

# Performance of a Spiral Symmetry Stream Anaerobic Bioreactor for Bamboo Degumming Wastewater Treatment Under Varying Hydraulic Retention Time

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**Abstract:** This study evaluated the effectiveness of a spiral symmetry stream anaerobic bioreactor (SSSAB) treating bamboo degumming wastewater (BDW) under various hydraulic retention time (HRT) conditions. The reactor was operated across three phases with progressively decreasing HRTs of 20h, 14h, and 7h, while pH stability, ammonia nitrogen transformation, and COD removal efficiency were observed. The SSSAB performed effectively at HRT of 14 hours with COD removal efficiency of 75–80%, consistent effluent pH between 6.8 and 7.2, and active ammonification of organic nitrogen. The system demonstrated successful microbial acclimation at HRT of 20 hours, with COD elimination efficiency increasing from 50% to 75%. However, process instability developed when HRT was lowered to 7 hours, indicated by a dramatic drop in COD removal efficiency to 40%, effluent acidification to pH 5.2, and decreased ammonification activity because of inadequate contact time and possible biomass washout. These results provide crucial operational insights for the use of high-rate anaerobic bioreactors in the treatment of lignin-rich industrial wastewater. They demonstrate that although the SSSAB performs well under moderate hydraulic loading, there is a critical HRT threshold below which system failure occurs.

**Keywords:** Bamboo Degumming Wastewater; Hydraulic Retention Time; Spiral Symmetry Stream Anaerobic Bioreactor; Anaerobic Digestion; COD Removal; Ammonification.

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## I. INTRODUCTION

The demand for textile fibers is rising globally, and they are recognized as one of the most significant raw material resources. However, the process of extracting textile fibers from traditional raw materials is quite difficult since it usually involves a lot of energy, water, and chemicals. It also produces extremely toxic effluent with a variety of contaminants and causes major environmental issues. Therefore, in order to overcome the development barrier in the textile sector with regard to energy conservation, consumption reduction, and discharge reduction, it is necessary to redefine and study sustainable technologies of textile fiber extraction. Fibre processing is being done using environment-friendly technologies including biological catalysts like microorganisms or their enzymes that are catalysts [1].

Bamboo is a naturally occurring lignocellulosic material with a cellulose skeleton covered by hemicellulose and lignin, whose essential elements invade one another to form an interpenetrating network structure that stops cellulosic fiber extraction through degumming. In this case, the extremely small structure of bamboo culm necessitates a higher degree of degumming action to achieve fiber extraction, requiring a whole-degumming procedure that extracts all non-cellulosic components [2]. Untreated bamboo industry wastewater (BIWW) is a serious environmental problem in China. As a result of the breakdown of proteins and other nitrogenous components in the bamboo biomass, BIWW is characterized by high levels of chemical oxygen demand (COD) between 20,000 and 50,000 mg L<sup>-1</sup>, low PH between 2.5 and 5, rich color consumption of 800-1500 T, and high content of nitrogenous compounds like ammonia nitrogen (NH<sub>3</sub>-N). Additionally, BIWW contains organic molecules such as

saccharides, organic acids, amino acids, flavonoids, tannins, and phytochromes, making this type of wastewater complicated and more difficult to dispose of [3]. The development of effective and economical treatment technologies is necessary because the direct release of untreated bamboo degumming wastewater (BDW) can seriously eutrophicate and harm aquatic life [4].

High-strength industrial wastewater can be treated with anaerobic digestion (AD), a promising technique that offers two advantages to the process of controlling pollution and recovering renewable energy in the form of biogas [5]. As compared to aerobic methods, AD uses less energy, generates less waste sludge, and produces methane-rich biogas that can be used to generate power and heat [6]. Retention of active biomass is a critical aspect of the treatment performance of anaerobic systems, and high-rate bioreactors have been developed, allowing the decoupling of both hydraulic retention time (HRT) and solids retention time. In the absence of an adequate HRT, biomass can be readily washed off with the effluent, due to its low settling characteristics, resulting in inferior degradation [4].

