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Removal of Total Suspended Solids by a Foam Fractionator in a Simulated Seawater Aquaculture System

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In a simulated seawater aquaculture system, effects of different operating factors like the superficial air velocity (SAV), hydraulic residence time (HRT), protein concentration and foam overflow height on the removal of total suspended solids (TSS) by a foam fractionator, with 20 cm diameter and 120 cm height, were investigated. This experiment was performed on batch and consecutive modes for different combinations of the tested factors, using synthetic wastewater. In 5 consecutive trials, TSS concentration in culture tank water decreased faster, when the foam fractionator was operated at higher SAV and lower HRT. In batch trials, with increasing SAV, TSS removal rate increased, but decreased with increasing HRT. Higher protein concentration in the bulk solution resulted in higher TSS removal rate. TSS concentration in the collected foam condensates increased but the foam overflow rate decreased with increasing foam overflow height. Foam fractionation was effective for removing TSS in seawater aquaculture systems and its performance largely depended on the operating parameters, especially superficial air velocity.

Keywords: TSS removal, Foam fractionator, Superficial air velocity, HRT, Foam condensate

Introduction

Recirculating aquaculture systems have many advantages over the traditional aquaculture systems, for example, reduction in quantities of water used and discharged wastewater, reduced environmental effects, enhanced siting flexibility of culture facilities, and most importantly, improved water quality for better growth of fish. At present, the obstacles for faster development and commercial application of recirculating aquaculture system are high investment and production costs, resulting in low or no profit. Hence the components of a recirculating system should be designed technologically sound and economically cost effective. Nowadays, seawater recirculating aquaculture systems attract more attention, as more expensive fish species and shrimp can be cultured to make up the profit margin. Increased concern for protection of marine environment and demand for live sea-food has promoted the development of seawater recirculating aquaculture systems.

The utility of a recirculating system depends largely on treatment efficiency of wastes generated in a system. Wastes that are of critical concern are ammonia and solids. Ammonia can be oxidized to less toxic forms of nitrogen or removed through biofiltration. The generated solids can be divided into two categories: settleable and non-settleable solids. Typically, closed production system units are subject to accumulation of fine suspended solids and dissolved organics (Timmons et al., 1995). Chen et al. (1993a) recorded that 95% of the suspended particles in three recirculating aquaculture systems had a diameter less than 20 microns. Fine, non-settleable suspended solids, which are more difficult to control, cause most problems in recirculating aquaculture systems. Fine solids are suspected to be responsible for fish death in a recirculating system (Timmons et al., 1987). Major (1998) reported that moderate TSS levels of 44 mg/L damages gills of fish. Chapman et al. (1987) also observed that the accumulation of fine particles was associated with lethal effects. Others have also reported the adverse effects of solids on fish health and gill damage (Stickney, 1979; Wickins, 1980). Biofilter could be easily clogged in recirculating systems with high solids concentration. Also, solids could generate more ammonia nitrogen and oxygen demand, if not removed out of the recirculating aquaculture systems as soon as possible. The recommended limit of suspended solid concentration in recirculating aquaculture systems is 15 mg/L (FIFAC, 1980; Reinemann, 1987; Timmons et al., 1987).

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Different methods are developed for solids removal in aquaculture systems. These can be classified as gravity separation (sedimentation), filtration (screen, granular media, porous media separator), and flotation (foam fractionation). Sedimentation is usually effective for removing particles greater than 100 micron (Rudolfs and Balmat, 1952), but is impracticable, due to low sedimenting velocity of fine particles. Chen and Malone (1991) also reported that filtration methods require fine media or screen filters; hence the removal of fine solids become more expensive due to pressure losses or frequent backwashing. Majority of these fine particles remain even after passing through biofilters (Muir, 1978).

After examination of several fish culture systems, Lomax (1976) noted that biofilter with foam fractionation was the best design combination both in terms of cost and effectiveness. Dwivedy (1973) found that foam fractionator removed solids and maintained pH in an oyster culture system. Besides, it can serve as a gas-stripping unit, which is usually a necessary treatment process in recirculating aquaculture systems (Chen et al., 1993a). Others also reported that foam fractionation can be used to remove fine solids and excessive nutrients (Chen, 1991; Weeks et al., 1992; Chen et al., 1993b,c; Chen et al., 1994a, b; Suh et al., 2000, 2002).

