing of wheat flour, starch extraction, separation and drying (Rausch, 2002). It produces large volume of wastewater up to 20-60 m^3/T of starch produced. Water pollution problems related to the starch industry are serious. The wastewater is highly organic and acidic by nature with COD up to 25000 mg/L and pH between 3.8-5.2 (Annachhatre and Amatya, 2000). High rate anaerobic processes offer an attractive alternative for treatment of starch industry wastewater (Lettinga, 1996). The most common high rate anaerobic reactor in the world today is the Upflow Anaerobic Sludge Blanket (UASB), with many existing full-scale reactors for the treatment of wastewater from the food and beverages industries (Austermann-Houn *et al*., 1999). The success of the UASB depends on the formation of active and settlable granules. These granules are involved in aggregations of anaerobic bacteria and self-immobilized into compact forms (Yan and Tay, 1997). Due to the relatively low densities of the UASB granules, the loss of biomass with effluent poses problems, especially during increased loading rates (Angenent *et al*., 2002). One of the many types of high rate reactors presently attracting growing interests is the Anaerobic Baffled Reactor (ABR) developed by McCarty and coworker (1981) at Stanford University. The ABR has been described as a series of UASBs which does not require granulation for its operation. Therefore, it has lower start-up period than the other high rate reactors. It includes a series of vertical baffles to force the wastewater to flow under and over them, and therefore the wastewater comes into contact with a large active biomass (Nachaiyasit and Stucky, 1997a). This reactor system has been reported to have many advantages over other systems. The most significant advantage of the ABR is its ability to separate acidogenesis and methanogensis longitudinally down the reactor, allowing the reactor to behave as a two-phase system without the associated control problems and high costs (Barber and Stucky, 1999). It is simple in design and requires no gas separation systems. Moreover, the hydrodynamic pattern reduces bacterial washout and enables it to retain biomass without the use of any fixed media (Grove *et al*., 1999; Vossoughi *et al*., 2003). The separation of two phases causes an increase in protection against toxic material and higher resistance to changes in environmental parameters such as pH, temperature and organic loading (Barber and Stucky, 2000; Uyanik *et al*., 2002). Among high rate reactors, ABR was recommended by several researchers as a promising system for industrial and also domestic wastewater treatment (Nachaiyasit and Stucky, 1997b; Barber and Stucky, 1999; Wang *et al*., 2004). The objective of this study was evaluation of the performance of the ABR during various hydraulic and loading conditions.

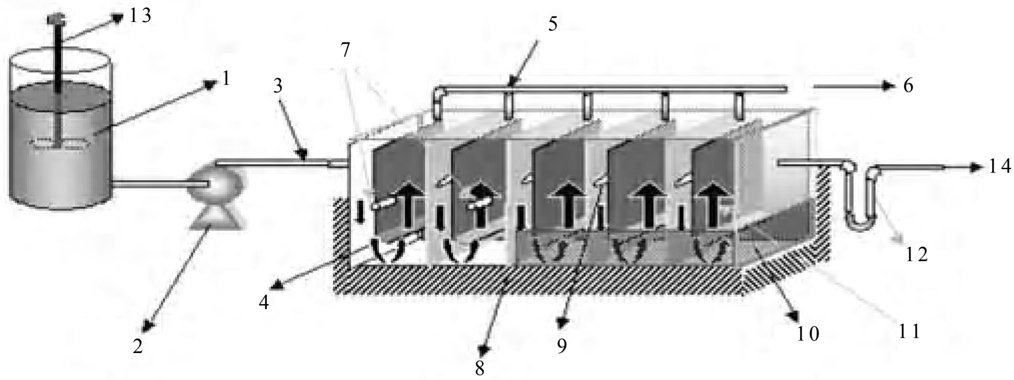
MATERIALS AND METHODS

Experimental set-up

The laboratory scale ABR was constructed from 6mm thick transparent Plexiglas, with external dimensions of 53cm long, 16cm width and a depth of 30cm, with the working volume 13.5L. Fig. 1 shows a schematic diagram of the reactor. The reactor was divided into five equal 2.7 L compartments by vertical baffles, each compartment having down comer and riser regions created by a further vertical baffle. The width of up comer was 2.6 times of the width of down comer. The lower parts of the down comer baffles were angled at 45º in order to direct the flow evenly through the up comer. This produced effective mixing and contact between the wastewater and anaerobic sludge at the base of each riser. Each compartment was equipped with sampling ports that allowed biological solids and liquid samples to be withdrawn. The operating temperature was maintained constant at 35±0.5ºC by putting the reactor in a water bath equipped with a temperature regulator. The influent feed was pumped using a variable speed peristaltic pump (Master flux L/S). The outlet was connected to a glass U-tube for level control and to trap solids. The produced gas was collected via portholes in the top of the reactor and daily volume was determined using the gas-water displacement technique.