Of these types of reactors, the upflow anaerobic sludge blanket (UASB) reactor and its derivatives have found much use in the treatment of a wide range of industrial wastewater, particularly because these reactors can sustain high concentrations of anaerobic granular sludge (AGS). Furthermore, the transformation of organic nitrogen into ammonia nitrogen during the anaerobic digestion process is a crucial aspect of process performance because high ammonia levels can impede the methanogenic process's activity, particularly in short HRT situations where the rate of ammonification can fluctuate [5].

Anaerobic bioreactor stability and treatment capacity are directly impacted by hydraulic retention time, a crucial operational parameter [7]. Lowering the HRT increases the organic loading rate (OLR) and upflow velocity, which could increase the efficiency and production of biogas. The challenge of working under overly short HRT conditions, however, creates a heavy load on the microbial community. Research has previously shown that lowering HRT to critical levels causes unstable fatty acid (VFA) accumulation, a drop in pH, and the process's eventual termination [8]. Additionally, the activity of ammonification is significantly influenced by variations in HRT, and a shorter retention period may promote the release of ammonia from the breakdown of organic nitrogen, increasing the volatility of NH<sub>3</sub>-N under high pH conditions and affecting the stability of the treatment overall. A novel high-rate reactor design, the spiral symmetry stream anaerobic bioreactor (SSSAB) has a unique spiral flow pattern that promotes mass transfer, homogeneous substrate distribution, and stable substrate-microbial interaction with the difficult-to-maintain hydrodynamic environment [5, 9]. Previous studies have demonstrated that SSSAB has outstanding shock load capacity and treatment stability when utilized to treat various industrial wastewater, including traditional Chinese medicinal wastewater and soybean processing wastewater [5, 10]. The reaction of the microbial population, particularly nitrogen transformation pathways, to

HRT-induced stress in this system is still little known, and the use of SSSAB for treating lignin-rich wastewater like BDW has not been thoroughly studied.

Therefore, the study's goal is to thoroughly examine how well an SSSAB treats effluent from bamboo degumming in various HRT circumstances. These specific goals are to: (1) ascertain the effectiveness of COD removal, ammonia nitrogen transformation, and process stability (pH) at progressively decreasing HRTs. The findings will provide crucial details on the operational limitations that define the stability of SSSAB in the treatment of complicated industrial wastewater.

## II. MATERIALS AND METHODS

### ➤ *Experimental Setup*

In this work, a laboratory-scale SSSAB was employed. The effective volume of the SSSAB was 7.2 L. The SSSAB's configuration parameters have been previously explained [5]. A peristaltic pump was used to continually provide BDW to the bioreactor. There were three sections to the SSSAB: upper, middle, and bottom. By covering the reactor with an insulating layer and using a temperature control mechanism, the SSSAB's temperature was kept at 38°C±1°C.

### ➤ *Wastewater and Inoculum*

BDW was obtained from our research group's bamboo fiber processing facility. Wastewater samples were collected every alternative day for the duration of the study. The characteristics of the BDW are listed in Table 1.

The pilot-scale SSSAB at the site of a wastewater treatment facility for soybean products provided the inoculated anaerobic granular sludge (AGS). The SSSAB was fed 4.5 liters of the inoculated AGS, which is around 60% of its effective volume.

### ➤ *SSSAB Operation Strategy*

As shown in Table 2, the experiment was carried out in three separate phases to fully examine SSSAB performance in response to changing HRT. Phase I was operated at HRT 20h, Phase II at HRT 14h, and Phase III at HRT 7h.

### ➤ *Analytical Methods*

COD was measured by using microwave digestion method by following the standard methods (GB11914-89). Ammonia-nitrogen (NH<sub>3</sub>-N) were measured by using UV1700PC UV-Vis spectrophotometer (Shanghai Aoxi Scientific Instrument Co., Ltd., Shanghai, China). pH measurements were performed using a pH-100B LICHEN pH meter.

## III. RESULTS AND DISCUSSION

### ➤ *HRT Effect on COD Removal Efficiency*

Three operational phases were used to assess how hydraulic retention time (HRT) affected the removal of COD. As seen in Figure 1, influent COD concentrations stayed mostly constant throughout the experiment, ranging from roughly 980 to 1032 mg/L, while effluent COD and removal

efficiency showed distinct phase-dependent fluctuations.

