Island Water TECHNOLOGIES

SENTRY-AD™

Real-time, performance monitoring of microbial activity in an anaerobic digestion system.

SENTRY-AD: Real-time, performance monitoring of microbial activity in an anaerobic digestion system

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SENTRY-AD™ is a real-time, bio-electrode sensor (BES) that monitors the microbial metabolic activity of exoelectrogenic bacteria and can be used in anaerobic digestion wastewater treatment processes. The data collected aids operators in:

- **Monitoring AD process stability:** Bio-electrode data allows operators to monitor, in real-time, the reactor's microbial health.
- **Protecting the AD from upset:** Imbalance or toxic shock events can be identified the instant they begin to impact microbial activity. This allows the operator to take immediate action to reduce the impact on system performance.
- **Process optimization:** Aggregation of data and integration with existing water quality and process information provides novel insights into system performance and patterns that can be used to tune operation and maintenance.

Island Water Technologies (IWT) partnered with ADI Systems (New Brunswick, Canada) to demonstrate SENTRY-AD in an experimental pilot anaerobic membrane bioreactor system for 9 months. The probe was installed in an existing recirculation line by insertion of a tee fitting.

The purpose of this study was to evaluate the SENTRY-AD technology's ability to predict system imbalance and identify trends in performance. SENTRY-AD was installed during reactor setup, and provided real-time and long-term insight into system operation.

SENTRY-AD identified:

- **Imbalances, in real-time:** SENTRY-AD data had a strong correlation ($p \leq 0.01$) with the VA/PA ratio (commonly used as an imbalance indicator) validating the predictive capacity of SENTRY-AD. SENTRY-AD signaled the onset of imbalance in real time. This increased resolution allows for constant monitoring and the maximum time for issue mitigation. SENTRY-AD indicated periods of process instability that operators were unaware of from routine monitoring and analysis. SENTRY-AD's ability to capture them demonstrate its novelty.
- **Long-term process characteristics:** The data was pooled into two populations punctuated by a system clean. Statistically it was demonstrated that these two periods were significantly ($p < 0.01$) different, demonstrating that SENTRY-AD is a useful tool for assessing long-term reactor operation and health and illuminating operational changes.
- **Emergent daily patterns:** SENTRY-AD's data was aggregated over a month and the daily data was overlaid. When doing so, a daily pattern became evident. SENTRY-AD had a cyclical range in performance of 6.3% over a day with the minima occurring at 10am and the maxima at 9pm. Operators were unaware of the cyclical variability in the process, and this information can be used to tune the operation of the system.

SENTRY-AD is demonstrated to predict imbalance events in real-time and provide key insights for optimization of AD operation.

Introduction

SENTRY-AD, a bio-electrode sensor (BES) technology, is a world-first real-time sensor solution that provides direct monitoring of microbial activity of the anaerobic digestion treatment process. The bio-activity data (metabolic activity) of the microbiology is relayed to the operators in real-time and provides the operators with measurement of the microbial stability - critical for ensuring biological treatment process performance. SENTRY-AD can be integrated with other water quality and operational data to aid in improving and optimizing system performance. There is no measurement delay allowing for immediate notification of process shifts and issues, and the high sampling frequency is instrumental in assessment of: long-term performance, trend and pattern recognition, and optimization.

The probe was installed via a tee junction for this study (as shown in Figure 1) but can be fully submerged. The waterproof control panel, suitable for harsh environments and outdoor use, was installed seamlessly at the facility. The probe was installed in a recirculation line. In full scale systems a probe would be preferentially placed in each anaerobic tank. For example if sequential tanks are present – for hydrolysis, acidogenesis etc. – a probe installation in each tank is recommended. A single probe was installed for this study, though each control panel supports up to four probes. The panel continuously transmits the biological data to the web server to allow operators to continually monitor system conditions (shown in Figure 1). This web interface is customized specifically for each installation and can automatically highlight important events and send notifications about changing system conditions which are impacting biological activity in the reactor.

