A COMPARISON OF CONSTRUCTED WETLANDS USED TO TREAT DOMESITC WASTES: CONVENTIONAL, DRAWDOWN, AND AERATED SYSTEMS

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ABSTRACT

This research assessed three design alternatives of subsurface flow constructed wetlands (conventional, aerated, and drawdown systems) used to treat domestic waste. The objective was to evaluate the capability of the systems to degrade wastes of varying strength. Emphasis was placed on comparing data between the different designs, rather than determining specific degradation rates.

Typha latifolia (common cattail) was used to represent typical plant species found in constructed wetlands, with the goal of creating a one-foot diameter by one-foot deep wetland section. A series of continuous flow experiments were conducted to evaluate the systems' reactions to changes in hydraulic retention times and waste constituents/concentrations in terms of root penetration and ammonia and BOD removal. Results indicate that the aerated system outperformed the conventional and drawdown systems in terms of organic and ammonia-N removal. The drawdown system performed slightly better than the conventional system. The rooting patterns were significantly affected by the supply of oxygen. The cattail roots in the aerated system spread vertically and had deeper penetration into the media at a quicker rate than the other systems. The roots in the drawdown system spread horizontally, creating a dense mass within the water level fluctuation zone.

KEYWORDS

Aeration, Ammonia, $CBOD_5$, Constructed wetlands, Drawdown, Rooting patterns

INTRODUCTION

Background

Wetlands, both natural and constructed, have been shown to be capable of transforming and cycling elements and retaining and removing pollutants (Wallace, 1998). These capabilities make wetlands a viable option in treating domestic wastes.

The use of wetland treatment systems is steadily increasing. New applications, technological enhancements, and geographical dispersion of constructed wetlands are occurring. These systems are categorized into two basic types of constructed wetlands: Free Water Surface (FWS) systems and Subsurface Flow (SSF) systems (Reed et al., 1992). Despite the recent increases in the number of wetland treatment systems, there is still a lack of consensus on the optimal design, construction, and operation of these systems. For domestic wastewater treatment the pollutants of most concern are total suspended solids (TSS), biochemical oxygen demand (BOD), total phosphorous (TP), total nitrogen (TN), and fecal coliform (Kadlec & Knight., 1996). This study assessed BOD and ammonia-N removal and plant root penetration in three design variations of the subsurface flow system (Lockhart, 1999).

Research Objectives

This research addressed design alternatives to the conventional subsurface flow (SSF) wetland system. A drawdown SSF system raised and lowered the water table around the roots of wetland plants. An aerated SSF system delivered a continual supply of oxygen to the root zone and media. The general objective was to evaluate the capability of conventional, drawdown, and aerated wetland systems to degrade a simulated waste of varying strength. Emphasis was placed on comparing the data between the different designs, rather than determining specific degradation rates. The specific objectives of this research are as follows: 1) to determine the effect of raising and lowering the water table in a wetland system on redox potential, and removal of organics and ammonia, 2) to determine the effect of delivering a continual supply of air into the media of a wetland system on redox potential, and removal of organics and ammonia, 3) to compare the performance of conventional, drawdown, and aerated systems, and 4) to determine the effect of design variations on the rooting patterns of *Typha latifolia*.

MATERIALS AND METHODS

Experimental Overview

Continuous-flow reactors were used to evaluate the three wetland system designs in terms of root penetration and ammonia and BOD removal. Two replicates were used for each of the three designs. The conventional systems had continuous flow through the reactors and the water level was kept constant. The aerated systems had continuous flow through the reactors, a constant water level, and a continuous supply of air. The drawdown system had a continuous flow of solution into the reactors, but a timed release of the solution. The water level fluctuated within the top 1.8 to 2.5 inches of the media, creating a drawdown zone of fluctuating water levels. This caused a fluctuation between aerobic and anaerobic conditions. The time interval between fluctuations was 24 hours. After a self-priming pump extracted the water from the zone (1-3 minutes), the water level was allowed to recover to the surface of the gravel media over a 24-hour period before the pumping procedure began again.

