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From the affinity constant to the half-saturation index: Understanding conventional modeling concepts in novel wastewater treatment processes

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ABSTRACT

The “affinity constant” (K_S) concept is applied in wastewater treatment models to incorporate the effect of substrate limitation on process performance. As an increasing number of wastewater treatment processes rely on low substrate concentrations, a proper understanding of these so-called constants is critical in order to soundly model and evaluate emerging treatment systems. In this paper, an in-depth analysis of the K_S concept has been carried out, focusing on the different physical and biological phenomena that affect its observed value. By structuring the factors influencing half-saturation indices (newly proposed nomenclature) into advectional, diffusional and biological, light has been shed onto some of the apparent inconsistencies present in the literature. Particularly, the importance of non-ideal mixing as a source of variability between observed K_S values in different systems has been illustrated. Additionally, discussion on the differences existent between substrates that affect half-saturation indices has been carried out; it has been shown that the observed K_S for some substrates will reflect transport or biological limitations more than others. Finally, potential modeling strategies that could alleviate the shortcomings of the K_S concept have been provided. These could be of special importance when considering the evaluation and design of emerging wastewater treatment processes.

1. Introduction

The Monod equation (Monod, 1942) is generally accepted as the basis of the Activated Sludge Models (ASM) (Henze et al., 2000) used for modeling the majority of biological treatment processes in the wastewater treatment field. Other models are available to describe microbial growth and substrate degradation kinetics, but Monod's formulation has the advantage of its simplicity and relatively accurate representativeness (Okpokwasili and Nweke, 2005). The basic output of the Monod equation is shown in Fig. 1a; its particular formulation allows switching from zero-order growth kinetics at high substrate concentration to first-order growth kinetics at low

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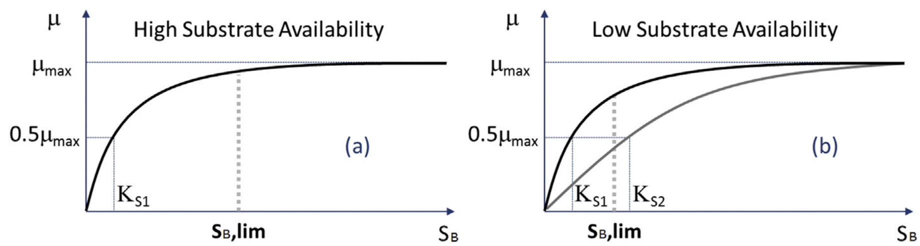

Fig. 1 – Illustration of the parameters limiting growth kinetics at different substrate availabilities.

substrate concentrations in order to emulate actual microbial behavior. Fig. 1a shows how at high substrate availabilities (in this case readily biodegradable substrate, S_B), growth kinetics are independent of substrate concentration and instead are determined by the maximum specific growth rate (μ_{max}). In contrast, at low substrate availabilities, growth kinetics become substrate limited and the so-called "half-saturation constant" or "affinity constant" (K_S, substrate concentration at which the growth rate corresponds to half the μ_{max}) is the main parameter influencing growth rate (Fig. 1a). In low substrate availability conditions, microbial competition for substrate becomes a relevant phenomenon; it is common process understanding that the organism with the highest affinity towards the substrate (lower K_S) will outcompete the other ones present in the culture. This understanding can be explained using the Monod equation; in Fig. 1b, the organism with the lower K_S (K_{S1}) presents higher growth rates at low substrate availabilities than the organism with a higher K_S value (K_{S2}), given that μ_{max} is the same. From the previous statements, it follows that at low substrate availabilities, process performance according to the model will be determined to a large extent by the value of the "half-saturation constants". Hitherto, the operation of wastewater treatment processes has been closer to the situation shown in Fig. 1a than to the one shown in 1b (especially in systems with low solids retention times), with specific maximum growth rates determining the rates and extent of contaminant removal (Jenkins and Wanner, 2014). As effluent regulations are becoming more stringent and a number of emerging wastewater treatment processes that operate with low substrate concentrations are becoming increasingly implemented at the full-scale, there is a growing interest in determining the values of "half-saturation constants" for different substrates, biological reactions and organisms. Particularly, biological wastewater treatment processes and transformations where K_S values are relevant include the following:

a) Treatment processes requiring very low effluent levels of a certain contaminant (e.g. low ammonium or phosphate levels for plants requiring very low effluent nutrient levels).
b) Processes that use low concentrations of a certain substrate or electron acceptor as a possible strategy for process control (e.g. partial nitrification/anammox processes).
c) Processes where significant substrate concentration gradients are established or substrate transport is impaired (e.g. biofilm processes, membrane bioreactor processes).
d) Processes operating at low concentrations of a certain substrate or electron acceptor (e.g. simultaneous nitrification/denitrification, low oxygen nitrification).
e) Processes where low substrate or electron acceptor concentrations cause undesired operational issues (e.g. N_2O emissions, bulking sludge occurrence).

In this framework, a number of studies have focused on measuring experimentally or calibrating "half-saturation constants" for different substrates in the context of different biological processes. As an increasing number of studies are being published presenting and discussing measured and calibrated values of K_S, it is becoming evident that these have a high degree of variability; the values obtained are not always consistent between publications. These inconsistencies can be illustrated simply with the case of the partial nitrification process, where ammonia-oxidizing bacteria (AOB) have to outperform nitrite oxidizing bacteria (NOB). The general process understanding is that AOB have higher dissolved oxygen (DO) "affinities" (lower K_{DO} values) than NOB (Rittman and McCarty, 2001), and thus oxygen can be used consistently as a means to washout NOB from the process. Table 1 shows different K_{DO} values reported for NOB and AOB for a selected number of studies. As can be seen, the values reported for the "half-saturation constants" vary significantly from one study to the other (0.03–1.16 mg O_2/L for AOB and 0.13–3 mg O_2/L for NOB). Additionally, some studies report lower "half-saturation constants" for NOB as compared to AOB, contradicting common process understanding (Regmi et al., 2014). In this framework, the actual performance of the partial nitrification process and the ability to use consistently low DO values to washout NOB is not generalizable and has to be assessed in a case-to-case basis. Similar inconsistencies in "affinity constants" can be found for other substrates and biological processes.

In order to account for the inconsistencies existent in published data, several explanations are commonly provided in the literature. The "strategist explanation" is commonly used; this is a biology-based account where some organisms will thrive at high substrate concentrations (r-strategists), while some others will do so at low substrate concentrations (K-strategists). Using the AOB-NOB example, some studies have attributed the unexpected lower K_{DO} values for NOB as compared to AOB to the fact that low DO conditions might select for NOB species that are K-strategists (*Nitrospira* sp.), as compared to the more commonly encountered *Nitrobacter* sp.,