Wastewater characteristics

The combined starch wastewater from a wheat starch factory in the central province of Iran



1-Feed tank	6-Biogas	11-Upflow current
2-Peristaltic pump	7-Sampling ports	12-Siphon
3-Feed influent	8-Water bath	13-Mixer
4-Fluid current	9-Passing window	14-Effluent
5-Gas collection	10-Sludge bed	

Fig. 1: Schematic diagram of anaerobic baffled reactor

(Ardineh starch CO, Isfahan) was used as feed. Wheat starch industry combined wastewater has low pH, high suspended solids and high COD. The supernatant of the combined wastewater after the simple gravity settling used in the investigation, had lower TSS, as approximately 90% of the solids were removed. Typical characteristics of the wheat starch wastewater are given in Table 1.

Table 1: Wheat starch wastewater characteristics

Parameter	Combined wastewater	Supernatant wastewater
COD (mg/L)	16200-26500	12000-20375
TSS (mg/L)	9440-11940	392-666
VSS (mg/L)	8930-11100	372-588
pH	3.5-4.2	3.5-4.2
TKN (mg/L)	-	50-100
Orthophosphate as P (mg/L)	-	25-35

The supernatant wastewater was diluted to achieve the COD concentration required for each loading rate with tap water. In order to pH and alkalinity adjustment, the supernatant was neutralized by NaOH and $NaHCO_3$. A COD:N:P ratio of 300:5:1 was kept during operation using NH_4Cl and K_2HPO_4. The micro-nutrient deficiency was added occasionally to correct growth conditions according to Angenent *et al*., (2002).

Seed sludge

The reactor was seeded with anaerobic digested sewage sludge taken from an anaerobic digester an Isfahan south municipal sewage treatment works. It was first sieved (<2mm) to remove any debris and large particles and was then introduced into five compartments of reactor. Each compartment was filled with 50% sludge which had a suspended solids composition of 30980 mg TSS/L and 20880 mg Volatile Suspended Solids (VSS) per liter giving a total of 140.94 g VSS in the reactor. This value (10.44 g VSS/L) is in accordance with the initial VSS value used in other studies with ABR (Barber and Stucky, 1999). The remaining parts of each compartment were filled with tap water. After seeding the reactor, the lids were sealed. The reactor was then allowed to stabilize for 24h without further modification before starting the experiments.

Analysis

Monitoring included the analysis of samples from influent and each compartment of the ABR system for COD, TSS, VSS, alkalinity and pH. All samples were analyzed according to the standard methods for examination of water and wastewater (APHA,1995). pH and temperature were monitored daily.

RESULTS

Reactor start-up

In order to reactor start-up, the batch operation of ABR was started using an initial sludge concentration of 10440 mg VSS/L. The system was run on batch for 2 weeks. During this time the content of the reactor was recycled for homogeneity. After these weeks the ABR was run continuously and observation were made for 42 days with an initial organic loading rate of 1.2 kgCOD/m^3.d with influent COD in the range of 4225-5975 mg/L. When there was no more fluctuation in COD in each compartment, then the Organic Loading Rate (OLR) was increased up to 1.5 kgCOD/m^3.d for one week and then OLR were increased gradually up to 10 kgCOD/m^3.d for 40 days. At the end of this period, the biogas production rate increased (data not shown).

COD removal

OLR and HRT employed during the reactor operation period are shown in Fig. 2. As can be seen, there were an inversely relationship between OLR and HRT. Fig. 3 shows the effects of increase of influent COD concentration on COD removal rate under steady-state conditions. It also indicates the reactor effectiveness as percent COD removal. According to Fig. 2 and Fig. 3, the COD conversion during the start-up period was obtained up to 61%, with HRT of 3 days (OLR of 1.5 kgCOD/m^3.d). After each increase in OLR the COD concentration in effluent increased. When the OLR was increased to 2.5, 5 and 10 kgCOD/m^3.d at HRT in the range of 1.43-2.45 d, the efficiency of COD removal was achieved as 67%, 55% and 40%, respectively. Fig. 4 shows the COD removal efficiency based on organic loading rates. The best performance of reactor was observed with an OLR of 2.5 kgCOD/m^3.d (HRT of 2.45 d) and the COD conversion of 67% was achieved (Fig. 4). The variations of COD in the reactor are illustrated in Fig. 5.

