The effect of low sludge age on wastewater fractionation (S_S, S_I)

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Abstract In lab-scale experiments at the 2-stage activated sludge pilot plant of Vienna's central WWTP it is shown that the wastewater soluble COD concentration, which is inert to a sludge with SRT < 1 d (SI_A) is about double compared to the S_I concentration in sludge with SRT > 10 d (SI_B). Unexpectedly the ratio of SI_A/SI_B is independent of the sludge age between SRTs of 0.4 and 1.0 days. The difference between the two S_I fractions is soluble COD that is readily biodegradable by the sludge with SRT > 10 d. However, it is degraded at a lower maximum growth rate. These results comply with earlier results gained with different methods and at different WWTPs. It is hypothesised that very low sludge ages result in a selection of fast growing bacteria, which can utilise only part of the S_S in the raw wastewater. The other part of S_S therefore remains in the wastewater and can thus be utilised for enhanced denitrification in the second stage.

It is still unknown beyond which sludge age the soluble inert COD SI_A starts to decrease, finally reaching the value SI_B for low loaded systems (SRT > 5 days). From this point on S_I and S_S are assumed only to depend on the wastewater composition and not on the sludge age. The assumption of the Activated Sludge Model No.1 that the biodegradable fractions can be modelled as a single substrate and by a single removal kinetic (one Monod term) appears not to be applicable for low sludge ages. Some suggestions for mathematical modelling, design and operation of 2-stage activated sludge systems are given.

Keywords Activated sludge; microbial selection; modelling; sludge age; soluble COD

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Introduction

According to the Activated Sludge Model No.1 (ASM1) (Henze *et al.*, 1987) the organic content of municipal wastewater consists of at least 4 different fractions: soluble and particulate inert organics S_I and X_I and readily and slowly biodegradable organics S_S and X_S. In WWTPs with a sludge age longer than 5 days, it is assumed that the biodegradable fractions can be modelled as a single substrate and by a single removal kinetic (one Monod term). As the mean growth rate of the heterotrophs is far below their maximum growth rate, the removal of the biodegradable COD ($X_S + S_S$) is almost complete (> 98%) and the assumptions on the maximum growth rate have nearly no influence on the results of the model application. Because X_I is entrapped into the sludge flocs and accumulates in the system, the effluent COD consists mainly of the inert soluble fraction S_I. If the sludge age (= sludge retention time: SRT), however, decreases to 1 day and below, the assumptions of the ASM 1 with respect to COD removal may no longer be applicable. As full scale and pilot scale results show, a significant decrease of COD removal efficiency can occur, which cannot easily be modelled with standard kinetic values. As the growth rate of the heterotrophs within these short SRT systems is in the range of their maximum growth rate, it can be assumed that a washout of several heterotrophic species with lower maximum growth rate occurs depending on the applied SRT. Hence, the assumption of one substrate and one set of kinetic parameters becomes questionable.

Based on the theory of S_S utilisation in single stage activated sludge plants it is expected that almost no S_S will leave the first stage, if it is fully aerated, as the heterotrophic biomass should be able to metabolise the S_S completely. However, in lab-scale experiments with sludge from a 2-stage activated sludge system (AB process, Böhnke, 1977) it was shown that the inert soluble COD fraction (S_I) of the wastewater was always significantly higher if the wastewater was added to sludge with a SRT of ca. 0.5 days in comparison to a sludge with a SRT of ca. 20 d (Haider *et al.*, 2000). It was hypothesised that very low sludge ages result in selecting fast growing bacteria, which can utilise only part of the readily biodegradable COD (S_S) in the raw wastewater. The remaining part of S_S can therefore be utilised for enhanced denitrification in the second stage.

Because of its importance for understanding the nitrogen-removal capacities of 2-stage activated sludge systems, further experiments were performed at the pilot plant of Vienna's central WWTP. The hypothesis above should be investigated at various low sludge ages.