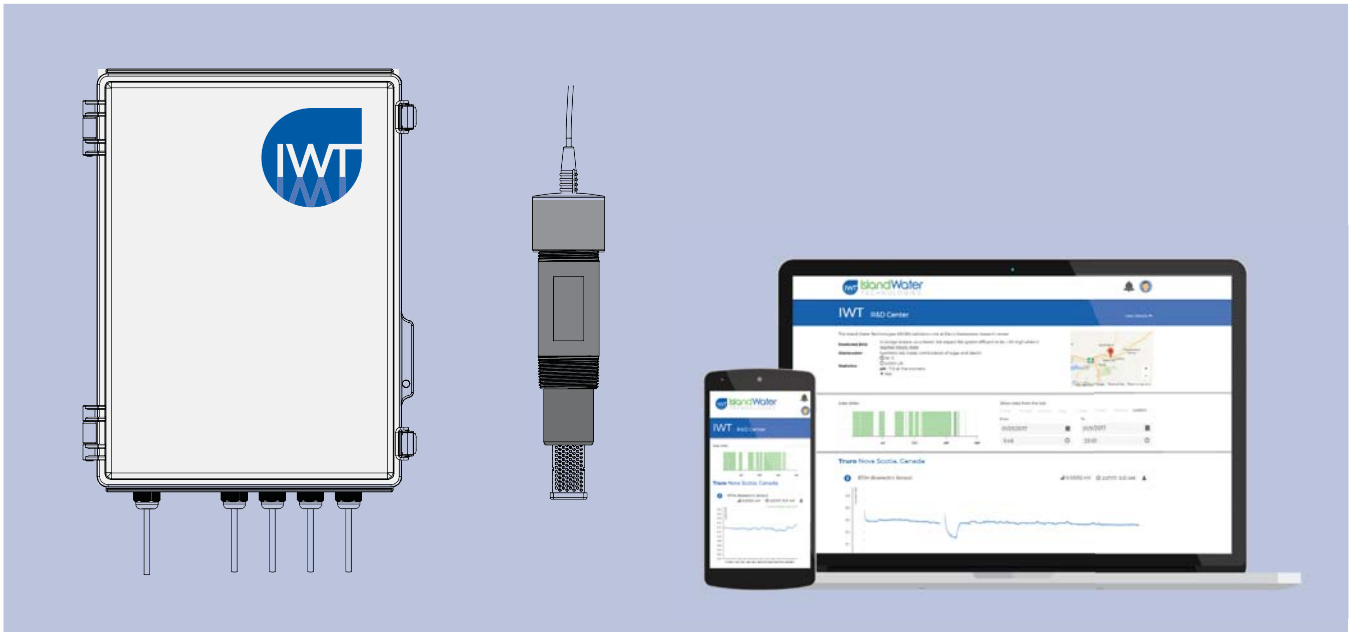

Figure 1: Key components relating to a SENTRY-AD installation

This real time data is a unique diagnostic tool to be used by system operators to predict system imbalance and reduced performance, optimize the biology in the wastewater system and understand stability and typical resonance in a system's performance. The transmitter inside the SENTRY-AD panel was fitted with 3G connectivity for this study. The panel is also easily compatible with Wi-Fi, 2G, or 4G modem, and other connection types for connecting into existing systems.

AD system failure can typically be broken out into three distinct groupings:

- **1: Poor system design and/or installation.**
- **2: Poor digester management** - Digesters require investment in operation and maintenance to maximize performance.
- **3: Introduction of toxins into the digester** – The methanogenic community is especially prone to the effects of toxins. Common toxins that can inhibit or kill methanogens include cleaning chemicals, pesticides and fertilizers. These compounds can affect the biology in a number of different fashions. The most common, signal of imbalanced microbial health are spiking concentrations of volatile acids (VA) and volatile fatty acids (VFA). Elevated concentrations of VAs and VFAs are inhibitory to methanogen and impact the balance of the bacterial community and may result in decreased process performance or failure.

Anaerobic Digesters are often operated to maintain a VA/PA ratio of <0.3 for stability. Values greater are an indication of potential digester imbalance, because the buffering capacity is unable to neutralize the volatile acids being produced by acidogenesis, and acidogenesis is occurring more rapidly than methanogenesis. Methanogens, the most sensitive microbial community group, use the volatile acids as a substrate but are negatively impacted at high concentrations (resulting in depressed pH) leading to reduced or failed methanogenesis and reactor upset.

Materials and Methods

The SENTRY-AD system was installed at the ADI testing facility (Fredericton, New Brunswick, Canada) in Q1 2016. The probe was installed in the recirculation line of the anaerobic digestion system. The AD system consisted of a continuous stirred-tank reactor (CSTR) style reactor with membrane separation to keep a high mixed liquor suspended solids (MLSS) and solids retention time (SRT). The probe was installed in a 3” recirculation line with a flow rate of 6000 L/hour, and water quality conditions representative of the reactor. The probe was not disturbed during the duration of the project.

Throughout the test period the wastewater treatment system underwent both planned and unplanned imbalance events. Planned events included; a ramp-up and reactor inoculation phase, an increase and decrease of organic loading rates, temperature fluctuations, and a membrane cleaning.

The performance of the treatment system was monitored with daily measurements taken for: flow through the system, organic loading rate, recycle flowrate, pH, COD, TSS, VSS, BOD, NH3-N, TKN, TP, phosphate, temperature, biogas production and alkalinity (total, partial and volatile). On-site system operators carried out daily inspection and analysis of the system. IWT personnel monitored both the daily sample results received from ADI and the real-time data from the SENTRY-AD probe measured in microbial electron transfer. When fluctuations in SENTRY-AD data were identified by IWT personnel, this information was relayed to on-site operators to determine whether any known process event had taken place.