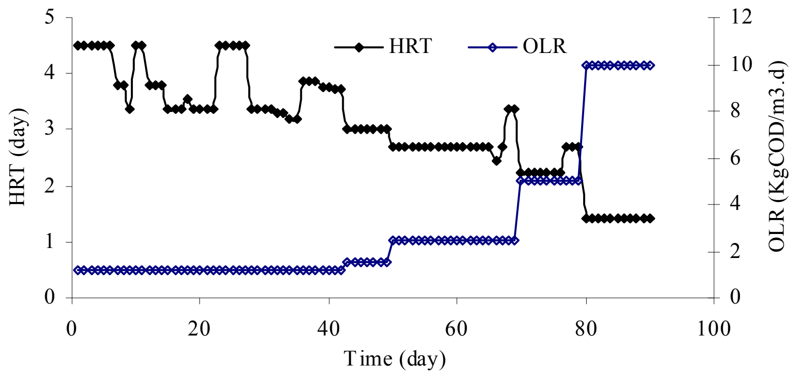


Fig. 2: Organic loading rate and hydraulic retention time employed during reactor operation period

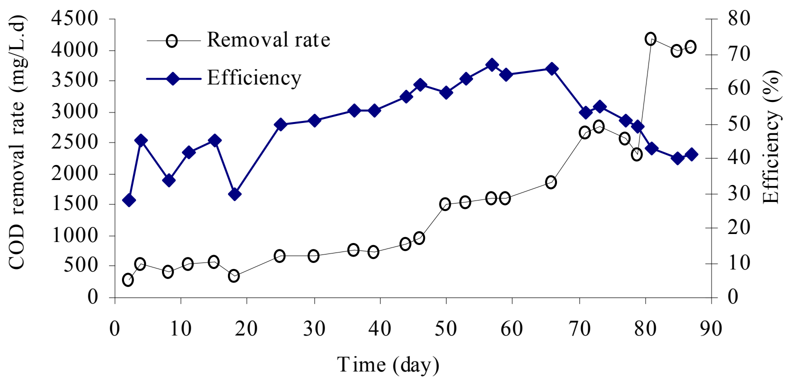


Fig. 3: COD removal rate in the reactor during operation period

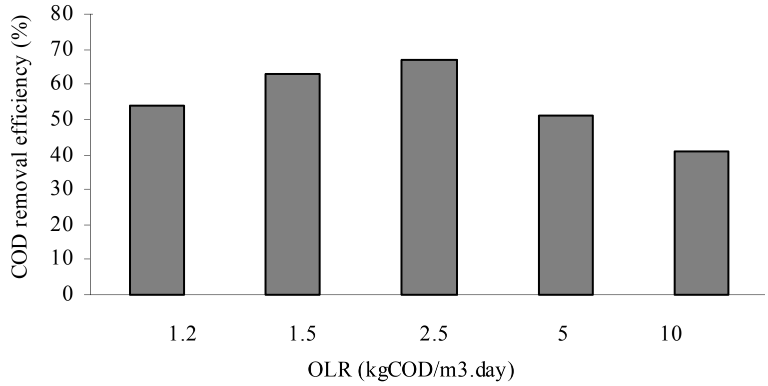


Fig. 4: COD removal efficiency based on organic loading rate

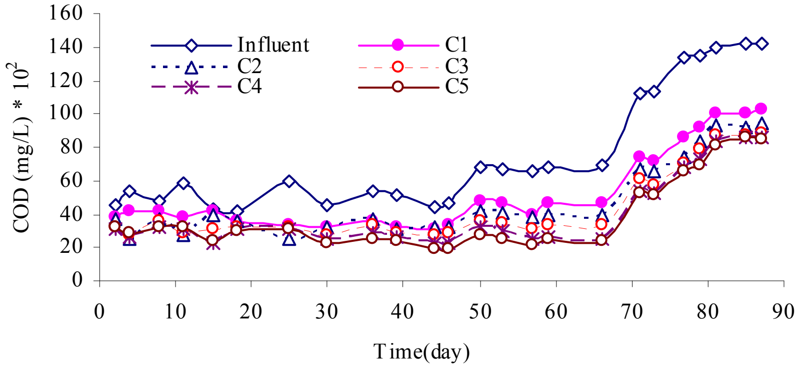


Fig. 5: COD variation profile at different compartments of ABR systems (C_i = Compartment)

Alkalinity and pH

As shown in Fig. 6, the feed alkalinity after pH adjustment was approximately 1000-3000 mg/L, while the effluent alkalinity was always in the range of 2000-5000 mg/L. The results of pH variations along with the reactor showed that the pH decreases in compartments 1 and 2 upto pH<6.5 during the reactor operation. However, although the pH in compartments 3-5 returned to near neutrality, compartment 1 stayed at approximately pH=6.4 for the rest of the experiment. This is clearly shown in Fig. 7.