Materials and methods

Pilot plant and batch tests

The pilot plant (Figure 2) of Vienna's central WWTP was operated in 2-stage-mode with a sludge age in the 1st stage ("A-stage") < 2 days and a sludge age in the 2nd stage ("B-stage") > 10 days. The influent flow was constant at 2 m^3/h. The pilot plant was designed for 400 population equivalents, with a 1st stage bioreactor volume of 4 m^3 and 2nd stage volume of 14.5 m^3. The plant was equipped with a primary, an intermediate and a secondary settling tank (PST, IST and SST). All relevant flow and concentration parameters, including turbidity and UV-absorption in the effluent of the 1st stage, were measured on-line. Additional information was derived from laboratory data. From on-line and laboratory data the actual $SRT_{stage\ 1}$ could be determined quite accurately, also considering the (significant) amount of biomass washed out with the effluent of the 1st stage.

At sludge ages in the 1st stage between 0.4 and 1.0 day the following experiments were carried out (Figure 2). From the last cascade of the bioreactor in the 1st stage a 2 litre sludge sample was taken and aerated separately while constantly mixing with a magnetic stirrer. During ca. 4 hours the 0.45-membrane-filtrated COD (COD_μ) concentration of the sludge was measured by sampling (every 10 to 20 minutes) and immediate analysis. In between, after ca. 2 hours of aeration, when it could be assumed that no further degradation of $\boldsymbol{S_S}$ took place, the sludge was allowed to settle (for a few minutes) and 800 ml of the supernatant ($V_{Ü\_A}$) were added to 300 ml pre-aerated sludge from the 2nd stage (V_B; in 2 experiments the ratio V_B/ $V_{Ü\_A}$ was different). The mixture was aerated and the COD_μ concentration was again measured during ca. 3 hours in the same way. In addition to the COD_μ concentrations, the actual (OUR_0) and maximum oxygen uptake rates (OUR_m) for carbon degradation (with 5–10 mg/l ATU in the mixture to inhibit nitrification) were determined in a small respirometer. For determination of OUR_m an artificial readily biodegradable substrate (including pepton, meat extract, glucose and acetate) was added in excess to the mixture.

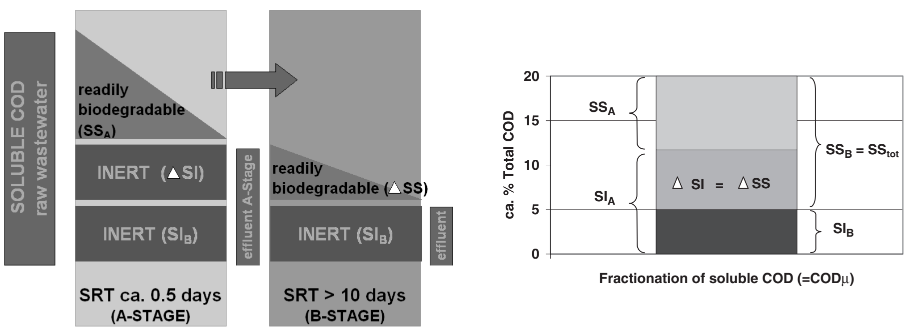

Figure 1 Different soluble COD fractions for low and long sludge age

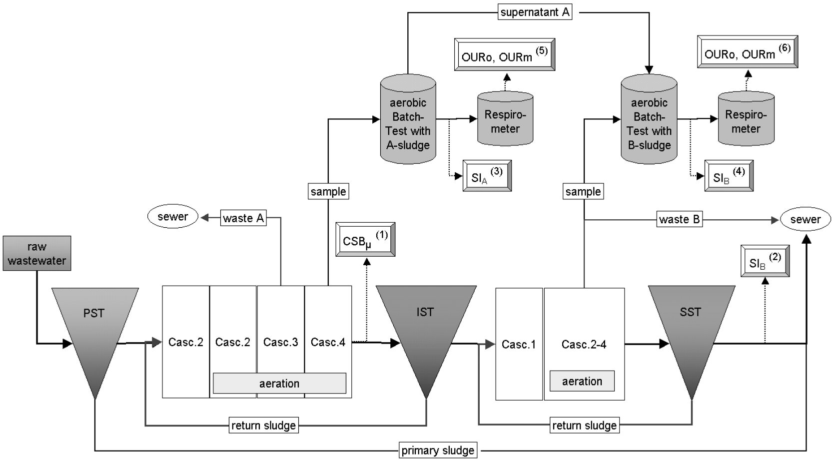

Figure 2 Experimental design: 2-stage pilot plant, batch-tests, COD- and OUR-measurements
Legend: (1) total soluble COD effluent A-stage (measured); (2) inert soluble COD effluent B-stage (no S_S left) (measured); (3) inert soluble COD A-sludge (measured and calculated from Eq. (1)); (4) inert soluble COD B-sludge (measured & calculated from equation 1); (5) actual and maximum O_2-uptake rate A-sludge (measured); (6) actual and maximum O_2-uptake rate A-sludge (measured).