Lomax (1976) confirmed removal of solids by a foam fractionator and recommended that the substances responsible for foam fractionation should be identified. However, most experiments cited above were made in freshwater systems. Recently, Suh et al. (2000) investigated removal characteristics of solids in seawater systems using synthetic wastewater, which was made by mixing collected foam condensate with seawater; however, they gave no details on operating parameters. Huguenin and Colt (1989) pointed out the lack of the actual performance data and the need to identify and quantify the organic components involved in foam fractionation process.

Spotte (1979) has stated that the main factors affecting the efficiency of foam fractionation include hydraulic residence time, bubble size, air flow rate, diffuser submergence depth, foam overflow height, and the configuration of foam fractionator itself. The factors affecting the performance of existing foam fractionator are the air flow rate, water flow rate, and foam overflow height (Weeks et al., 1992).

In present experiment, TSS removal efficiency of an air drift foam fractionator was evaluated at different foam overflow heights, superficial air velocities, and hydraulic residence time in a simulated seawater aquaculture system. Synthetic wastewater was obtained by mixing waste collected from a freshwater recirculating aquaculture system with artificial seawater. The contents of protein and solids in synthetic wastewater were within the ranges that are usually reported in recirculating aquaculture systems. The results are expected to help selection of operational parameters in applying foam fractionation in seawater aquaculture systems.

Materials and Methods

System configuration and experimental procedure

The experiment system consisted of a round, 300-L plastic culture tank, a recirculating pump, a foam fractionator, an air distribution system, and foam collection facilities (Fig. 1). Synthetic wastewater was pumped from the culture tank into the foam fractionator and then returned to the culture tank or wasted, according to different set of trials. A bypass was connected for adjusting the water flow rate through the foam fractionator.

To obtain equal solid and surfactant concentrations in culture tank water for each trial, sediments from the first sedimentation basin of a recirculating system in Pukyong National University were collected and mixed by electric stirrer, and then equal aliquots were frozen in a refrigerator. The sedimentation basin was cleaned once a day to keep the freshness of sediment consisting of mostly feces and uneaten feed, the main solid wastes in fish culture system. Foam condensates, produced in the same recirculating aquaculture system, were also collected and stored, as for the sediments. Foam condensate and sediments were mixed together to form the synthetic wastewater with desired levels of protein and solids. All the tests were conducted at water temperature of 20 °C and pH values was kept within 7.8~7.9.

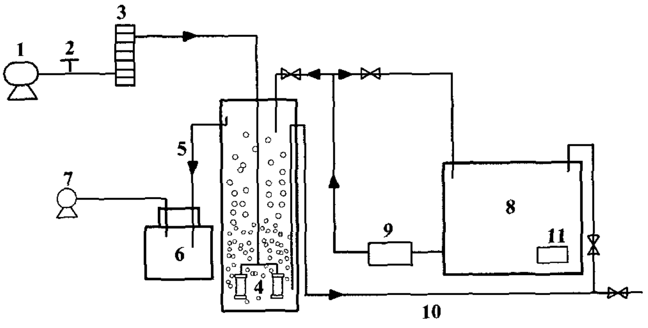

Fig. 1. Schematic diagram of foam fractionation system. 1, air blower; 2, pressure regulator; 3, air flow meter; 4, air diffuser; 5, foam collection pipe; 6, foam collection bottle; 7, vacuum pump; 8, culture tank; 9, recirculating pump; 10, outflow line; 11, mixing pump. (Arrows indicate water, air or foam condensate flow direction).

TSS removal rates were evaluated at 4 different air flow rates of 7, 14, 21, and 28 L/min, 5 hydraulic residence times (HRTs) of 1, 2, 3, 4, and 6 min, and 4 foam overflow heights of 1, 3, 5, and 7 cm. Superficial air velocity (SAV) was used instead of air flow rate, as it is a convenient way of expressing air flow velocity through foam fractionator column and corresponding SAV values were calculated as 0.371, 0.743, 1.114, and 1.486 cm/sec, respectively.