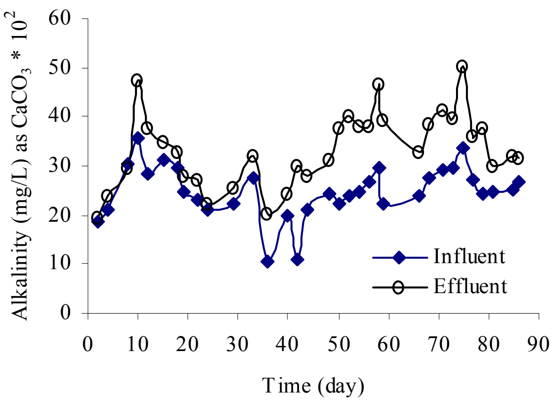


Fig. 6: Influent and effluent alkalinity during reactor operation period

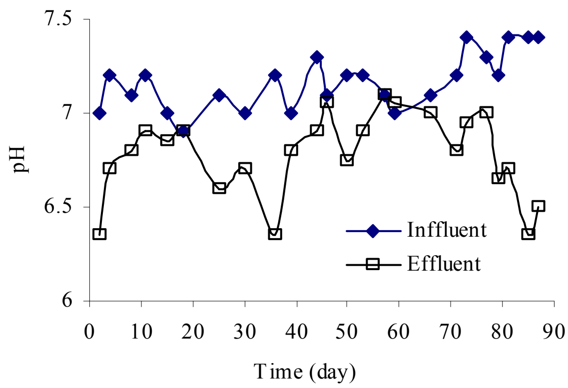


Fig. 7: pH variation profile during reactor operation period

Sludge characterization

The average TSS and VSS concentration and VSS/TSS ratio in the reactor at different times are presented in Fig. 8. At the time of reactor start-up, VSS/TSS was 0.67. The VSS/TSS ratio increased upto 0.77 by day 42 and later it slightly decreased till the end of operation. Sludge washout was negligible in the experiments since the effluent suspended solids concentrations were in the range of 14-272 mg TSS/L, which indicates that the ABR was stable to high shock loads. Details of reactor operation data are shown in Table 2.

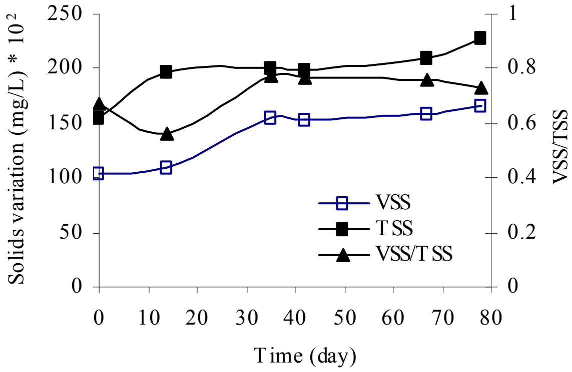


Fig. 8: Variation of VSS/TSS ratio in the reactor during operation period

Table 2: Summary of reactor operation conditions

Parameter	Start-up	Period 1	Period 2	Period 3
COD_{in} (mg/L)	4225-5975	6525-6875	11250-13500	14000-14300
COD_{out} (mg/L)	1800-3400	2150-2650	5100-6850	8000-8525
pH (first-fifth compartments)	6.2-7	6.4-7.05	6.45-7	6.1-6.7
TSS_{out} (mg/L)	14-30	52	272	206
HRT (d)	3-4.5	2.45-2.7	2.25-2.7	1.43
OLR (kgCOD/m3.d)	1.2-1.5	2.5	5	10
Time (d)	49	20	10	10
Efficiency (%)	28-61	59-67	49-55	40-43