Parallel to the batch tests COD_μ-concentrations were measured directly by random sampling the effluent of the intermediate and secondary clarifier.

Determination of SI_A and SI_B

Assuming that COD_μ in the supernatant of the A-sludge is NOT further degraded by the B-sludge, i.e. SI_A is equal to SI_B, the following equation holds:

$$COD_\mu^{B+Ü\_A} = \frac{(V_B \times COD_\mu^{B}) + (V_{Ü\_A} \times COD_\mu^{A})}{(V_B + V_{Ü\_A})} \quad (1)$$

(1) $COD_\mu^{B+Ü\_A}$ ....COD_μ in B-sludge after adding supernatant from A-sludge and reaching a lower plateau (mean of the last 2 COD_μ data)
(2) COD_μ^{B} ....COD_μ in B-sludge after adding ATU, before adding supernatant A
(3) $COD_\mu^{A.}$ ....COD_μ in A-sludge (in case of further degradation after sampling and starting aeration the mean value after reaching a lower plateau was taken)
(4) $V_{B.}$ ....Volume of B-sludge before adding supernatant A
(5) $V_{Ü\_A}$ ....Volume of supernatant A

If, however, the hypothesis, that SI_A is bigger than SI_B, holds, it follows that COD_μ^A is further degraded by B-sludge and that the $COD_\mu^{B+Ü\_A}$-concentration at the end of the batch-test is therefore smaller than calculated by equation 1. On the other hand, by solving equation 1 for COD_μ^A knowing the variables (1), (2), (4) and (5) the part of COD_μ^A which is inert for B-sludge (SI_B) can be calculated. The difference between the measured and calculated concentration of COD_μ^A is further degraded by B-sludge.

$$\frac{\text{calculated } COD_\mu^A}{\text{measured } COD_\mu^A} = \frac{SI_B}{SI_A}$$

Results

Eight experiments were performed at a 1st stage sludge age between 0.4 and 1.0 day. The sludge age calculated from the amount of waste sludge was corrected for the mass of sludge washed out with the effluent of the 1st stage, leading to significantly lower values of SRT (till minus 50%) as shown in Figure 3.

In all experiments at $SRT_{stage\ 1}$ between 0.4 and 1.0 day the COD_{μ} concentration in the sludge from the 1st stage remained constant, while the COD_{μ} concentration in the mixture was further degraded in a short period of time, indicating the presence of S_S. Figure 4 shows the results of one of these experiments.

For the experiment on 03.10.2000 two different inert soluble COD-fractions, for activated sludge from stage 1 (SI_A) and for sludge from stage 2 (SI_B), could be determined:

$$SI_A \text{ (= measured } COD_{\mu}^{A\text{-sludge}}) = 67 \text{ mg/l}$$
$$SI_B \text{ (= calculated } COD_{\mu}^{A\text{-sludge}}) = 28 \text{ mg/l}$$

Figure 5 shows the SI_B- and SI_A- concentrations determined in Ghent and Vienna (in Ghent the COD in flocculated filtered samples was used for the determination of SI_B and SI_A). In both cases SI_B is only about half of SI_A. The similarity in results supports the above mentioned hypothesis.

The results from the batch tests in Vienna were confirmed by the directly measured COD_{μ}-concentrations in the effluent of the intermediate and secondary clarifier. Considering the diurnal variations in concentration and the hydraulic retention times, the mean ratio of COD_{μ} of effluent B to COD_{μ} of effluent A was 0.50. The measured data also