Five experiments were designed to examine these systems' reactions to changes in hydraulic retention time (HRT) and waste constituents and concentrations. The HRT was varied between 3.5 and 7 days. Acetate and glucose were selected as the organic compounds used to simulate the BOD exerted on the systems. These compounds were chosen because they are degradable by many microorganisms, soluble, and do not readily sorb to reactor materials. The concentration of organics was varied from 100 mg BOD_L/L to 1000 mg BOD_L/L. The concentration of the influent ammonia was varied between 43 mg/L to 192 mg/L.

The systems in this study were loaded with acetate, glucose, and ammonia. Glucose can be transformed aerobically to pyruvate (Chapelle, 1993). Pyruvate can subsequently be transformed anaerobically to acetate by acetogenic bacteria. Glucose can also be transformed via Bifidum mechanism to lactate and acetate (Chapelle, 1993). Glucose can also be fully oxidized to carbon dioxide and water (Chapelle, 1993). Acetate can anaerobically undergo methanogenic respiration and can be converted to methane and carbon dioxide (Chapelle, 1993). Acetate can also be fully oxidized to carbon dioxide and water.

Nitrogen transformations in wetland soils are a complex assortment of processes mediated by microbes and strongly influenced by the redox status of the soil (Faulkner et al., 1989). Major microbial processes that determine what state nitrogen will be present as include: nitrification, denitrification, nitrate reduction, and nitrogen fixation (Metcalf & Eddy, 1991). In nitrification ammonia is oxidized to nitrite, which is subsequently oxidized to nitrate (Metcalf & Eddy, 1991). Different microorganisms are involved in each of these steps (Chapelle, 1993). The organisms that convert nitrite to nitrate are typically faster than the microbes that convert ammonia to nitrite (Chapelle, 1993). Therefore nitrite is typically not seen in high concentrations unless a system is deficient in oxygen or carbon (Faulkner et al., 1989). Denitrification is the process by which nitrate and nitrite are reduced by bacteria, yielding nitrous oxide and nitric oxide, which may be further reduced to nitrogen gas (Knowles, 1982).

Experimental Apparatus

The reactor setup consisted of six clear cylindrical reactors made of polyurethane fiberglass material resistant to sorption of chemicals. The diameter of each reactor was 30.5 cm and the height was 122 cm. Each reactor was filled to a depth of 30.5 cm with unseeded 0.64 cm pea gravel. One to two cattails were planted 0.64cm to 2.54 cm down into the gravel media. Artificial light was supplied by Vita-lite full spectrum natural light bulbs. The lights were set on a timer and ran on a cycle of 16 hours on and 8 hours off.

All reactors were continually supplied waste feed solution using peristaltic pumps. The conventional and aerated reactors were supplied feed solution via a connector port located 1.27 cm from the bottom of the reactors. The fluid flowed up through the media to the overflow port located at the top of the gravel media. This kept the fluid at a constant level inside the reactors. A sample port was located 1.27 cm from the top of the gravel media. Aquarium air pumps supplied air to each aerated system through diffuser stones located at the bottom of each reactor. The drawdown systems were supplied feed solution at the top of the media. The fluid flowed down through the media and was pumped out the bottom. A self-priming pump was set on a programmable timer to draw down approximately one fifth of the total fluid volume reactor. After the pump extracted the volumes, the fluid was allowed to recover to the surface of the gravel media, and then the pumping procedure began again. The water levels in these two reactors fluctuated within the top 6.35 cm of the media, creating anaerobic conditions as the water submerged the media, and aerobic conditions when the water level was pumped down. The sampling port for the drawdown system was located approximately 2.54 cm from the bottom of the reactors. Figure 1 shows schematics of the three reactor systems.

Samples of the feed solution and reactor effluents were analyzed for acetate, glucose, ammonia-N, nitrate, and nitrite. Redox potential were also measured in all effluent samples. A half-strength Hoagland's Solution was selected as the basis for the feed solutions used in the experiments. The recipe provided the basic nutrients needed by the plants within the reactor systems. However, the salts in the recipe were changed to remove nitrate, making ammonia the primary source of nitrogen.