The reactor experienced an acclimation phase during Phase I (HRT 20h). As COD removal efficiency increased from 50% to 75%, effluent COD steadily dropped from roughly 490 mg/L to 209 mg/L. This improvement is explained by microbial acclimation to bamboo degumming wastewater (BDW), which is made possible by the longer HRT's adequate substrate-microbe contact time.

The reactor reached its peak performance in Phase II (HRT 14h). Effluent COD levels were constantly between 202 mg/L and 237 mg/L, with removal efficiency ranging from 75 to 80%. The microbial population was well-adapted to the wastewater properties under moderate hydraulic stress, as

evidenced by this phase's optimal balance between organic loading rate and hydraulic retention time.

In Phase III (HRT 7h), there was a noticeable drop in performance. While removal efficiency decreased from 75% to 35%, effluent COD gradually increased from roughly 221 mg/L to 644 mg/L. Inadequate treatment time and potential biomass washout, which led to overload circumstances that exceeded the system's capacity, are probably the causes of the significant decrease in treatment efficiency under the shortest HRT. These findings show that decreasing HRT has an adverse impacts COD removal efficiency, with optimal performance achieved at a moderate HRT of 14h under the tested conditions.

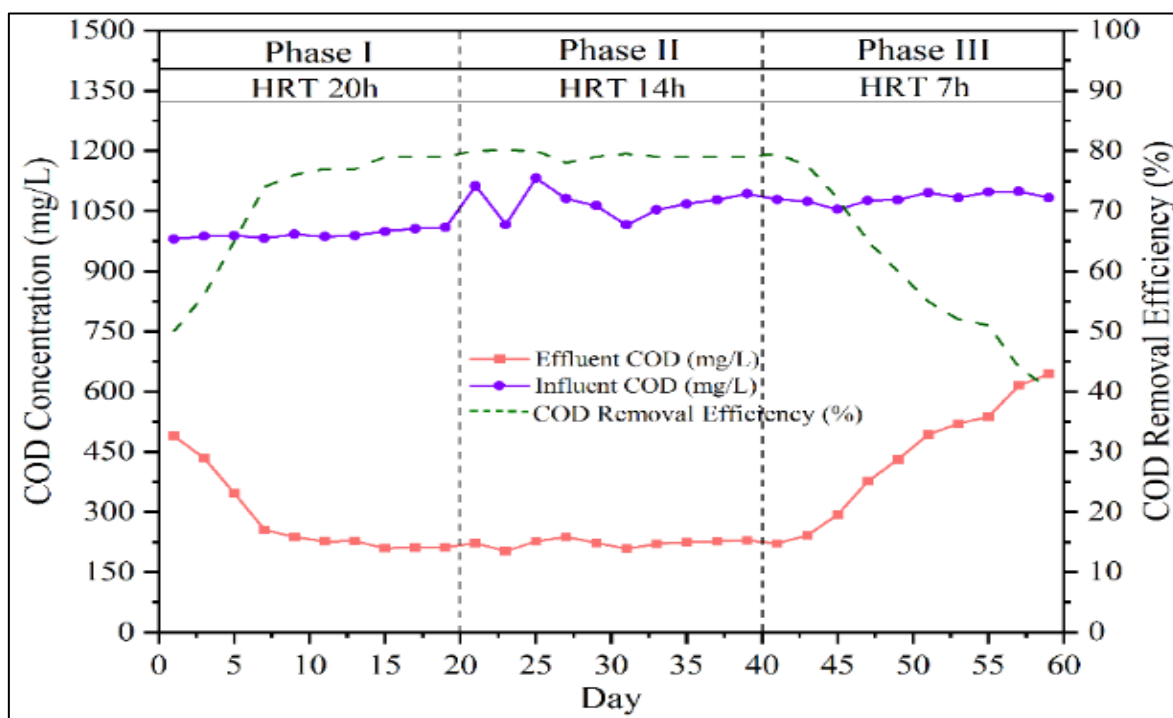


Fig 1 Variation of COD Concentrations and COD Removal Efficiency Under Different Hydraulic Retention Times

➤ *HRT Effect on pH*

Effluent pH was monitored as an indicator of process stability because the influent BDW was constantly acidic, with pH values ranging from 4 to 6.5.

As shown in Figure 2, the effluent pH stayed consistent at roughly 6.9–7.5 during Phase I (HRT 20h), indicating that the anaerobic system had enough buffering ability to neutralize the acidic influent. Maintaining optimal conditions for methanogenic activity depends on this stability.