In the first set of trials, selected combinations of operating parameters were tested and were conducted on batch mode, which means the synthetic wastewater flew through the foam fractionator and then was discharged out of the system. TSS removal rates were also tested at different initial protein concentrations. Removal rates were calculated according to Suh et al. (2000).

$$-r_a = \frac{C_{i,a} \times Q_i - C_{o,a} \times Q_i}{V}$$

where, $-r_a$, the removal rate (g/L · day), $C_{i,a}$, the TSS concentration in inlet water, $C_{o,a}$, the TSS concentration in outlet water and V, the volume of fractionator.

In the second set of trials, changes in TSS concentration in culture tank water was monitored till no foam was collected for 5 combinations of HRT and SAV and each was conducted on consecutive mode, which means the synthetic wastewater was continuously recirculated within the system. Foam overflow height was set at 3 cm for all the 5 consecutive trials. Gas holdup, which is the fractional increase in column liquid height due to supply of aeration, was measured, as it is essential for determination of foam overflow height. It was determined by measuring the difference in the height of column liquid before and after aeration.

Foam fractionator

Figure 2 is the schematic diagram of the foam fractionator used in present experiment. This foam fractionator was made of acrylic pipe with a diameter of 20 cm and a height of 120 cm. The water inlet and outlet were positioned at such levels to generate a counter-current flow pattern in the foam fractionator column. A 40-mm PVC elbow was installed at 90-cm height for foam collection. Foam overflow height was controlled by changing the length of nipple pipe that was connected to the elbow. Foam outlet was connected to a collection bottle and a vacuum pump was used for quick collection of foam produced on top of the nipple pipe. The air distribution system included an air blower, an air flow meter (Dwyer instruments, model RMA), and a pressure regulator (Fig. 1). Two coarse air stones with a diameter of 3.2 cm and length of 9 cm were used to disperse air bubbles.

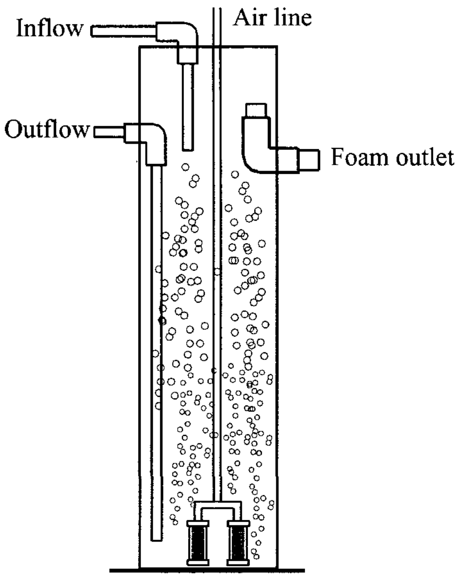

Fig. 2. Schematic diagram of the foam fractionator column.

Sample and analysis

Samples were taken at 10, 20, 30 min and subsequently then at half hour intervals from culture tank water after commencing air supply in trials conducted on consecutive mode to monitor changes of TSS concentrations in culture tank water. In trials conducted on batch mode, 4 samples were taken at the inlet and outlet water of foam fractionator at intervals of 1-6 min. Protein analysis was made, according to Lowry et al. (1951). TSS was measured according to standard methods (APHA, 1995). Filter paper was rinsed successively 6 times with 20 ml distilled water for removing the salts left on the filter paper.

Results and Discussion

Figure 3 shows the changes in TSS concentrations in culture tank water at three HRTs of 2, 3, and 6 min and constant SAV of 1.486 cm/sec in the consecutive trials. Initial protein concentration was 34.7±0.1 mg/L. TSS concentration in culture tank water decreased faster at lower HRT. In other words, increasing water flow rate through the foam fractionator column increased TSS removal rate. Also, TSS removal rate increased with decreasing HRT at constant protein level of 32.5±0.1 mg/L, when the trials were conducted on batch mode (Fig. 4). TSS removal rate decreased from 33.1 to 17.3