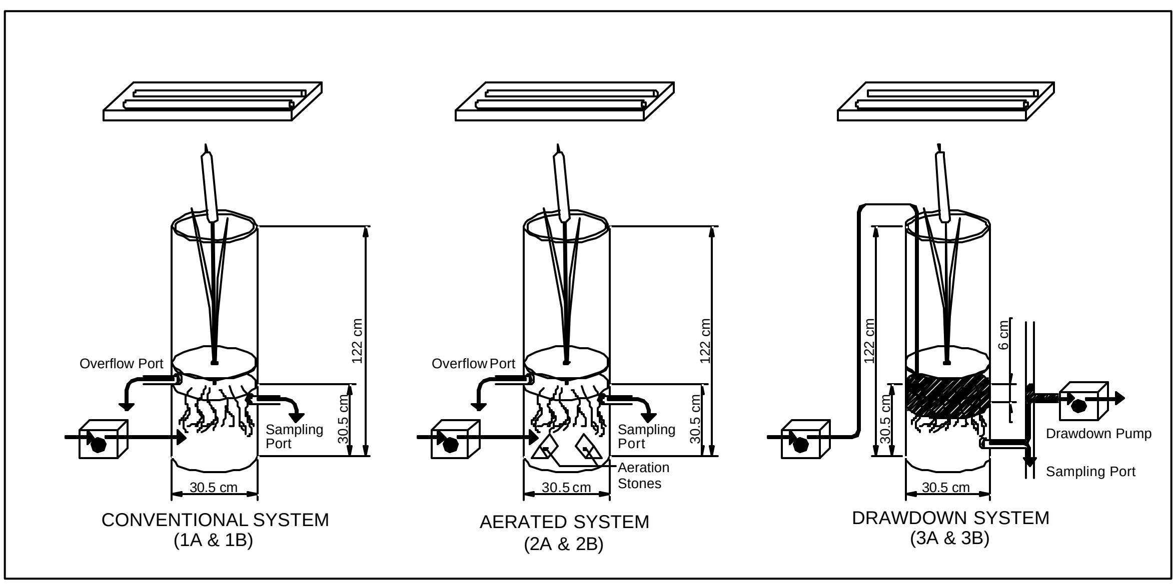


Figure 1 – Schematic of Conventional, Aerated, and Drawdown Systems

RESULTS AND DISCUSSION

Comparisons Between Systems

Three continuous flow reactor (CFR) experiments were conducted. Each experiment extended 21 days (6 HRTs). Table 1 below summarizes the results of Studies 2, 3, and 4 to compare the differences between the three systems. CFR Study 1 was not included because it ran only 14 days (2 HRTs). The table lists the influent and average effluent concentrations of acetate, glucose, ammonia-N, nitrate, nitrite, and the oxidation-reduction potential (ORP) measurements for the three systems. The values were calculated by averaging the averages of the duplicate reactors. It should be noted, however, that variation occurred in these values and had somewhat large standard deviations.

Table 1: System Comparison Between Experiments
ORP, Organic, and Nitrogen Parameters

Parameters	CFR Study 2				CFR Study 3				CFR Study 4			
	Influent	Conventional	Aerated	Drawdown	Influent	Conventional	Aerated	Drawdown	Influent	Conventional	Aerated	Drawdown
ORP (Ave) (mV)	NA	-119.5	-13.0	-84.9	NA	43.2	174.5	159.1	NA	-13.0	194.5	89.6
Acetate Conc. (Ave) (mg/L)	505.0	545.4	18.6	571.4	242.0	171.3	60.9	218.2	0.0	5.6	4.0	9.9
Glucose Conc. (Ave) (mg/L)	644.0	17.4	6.8	16.4	273.0	3.9	2.3	6.8	535.0	12.7	2.3	8.3
Ammonia Conc. (Ave) (mg/L)	192.0	137.5	32.1	129.4	144.0	109.3	26.0	113.4	132.0	100.9	23.8	94.3
Nitrite Conc. (Ave) (mg/L)	0.0	0.0	0.0	0.0	0.0	9.4	4.8	8.2	0.4	0.2	0.1	0.3
Nitrate Conc. (Ave) (mg/L)	1.0	0.4	10.0	1.6	1.8	0.5	12.6	2.1	0.0	0.0	0.8	0.0

The table shows that in CFR Study 2 the lowest redox potentials were seen in the conventional system. The conventional system also had the highest average glucose and ammonia concentrations. The drawdown system had the highest acetate concentrations, with apparent production of acetate in the drawdown and conventional systems. Acetate was significantly removed in the aerated system. The aerated system had the highest average nitrate concentration. There was little nitrite detected in any of the system.