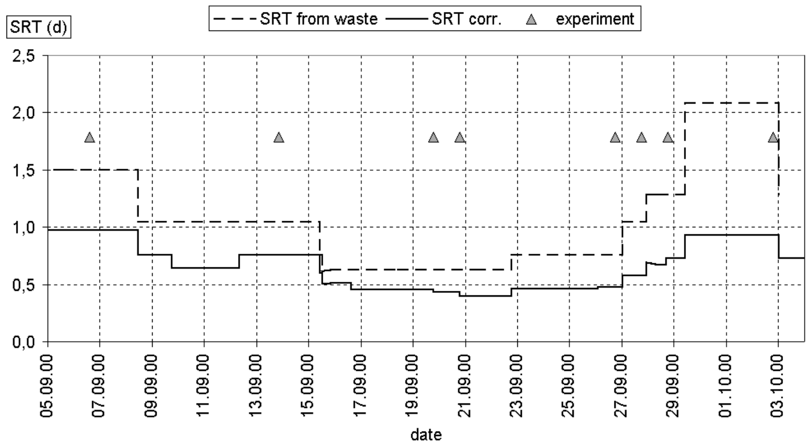

Figure 3 Variation of sludge age in the 1st stage: SRT calculated from waste sludge and SRT corrected for the mass of sludge washed out with the effluent

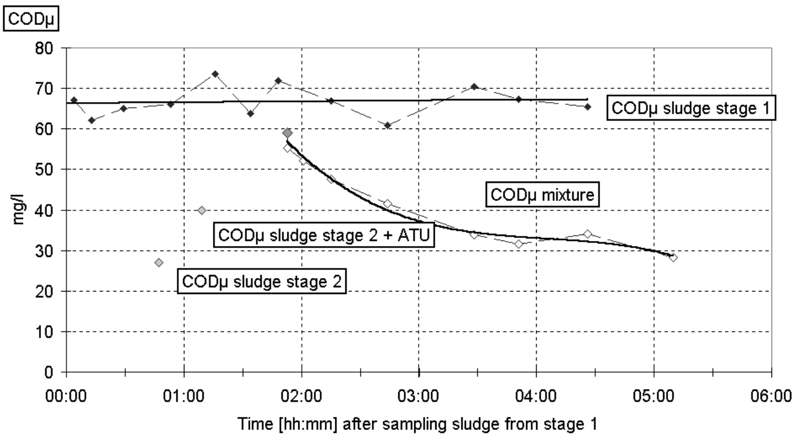

Figure 4 COD_{μ} concentrations during the experiment on 03.10.2000 at $SRT_{stage\ 1} = 0.9$ days

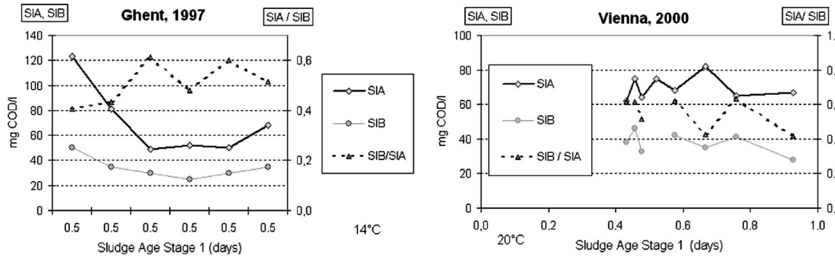

Figure 5 Inert soluble COD concentrations in sludge from stage 1 and stage 2 of the pilot plants in Eschweiler (Ghent, 1997) and Vienna (2000)

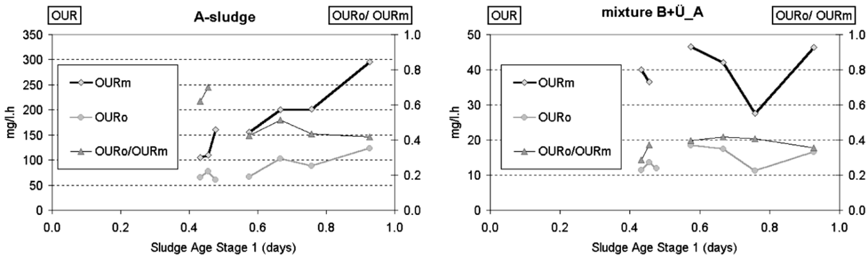

Figure 6 OUR_0 (at the beginning of a batch-test) and OUR_m (maximum) with A-sludge (left) and with the mixture of B-sludge with the supernatant of A-sludge (right) (experiments Vienna 2000)

showed that the SS_A-concentrations in the effluent of the 1st stage were close to zero, if the sludge age was > 0.5 days. The mean SI_B/SI_A ratio could be calculated to be 0.55.