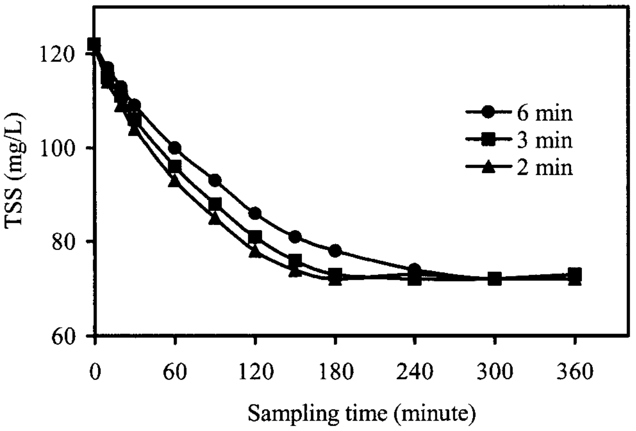

Fig. 3. Changes in TSS concentration in culture tank water at 3 different hydraulic residence times of 2, 3, and 6 min (SAV, 1.486 cm/sec; foam overflow height, 3 cm) in trials conducted on consecutive mode.

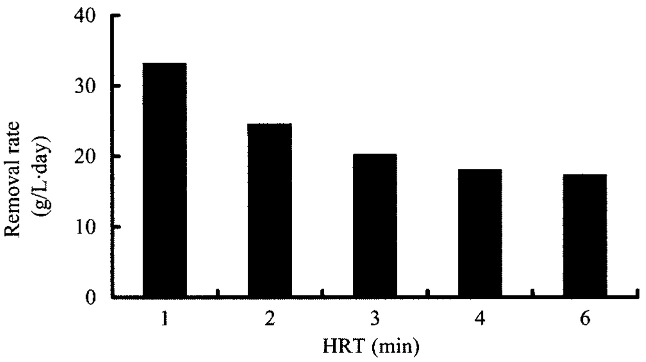

Fig. 4. TSS removal rates at different hydraulic residence times of 1, 2, 3, 4, and 6 minutes (SAV, 1.486 cm/sec; protein concentration, 32.5 mg/L; foam overflow height, 3 cm) in trials conducted on batch mode.

g/L/day, when HRT increased from 1 to 6 min. Increase in HRT meant increase in water and air contact duration, which provided a longer contact duration of solids with air bubbles at water-air interface and thus increased the removal efficiency of solids. On the contrary, decrease in HRT increased the contact frequencies of solids with air at the water-air interface and thus increased the removal rate. Lower HRT resulted in faster drop of TSS concentration in culture tank water.

Suh et al. (2000) reported relatively higher values for TSS removal rate at different HRTs. However, they did not provide protein concentrations in the bulk solution, thus making the comparison difficult. A possible explanation may be drawn from the fact that they used a small foam fractionator column in their experiments; a foam fractionator column with smaller cross-sectional area is regarded as more efficient (Know, 1971).

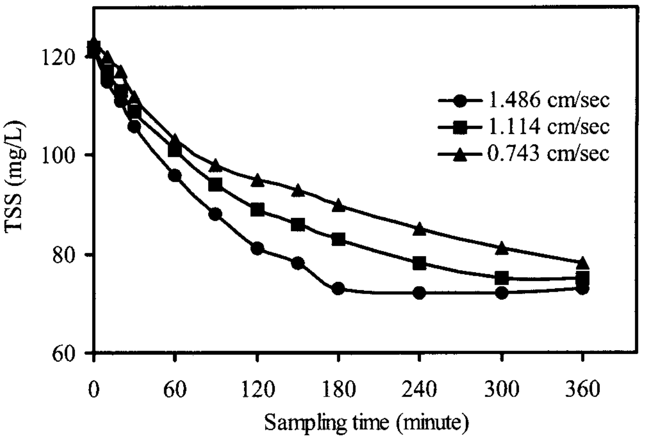

Fig. 5. Changes in TSS concentration in water of culture tank at 3 different superficial air velocities of 0.743, 1.114, and 1.486 cm/sec (HRT, 3 min; foam overflow height, 3 cm) in trials conducted on consecutive mode.