In CFR Study 3 the lowest ORP measurements were again seen in the conventional system and the highest ORPs were seen in the aerated system. Acetate was highest in the drawdown system and lowest in the aerated system. Glucose concentrations were similar for all systems. Ammonia concentrations were approximately the same in the conventional and drawdown systems and considerable lower in the aerated system. Nitrite was detected in all three systems with averages less than 10 mg/L. Nitrate was highest in the aerated systems.

For CFR Study 4 the lowest average ORP measurements were again seen in the conventional system, and highest ORP measurements were seen in the aerated system. Little acetate was produced in any of the systems. The glucose concentrations were all similar and reduced by greater than 97%. Again ammonia was approximately the same in the conventional and drawdown systems and reduced in the aerated system. Little nitrite or nitrate was produced in any of the systems during this experiment.

Overall the highest organic removal rates occurred in CFR Study 4. Essentially 98% of the total BOD exerted on all systems was removed, when only glucose was added to the systems. If acetate and glucose were both added, the aerated systems removed the most BOD. The highest ammonia removal occurred in CFR Study 2. The aerated reactors had the highest ammonia removals in all three experiments. In general little nitrite or nitrate was detected in any of the experiments.

Media Conditions and Rooting Patterns

Media Conditions. The conditions of the gravel media were visibly different between the three systems (Figure 2). The surface of the media in the aerated system was free of film and build up. It was possible to see air bubbles trapped within the media, with no dark black zones or buildups noted anywhere along the depth. This suggests that these reactors were operating under entirely aerobic conditions. The conventional reactors had black zones along the entire length of the reactor. This dark black coloring is typical of anaerobic conditions. The drawdown reactor had dark anaerobic zones below the drawdown zone, but clear conditions within the drawdown zone. This indicates that the drawdown area was operating under aerobic conditions and the section below the zone was operating under anaerobic conditions.

It is also interesting to note how the roots of the rhizosphere affect media conditions. Figure 3 shows how the dark zones are affected by root penetration. Around the root, the media and solution are free of buildup and film. This indicates that the rhizosphere is producing oxygen and countering the reduced environment. During the resting periods between experiments, the media conditions would recover and there would be reduction in the amount of dark zones.