In Phase II (HRT 14h), the effluent pH remained stable between 6.5 to 7.4, indicating sustained optimal biological activity. Despite the increased hydraulic loading, the system was still able to buffer.

The pH of the effluent decreased significantly in Phase III (HRT 7h), from roughly 7.09 to 5.2. Due to an imbalance between acidogenesis and methanogenesis under the shortest HRT, this acidification trend leads to the build-up of volatile fatty acids (VFAs). The pH drop signals the beginning of process instability and is closely correlated with the observed drop in COD removal efficiency.

These results verify that at higher HRTs (20h and 14h), the reactor maintained stable neutral pH values; but, at extremely low HRTs (7h), it became acidic, which negatively impacted treatment performance.

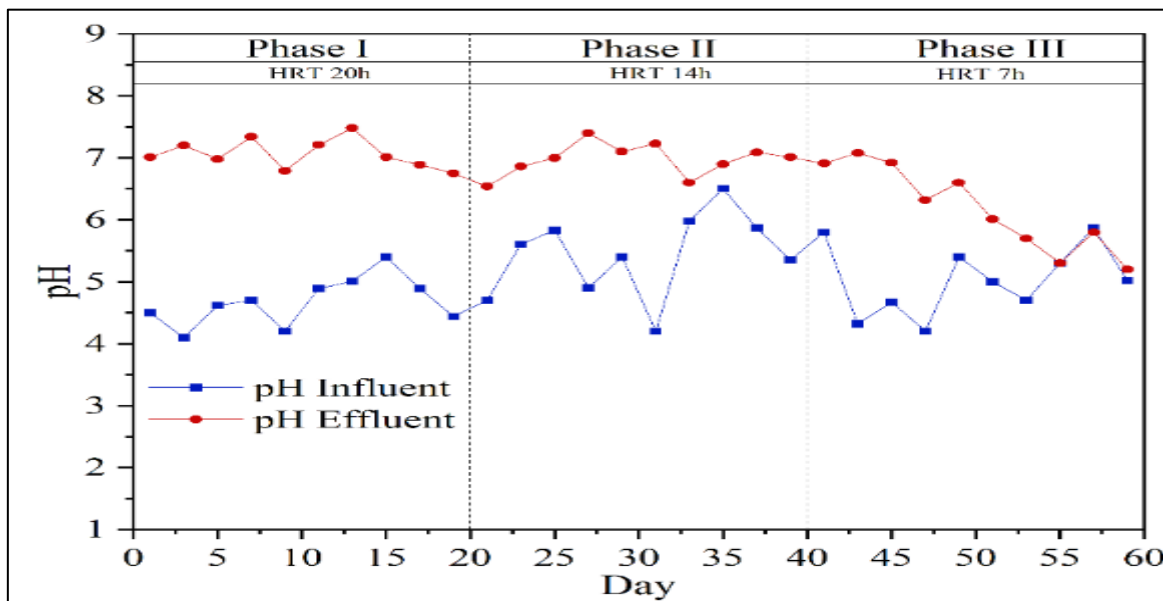


Fig 2 Variation of pH Values Under Different Hydraulic Retention Times

➤ *HRT Effect on Ammonia Removal Efficiency*

Ammonia nitrogen (NH<sub>3</sub>-N) dynamics were examined to understand nitrogen transformation mechanisms under various HRT conditions. Throughout the experiment, active ammonification, the conversion of organic nitrogen to ammonia, was demonstrated by the fact that effluent NH<sub>3</sub>-N concentrations were typically higher than influent values, demonstrated in Figure 3.

During Phase I (HRT 20h), influent NH<sub>3</sub>-N dropped from roughly 28 mg/L to 18 mg/L but effluent NH<sub>3</sub>-N varied from 35 mg/L to 22 mg/L with an increasing rate of 10–13%. This demonstrates that ammonification, which releases ammonia from organic nitrogen molecules in the BDW, was the primary nitrogen transformation activity.

During Phase II (HRT 14h), both influent and effluent NH<sub>3</sub>-N concentrations varied with the increasing rate reaching

at roughly 14%. This phase showed the highest ammonification activity, indicating that under moderate HRT conditions, microbial activity associated with nitrogen transformation was most active.