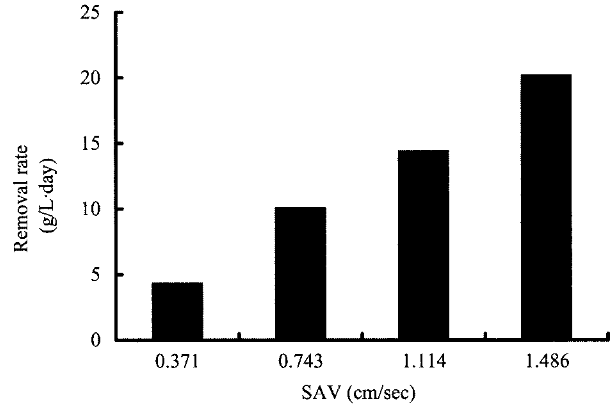

Fig. 6. TSS removal rates at different superficial air velocities of 0.371, 0.743, 1.114, and 1.486 cm/sec (HRT, 3 min; protein concentration, 32.5 mg/L; foam overflow height, 3 cm) in trials conducted on batch mode.

Figure 5 shows the changes in TSS concentration in culture tank water at SAVs of 0.734, 1.114, and 1.486 cm/sec and constant HRT of 3 min, when the trials were conducted on consecutive mode. Initial TSS concentration was around 122 mg/L. TSS concentration in culture tank water dropped rapidly at higher SAVs. Higher SAV also greatly increased the TSS removal rate at the constant HRT of 3 min, when the trials were conducted on batch mode (Fig. 6). TSS removal rate increased from 4.3 to 20.2 g/L/day, as SAV increased form 0.371 to 1.486 cm/sec. The increase in TSS removal rate was nearly proportional to the tested SAVs. Usually, higher SAV increased the areas of air-water interface in a given period. Consequently, it increased the frequencies for solids to be adsorbed on the air-water interface and thereby increased the TSS removal rate. Similar results were also reported for foam fractionator operated in seawater system by Suh et al. (2000). In fresh water aquaculture systems, Suh et al. (1997) also reported similar trends for TSS removal at different SAVs.

Figure 7 shows the TSS removal rate at different initial

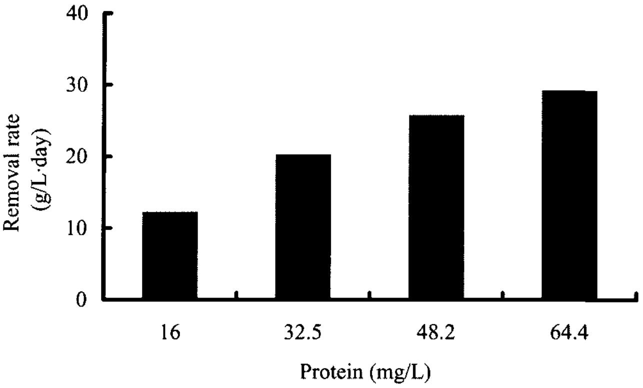

Fig. 7. TSS removal rates at different initial protein concentrations of 16, 32.5, 48.2, and 64.4 mg/L (HRT, 3 min; SAV, 1.486 cm/sec; foam overflow height, 3 cm) in trials conducted on batch mode.

protein concentration. The TSS removal rate increased with the increasing initial protein concentrations. it increased from 12.1 to 29.1 g/L/day, as initial protein concentration increased from 16 to 64.4 mg/L. Protein from the high protein containing feed is usually considered as the main source of surfactant in aquaculture water (Chen et al., 1993b), Essentially, all proteins are volatile solids (Timmons et al., 1995), which are considered to be the main substances that can be removed by foam fractionation (Weeks et al., 1992). The great impact of protein concentration on TSS removal is easily understood.

Foam condensates produced in the 5 trials conducted on consecutive mode were collected till the separation process ceased. TSS concentration in the foam condensates, foam overflow rate, time consumption, and gas holdup data are summarized in Table 1. Higher SAV resulted in greater foam overflow rate but lower TSS level in the foam condensates. Weeks et al. (1992) found a similar trend in a freshwater aquaculture system. In the present experiment, the TSS concentration in the collected foam condensates was about 17.8-32.7 times of the initial TSS concentration in culture tank water. Weeks et al. (1992) observed that the TSS concentration in the foam condensate was 25 times higher than that in the untreated fish culture water in a freshwater system. These results show that TSS enrichment in foam condensate can be substantial. Hydraulic residence time has significant effects on foam flow rate, and the period required for TSS removal in culture tank water. The TSS concentration in foam condensates was higher at lower HRT. Period required for TSS removal from culture tank water were about 2.5, 3, and 5.4 hours at HRT of 2, 3, and 6 min, respectively. Wide differences in TSS concentrations in the collected foam condensates were found among the different SAV treatments at constant HRT of 3 min. However, no marked difference was noted among the different HRT treatments at constant SAV of 1.486 cm/sec.