The OUR measurements for A-sludge were different from those for the mixture of B-sludge and supernatant A. While sludge age increased from 0.4 day to 1.0 day the ratio OUR_0/OUR_m decreased from 0.65 to 0.40 indicating the presence of a lot of readily biodegradable, partly stored, material at very low sludge age. The ratio OUR_0/OUR_m in the mixture B+Ü_A was low at ca. 0.40 for all experiments, at first sight indicating little remaining readily biodegradable substrate (Figure 6). The absolute values of OUR for A-sludge increased with higher sludge age as the TSS-conc. increased from 1.5 to 3.0 g/l. The absolute values of OUR in the mixture B+Ü_A also varied because TSS_B and the ratio of $V_B/V_{Ü\_A}$ were not constant. Hence, only the ratio OUR_0/OUR_m should be interpreted.

Discussion

The results lead to 3 main conclusions:

- Low sludge age selects fast growing bacteria which can degrade only part of the total S_S in the wastewater, the rest of S_S adds to the inert soluble COD, i.e. $SI_A > SI_B$, and is degraded like readily biodegradable COD in the 2nd stage.

  The simplified approach of only one Monod function to describe the relationship between heterotrophic growth rate and substrate concentration works sufficiently well in a long sludge age plant, as the actual mean growth rate is even lower than the minimum of all maximum growth rates of the different organisms in the various substrates. Therefore most of the different substances can be degraded. At short sludge age, however, the actual growth rates are much higher ($\mu_H = 1/SRT$). Only substances, which support high growth rates can be degraded and only heterotrophic species, which are capable of those growth rates can survive in the system (Figure 7). Although these organisms may possess the capability of also degrading the rest of S_S (ΔS_I) after suffi-

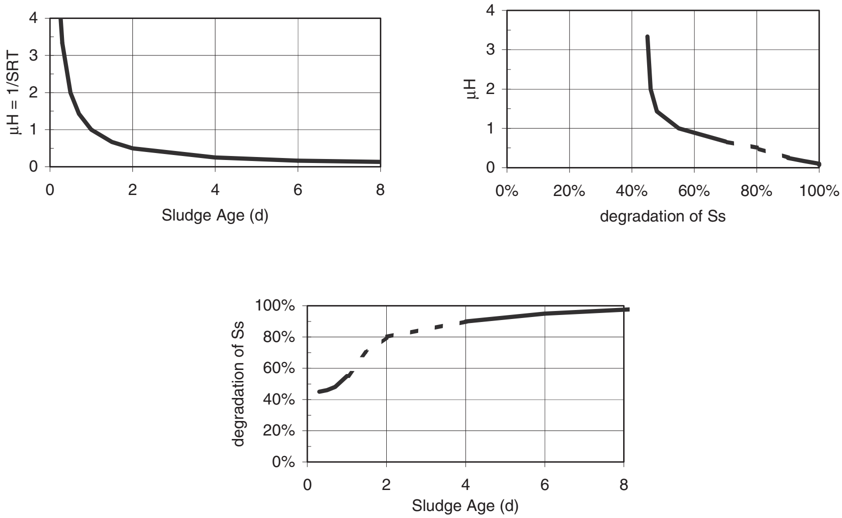

Figure 7 Functions between growth rate, sludge age and maximum degradation of S_S

cient adaptation, they are not able to do so within several hours (duration of 1 batch test with sludge from the 1st stage).

- The difference between SI_A and SI_B (ΔS_I) is readily biodegradable substrate (SS_B), which can be degraded within a short period of time by adapted organisms (1st removal is considered too fast to be explained by hydrolysis).

  The readily biodegradable substrate S_S, as defined in the ASM1, consists of various single substrates. About 50% of total S_S can not be degraded by sludge younger than 1 day, but is rapidly degraded by sludge older than 5 days, i.e. $S_S = SS_A + SS_B$.
- ΔS_I from the 1st stage is degraded at a lower μ_{Hmax} in the 2nd stage than S_S in raw wastewater or in artificial readily biodegradable substrate. This conclusion can be drawn by interpreting the OUR data as explained below.