DISCUSSION

The reactor operation lasted for three months. Because of increment different influent COD at each period from wide range of 4225 to 14300 mg/L, the COD removal rate (in term of mg/L.d) increased in accordance with OLR increasing. However, in spite of incremental trend in COD removal rate, when the reactor was fed with an organic loading rate of 5 kgCOD/m^3.d after 69 days, the treatment removal efficiency decreased. This is obviously illustrated in Fig. 3. It is evident from data that the COD removal rate did not gratify in comparison with lower organic loading rates. Since in the present study at higher OLR, the influent COD concentration and volume of flow rate increased significantly and affected the quantity of COD removal rate. It also led to high COD concentration in the effluent. The relatively poor performance of ABR at higher organic loading rates can be attributed to the presence of high substrate gradient. In this study, the best reactor performance was observed with an OLR of 2.5 kgCOD/m^3.d and 67% COD removal efficiency was obtained (Fig. 4). The highest OLR tested (10 kgCOD/m^3.d) resulted in only 40% decrease in the COD concentration and the remaining high COD in the effluent. This high OLR and high flow rate probably caused channeling through the biomass bed, resulting in poor substrate-biomass contact and minimal degradation of the incoming COD. This provides further support to the earlier supposition that under plug-flow conditions, incoming substrate remains in the reactor for one retention time allowing maximum time for conversion. However, the high substrate concentration resulting from lack of dispersion may inhibit bacterial activity (Sallis and Uyanik, 2003). These results support the findings of the other studies. Kalyuzhnyi *et al*., (1998) worked with UASB reactor for chip-processing industry wastewater. The organic loading rate achieved in the lab scale reactor had approximately 14 gCOD/L.d with treatment efficiencies higher than 75% and 63% on the basis of centrifuged and total COD of the effluent. Grover *et al*., (1999) have shown that a maximum COD reduction of about 60% at an organic loading rate of 5 kgCOD/m^3.d at hydraulic retention time of 2d and 35°C was recorded with anaerobic baffled reactor treating pulp and paper liquors. In other study to treat tapioca starch industry wastewater with UASB process, COD removal upto 95% has been obtained at an OLR of 16 kgCOD/m^3.d (Annachhatre and Amayta, 2000). A comparison of the results achieved with those reported for other anaerobic treatment systems and for similar wastewaters illustrate that our results are satisfactory, though an actual comparison between various data sets can be based only on experiments where the same wastewater and reactors of comparable size with the same operation temperature are used. The variation in the COD profile in ABR was shown in Fig. 5. As it can be seen, most of COD was removed in compartment 1 (35%), increasing the initial OLR enhanced the biological oxidation upto a certain point at which OLR started to inhibit the degradation rate. Because in strong wastewater containing high organic load, significant amounts of fatty acids can develop from partial degradation of substrate and these can inhibit the methanogenic population in the reactor (Uyanik *et al*., 2002).

According to Fig. 6, the effluent alkalinity was always more than the feed alkalinity. The most likely explanation for this observation is the formation of HCO_3^- due to the reaction of OH^- with CO_2 produced during anaerobic degradation (Annachhatre and Amayta, 2000). The pH levels in the reactor followed a similar pattern throughout the experiment, dropping rapidly to pH less than 6.4 at reactor start-up and at higher OLR (Fig. 7). The pH decrease in compartments 1 and 2 can be attributed to the fact that high concentration of volatile fatty acids (VFAs) were present in these compartments, while in later compartments due to conversion and stabilization of intermediate products i.e. VFAs to methane and activity of methanogenic bacteria the pH value increased to neutral range (Uyanik *et al*., 2002). Very little washout of the reactor solids occurred in the reactor operation (Table 2), which show that the reactor was stable to severe shocks loads. This is consistent with the published literature which indicates that ABR process is stable to large transient shock loads (Nachaiyasit and Stucky, 1997b). Determination of VSS/TSS ratio gives correlation to the biomass growth and its quality. As it can be seen in Fig. 8, at the start-up of reactor, VSS/TSS ratio was 0.67 and increased to 0.77 by day 42 at OLR of 1.2 kgCOD/m^3.d. After this period, it gradually decreased over the entire course of experiment to 0.73 by day 79 at OLR of 10 kgCOD/m^3.d. This provides further support to the earlier hypothesis that biomass growth rate is limited in high organic loading rate (Metcalf & Eddy, 2003). As a final conclusion, it could be concluded that this type of reactor configuration has potential in treating food industrial wastewater that vary in both flow and concentration. Also because of equalization characterization ABR process is a good system as pretreatment for other anaerobic or aerobic wastewater treatment processes.

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