In 5 consecutive trials, incomplete removal of TSS was recorded for the tested treatments. Approximately, 40% of the TSS was removed from culture tank water. This would be partially due to the low protein level in the synthetic culture tank water. On the other hand, the foam condensates and sediments were frozen-stored, though the collected wastes were well mixed before supplying to culture tank water, coagulation of solids would attribute to the low TSS removal rates.

Foam condensates were collected in trials conducted on consecutive mode, implying that a continuous reduction in the TSS concentration in culture tank water occurred in treatment time, which would affect the overall performance of foam fractionator. Yet these results confirmed that high SAV would induce fast TSS removal and HRT might affect the TSS concentration and volume in foam condensates.

Effects of foam overflow height on performance of foam fractionator are shown in Table 2. Enrichment factor is defined as ratio of the TSS concentration in foam condensates to that in the untreated bulk solutions. TSS concentration and enrichment factors in the foam condensates increased with increasing foam overflow height. However, foam overflow rate decreased with increasing foam overflow height. This was because that foam was swept out at a faster rate at lower foam overflow height, which did not allow excess water to be drained from the foam. Higher foam overflow heights would increase the TSS concentration and lower the foam volume. In a fresh water system, Weeks et al.

Table 1. Summary of analysis results of foam condensates collected in 5 consecutive trials

HRT (min)	SAV (cm/sec)	TSS (mg/L)	Time (hours)	Flow rate (ml/min)	Holdup (cm)
6	1.486	2790	5.4	12	5.6
2	1.486	2135	2.5	32.6	5.6
3	1.486	2305	3	25.4	5.6
3	1.114	2625	3.9	16	4.2
3	0.743	3920	5.6	6.8	2.8

Table 2. Performance at different foam overflow height (FOH) and fixed TSS concentrations of 120 mg/L and protein concentrations of 34 mg/L

FOH (cm)	Concentration (mg/L)	Enrichment factor	Foam flow rate (ml/min)
1	936	7.8	76.4
3	2762	23	25.2
5	3994	33.3	15.6
7	4890	40.8	12.3

(1992), found similar trends but the differences were not as wide as those found in the present experiment. Foam condensate used in the synthetic wastewater should have contributed to this. Suh et al. (1997) also found an increase of TSS concentration in the foam condensate with the increasing of foam overflow height. These results suggested that high overflow heights may produce extremely concentrated foam condensate, but the production rate may be extremely low. For practical application of foam fractionation in aquaculture systems, the foam overflow height should be selected so that the desired results, e.g. minimizing the effluent volume or maximizing substrate removal, could be obtained.

Gas holdup values were higher for higher SAVs. However, the values were same at constant SAV and different HRTs. This indicated that gas holdup is not related to water flow rate through a foam fractionator column. This coincides with the results reported by Chen (1991).

In conclusion, the performance characteristics of foam fractionator are highly depended on the operating factors including SAV, HRT, and foam overflow height. TSS removal rate increased with increasing SAV and decreasing HRT. Higher initial protein concentration resulted in greater TSS removal rate. As the foam overflow height increased, foam condensate production decreased and the TSS concentration increased. The TSS concentration in the foam condensates collected from the 5 consecutive trials indicate that water flow rate has no effect on overall TSS removal. Though high SAV would accelerate the TSS removal rate, extremely high SAV may result in the formation of gas slugs (Timmons, 1994) and reduce substance removal rates. But this is out of the scope of this study. Foam fractionation process is very effective for trapping solids in the foam condensate. However, it is our observation that solids remain in the filtrate, even after being filtered through 0.45-micron filter papers. Hence a detailed analysis of the size distribution of solids in foam condensate will be helpful for accurate evaluation of the kind of solid that could be removed with foam fractionator. Also, lack of performance data on foam fractionator in seawater recircluating aquaculture systems makes the interpretations of the data obtained in present experiment difficult; the practical application of the present findings to aquaculture systems is doubtful, since large differences could be introduced by different managing strategies and dimensions of the foam fractionator used.

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