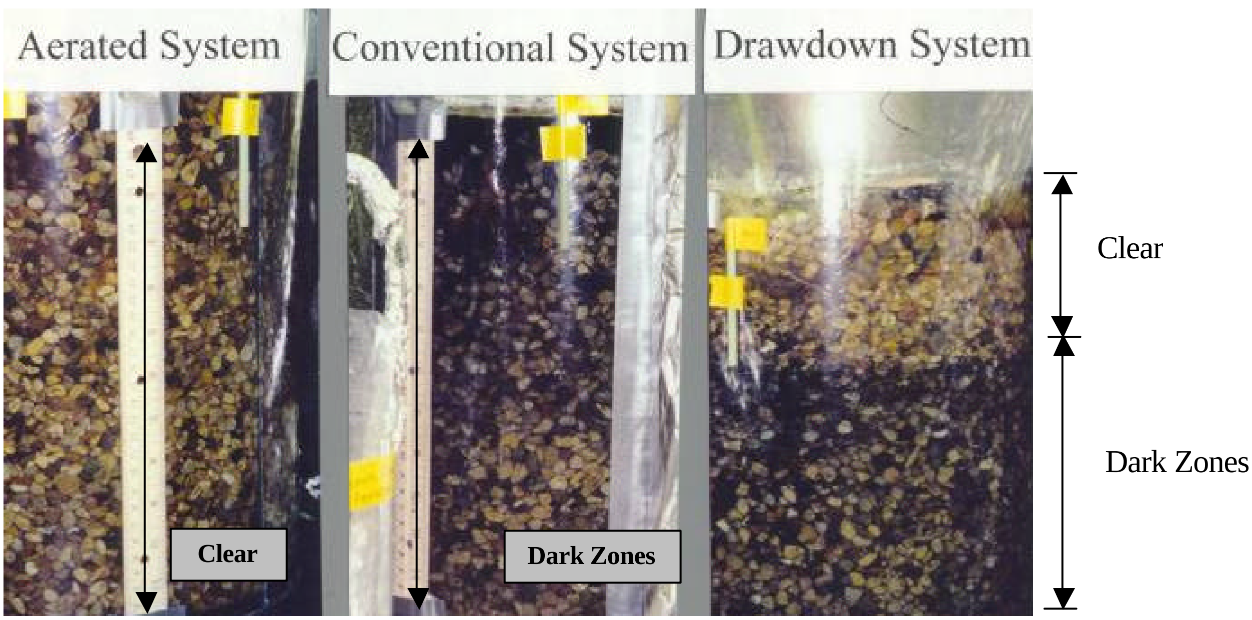
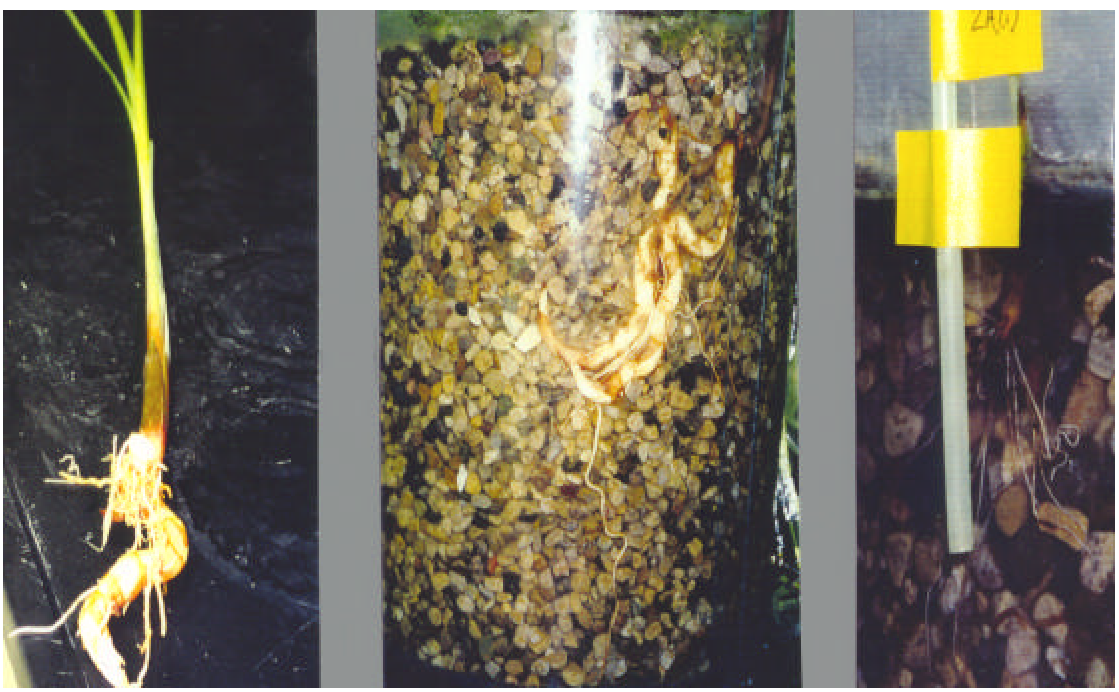


Figure 2 – Media photograph of aerated, conventional, and drawdown reactors. The media in the aerated reactors had little to no film or buildup along the length of the reactor. The media in the conventional reactors had a black zone along the length of the reactors. The drawdown reactors had black zones below the drawdown zone.

Rooting Patterns. The basic design of the three systems affected the rooting pattern of the cattails within the reactors. Figure 3 illustrates the rooting patterns of the conventional and drawdown systems. The conventional system pictures are of the growing stages of the tubers, but it can be seen that the roots extend both horizontally and vertically, but not dramatically in either direction. The cattail tuber stays relatively close to the surface of the media. In drawdown system reactors the roots spread horizontally within the drawdown zone. There is a dense mass of root growth in this zone. The roots eventually spread vertically, but extended horizontally first. It would be interesting to see if this pattern would continue if the drawdown zone were expanded beyond the 2 inches that was used during these experiments. Figure 4 illustrates the rooting patterns of the aerated systems. In these reactors the root penetration was deep. The cattail tuber bases spread vertically and were found deep within the gravel media, not just at the surface. The length of the tuber was also extended vertically, compared to the roots in the conventional systems.