  According to ASM1 the oxygen uptake rate can be calculated as

$$\text{OUR} = \mu_{\text{Hmax}} X_{\text{H}} S_S/(K_S + S_S)\,(1-1/Y_{\text{H}})$$

Assuming that the yield (Y_{H}), the biomass conc. (X_{H}) and μ_{Hmax} are constant during the batch test, the ratio $\text{OUR}_0/\text{OUR}_{\text{m}}$ depends on the Monod Term $S_S/(K_S + S_S)$ and therefore mainly on the substrate concentration. Only if S_S is far bigger than the saturation value K_S, is the ratio $\text{OUR}_0/\text{OUR}_{\text{m}}$ independent of the S_S concentration and equals 1. This is in contradiction to the measurements shown in Figure 7 (left side), where the initial S_S con-

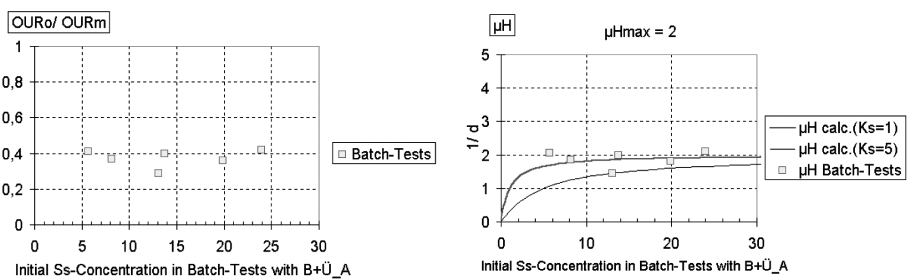

Figure 8 Ratio $\text{OUR}_0/\text{OUR}_{\text{m}}$ at initial $\Delta S_I = SS_B$ conc. (left) and calculated MONOD functions fitting estimated μ_{H}-values of Batch-Tests (right) with mixture B-sludge plus supernatant A-sludge

centrations in the batch-tests with B-sludge and supernatant from A-sludge were varying between 6 and 24 mg COD/l while the ratio OUR_0/OUR_m was nearly constant at about 0.4.

It is not possible to explain the constant OUR_o/OUR_m ratio with single Monod kinetics. The only reasonable explaination the authors found was that the S_S in the effluent of the 1st stage leading to OUR_o and the S_S in the artificial substrate leading to OUR_m are degraded at different μ_{Hmax} values because of the quality (not the concentration) of these substrates. Hence, assuming $\mu_{Hmax} = 5$ for OUR_m and $\mu_{Hmax} = 2$ for OUR_o and a low Ks-value of 1 mg COD/l the measured data can be fitted well as shown in Figure 8 (right side).

The most likely explanation is that the readily biodegradable COD in the effluent of the 1st stage is either degraded at the usual μ_{Hmax} rate by only part of the organisms of the second stage or degraded at a lower μ_{Hmax} rate by all heterotrophic organisms.

Conclusions

For modelling of 2-stage activated sludge WWTPs it is necessary to make a compromise between complexity and practicability. Usually similar models for both stages are intended. From the results above the following aspects should be considered:

- The set of μ_{Hmax} and K_S for the 1st stage must allow growth rates > 1/SRT to avoid washout of biomass.
- The readily biodegradable fraction S_S of the wastewater should be split into 2 fractions: SS_A and SS_B. The latter is not degradable in the 1st stage and increases the S_I fraction. In the effluent of the 1st stage the SS_B fraction is set free for degradation.
- The μ_{Hmax} for the 2nd stage can be the same for SS_B and raw wastewater that is bypassing the 1st stage (as in Vienna's new WWTP) as the substrate concentrations are much smaller than the K_S value.
- The K_S values of both stages have to be small enough to allow the complete degradation of SS_A and SS_B respectively. The increase of K_S in the 1st stage to ensure a part of S_S leaking to the 2nd stage without introducing the fraction SS_B can be an acceptable model simplification. However, in batch test simulation this method will lead to wrong results.

Consequences for design and operation

Generally a 2-stage activated sludge WWTP has to be designed and operated in such a way that sufficient substrate for denitrification is available in the 2nd stage. One way is to support the selection of highly specialised heterotrophic organisms, which utilise only part of S_S by applying a sludge age below 1 day in the 1st stage.

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