The NH<sub>3</sub>-N increasing rate decreased to 5–10% in Phase III (HRT 7h). This decrease suggests that partial ammonification resulted from the shorter HRT, most likely as a result of shorter contact time for microbial conversion of organic nitrogen. The amount of nitrogen transformation was constrained by the reduced biological activity under hydraulic stress.

Overall, the reactor primarily functioned as a system where ammonification dominated, but the efficiency of this process decreased significantly at the lowest HRT.

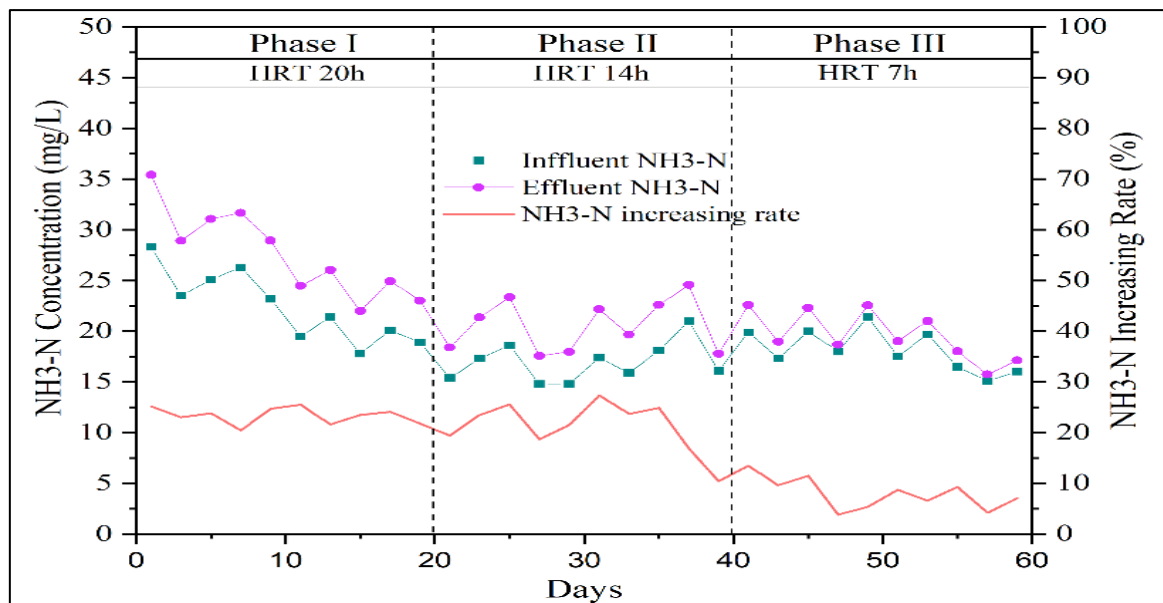


Fig 3 Changes in NH<sub>3</sub>-N Concentrations and NH<sub>3</sub>-N Increasing Rate at Different HRTs

Table 1 Characteristics of Bamboo Degumming Wastewater (BDW) Used in this Study

Parameter	Average Value	Units
COD	1048	mg/L
pH	5.05	-
NH <sub>3</sub> -N	19.16	mg/L
Lignin	502	mg/L

Table 2 Operational Phases of SSSAB Showing Hydraulic Retention Time (HRT) and Corresponding Operation Days.

Operation Phase	Operation Days (d)	HRT (h)
Phase I	1–20	20
Phase II	21–40	14
Phase III	41–60	7

#### IV. CONCLUSION

This study showed that in an SSSAB bioreactor treating effluent from bamboo degumming, hydraulic retention time is a crucial factor in determining treatment efficacy and stability. At HRT of 14 hours, the best COD elimination, pH stability, and ammonification activity were attained, indicating the most balanced operating condition. On the contrary, operating at HRT of 7 hours caused process instability, such as acidification and decreased treatment efficiency, suggesting that there is a critical HRT threshold below which system failure takes place. These results emphasize the significance of HRT adjustment for high-rate anaerobic wastewater treatment that is rich in lignin. Future research should concentrate on methods to improve biomass retention and buffering capacity, allowing stable operation at lower HRTs in order to increase treatment capacity without reducing performance.

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