Conventional Reactors **Drawdown Reactors**

Figure 3 - Rooting patterns of the conventional and drawdown reactors. In the conventional reactors the roots spread both horizontally and vertically, but not extensively in either direction. The media surrounding the roots is clear, indicating that the rhizosphere is producing oxygen and creating an aerobic area. This is contrasted by the dark anaerobic zone below the root. In the drawdown reactors the roots spread horizontally and formed a dense mass within the drawdown zone of the reactors. The roots eventually spread vertically, but extended horizontally first.



Aerated Reactors

Figure 4 - Rooting patterns of the aerated reactors. The roots spread vertically and the length of the cattail tuber also extended vertically. Cattail tubers penetrated deep into the reactor media and did not remain on the surface.

It is believed that the driving force behind these rooting patterns is the supply of oxygen. In the aerated reactors the bubble stones were placed at the bottom of the reactor. The roots in this system were stretching towards this high oxygen source. In the drawdown reactors the drawdown zone had alternating aerobic conditions. The roots in this system expanded and populated this 2-inch deep area, which was rich in oxygen. In the conventional system the main source of oxygen was reaeration at the surface. The roots in this system expanded both horizontally and slightly vertically, as to stay close to the surface.

CONCLUSIONS

This study assessed three design alternatives of a constructed wetland system used to treat domestic waste – conventional, aerated, and drawdown systems. This study demonstrated that the design of constructed wetland impacts the removal of ammonia and BOD, and the rooting patterns of wetland plants. Overall the results showed that glucose was readily degradable by all systems. The acetate was degraded in the aerated reactors fairly consistently, but was not removed in the conventional and drawdown systems under similar conditions. It could be that acetate was produced in these systems by anaerobic fermentation of glucose or by plant exudation. It could also be that acetate was not removed due to time limitations; if conditions in the reactors were anoxic, methanogenic bacteria (that convert acetate to methane and have long generation times) perhaps did not have time to grow. Ammonia was removed completely in the aerated reactors in most cases, but there was little to no nitrite or nitrate production observed. The conventional and drawdown systems removed some ammonia, but not as effectively as the aerated reactors. This could be due to the population of the microbes in these systems, or the oxygen-limited conditions inside the reactors. Again, in these systems little to no nitrate or nitrite was detected. It could be hypothesized that nitrification was limited by oxygen availability. If nitrification did occur, then perhaps denitrification occurred quickly and was difficult to observe. Alternatively, any nitrate formed could have been taken up by the plants.

Raising and lowering the water table in the drawdown system creates an aerobic area in the drawdown zone of the reactor, as evidenced by the photographs of media conditions. There was also a small improvement in the degradation of waste constituents, as indicated by slightly higher removal rates of ammonia and organics over the conventional systems. This effect may not be significant due to the small differences between the conventional and drawdown removals.

A continual flow of air into the aerated system creates an aerobic media environment throughout the depth of the reactor, as evidenced by the photographs of media conditions and the positive redox potential measurements. This air supply also improves the degradation of waste constituents, based on the increased removal of ammonia, glucose, and acetate.

The aerated system outperformed the conventional and drawdown systems in terms of acetate, ammonia, and glucose removal. In general, the drawdown system outperforms the conventional system.

Media conditions are affected by wetland design, as evidenced by the redox potentials of the systems. The aerated system maintains the highest redox potentials or most oxidized media conditions, the drawdown system maintains the second highest ORP, and the conventional system maintains the lowest ORP or the least oxidized media conditions.

Rooting patterns are affected by the supply of oxygen. Cattail roots in the aerated system penetrate deeper into the media and spread vertically. The cattail tubers themselves elongate and stretch vertically. Cattail roots in the drawdown system spread horizontally, with a dense mass in the drawdown zone near the media surface. Cattail roots in the conventional system exhibit both horizontal and vertical root growth, but not as pronounced in either direction. In general, root penetration along the depth of the bed is optimal due to the large surface area for attached microbial growth and oxygen production in the rhizosphere.

This research has aided in the development of technological enhancements to subsurface flow constructed wetlands. One of the authors (Wallace) has developed a wetland aeration process, Forced Bed Aeration ™. Media conditions, rooting patterns, and removal rates observed during this study aided in the development of the technology. North American Wetland Engineering (NAWE) is currently using Forced Bed Aeration™ in constructed wetland designs and has systems operating that are successfully using this technology to treat high strength wastes.

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