In this study the sensor was set to record a reading of microbial electron transfer every minute and uploaded the results to the cloud server. In order to remove some of the natural sensor variability from the data without losing valuable time sensitive data, the previous one hour of SENTRY-AD data was averaged and used for the analysis. This minute by minute average was analyzed to determine a baseline for the system and what shift from that baseline data would signal a system upset event.

The data was separated into two distinct time periods with the punctuation between the periods being a membrane cleaning event. Statistical hypothesis testing, student's T-test, was used to compare the time periods and determine if there was a significant difference in SENTRY-AD performance and water quality characteristics before and after the event. A box and whisker chart was created to visually represent the difference in data before and after this event. The box portion of the chart represents the mean, upper quartile, and lower quartile. The whiskers, or lines coming from the box, represent the variability outside the upper and lower quartiles. Any outliers are presented as dots.

Correlations between the microbial electron transfer and other operational parameters were tested with the Pearson product moment coefficient test.

Results and Discussion

1. Real-time, imbalance identification:

The microbial electron transfer for the duration of this testing period is shown in Figure 2. The events of note are highlighted in Figure 2, and a full list events identified by SENTRY-AD as well as operator reported events are presented in Table 1. Data gaps in Figure 2 were due to the SENTRY-AD probe being disconnected due to connectivity issues and are only representative of the prototype used in this study.

IWT has determined a shift from the baseline SENTRY-AD reading to identify the presence of imbalance events. Table 1 outlines the events that were predicted by the SENTRY-AD probe and associates the predictions with events recorded by the on-site operator, and these were denoted as 'known' events. In addition, deviations from the baseline in the response of SENTRY-AD were compared to the provided process data of OLR, biogas production and VA/PA ratio for several days before and after the current changes and denoted as 'unknown' events. These events may not have produced obvious changes to the typical outputs of an AD system, however these changes can have important impacts on the system and can be observed with the Sentry-AD system.

Figure 2: SENTRY-AD data generated for the full pilot study. Real-time data predicts imbalance events that were known and unknown to the system operaton

Table 1: Event log and diagnosis

Event No.	Date	Events Registered by SENTRY-AD	Event Characterization
1	Mar 11	Unknown System Event During Inoculation	Non-Event
2	Mar 13	Unknown System Event During Inoculation	Non-Event
3	21-Mar		Missed Foaming Event
4	May 26	Temperature Fluctuation Event	Operator Induced Event
5	May 28	Temperature Fluctuation Event	Operator Induced Event
6	May 30	Temperature Fluctuation Event	Operator Induced Event
7	May 31	Temperature Fluctuation Event	Operator Induced Event
8	Jun 01	Temperature Fluctuation Event	Operator Induced Event
9	Jun 02	System Changes Following Temperature Event	Operator Induced Event
10	Jun 03	System Changes Following Temperature Event	Operator Induced Event
11	Jun 04	System Changes Following Temperature Event	Operator Induced Event
12	Jul 04	Unknown System Event	Non-Event
13	Jul 05	Unknown System Event	Spiking VA/PA = 0.44
14	Jul 06	Unknown System Event	Spiking VA/PA = 0.48
15	Jul 07	Unknown System Event	Spiking VA/PA = 0.48
16	Aug 08	Membrane Cleaning Event	Operator Induced Event
17	Aug 09	System No-Feed Beginning	Operator Induced Event
18	Aug 10	Fluctuation During No-Feed	Operator Induced Event
19	Aug 11	Fluctuation During No-Feed	Operator Induced Event
20	Aug 12	First Feeding After No-Feed	Operator Induced Event
21	Aug 13	Increased Activity due to Feeding	Operator Induced Event
22	Aug 18	Second No-Feed Event	Operator Induced Event
23	Aug 19	Fluctuation During No-Feed	Operator Induced Event
24	Aug 23	First Feeding After No-Feed	Operator Induced Event
25	Aug 24	Increased Activity due to Feeding	Operator Induced Event
26	Nov 07	Unknown System Event	High VA/PA = 0.46
27	Nov 08	Unknown Characterized by Spiking VA/PA > 0.6	High VA/PA = 0.6
28	Dec 30	System Imbalance Reported by Operator	Operator Confirmed Event
29	Jan 03	Unknown System Event	Spiking VA/PA = 0.7

The SENTRY-AD data coupled with a real-time alert system correctly identified 19 of 20 operator reported events, while also flagging 9 events that were not reported by the system operator (Figure 3). Of these unreported events, 6 were characterized by high or spiking VA/PA as indicated in Table 1. Only 3 events over the testing period were considered non-events and 2 of those were several days into the system inoculation. The one known event missed by the SENTRY-AD alarm was a system foaming event during the inoculation. This event was visually picked up by IWT staff when reviewing the data on the online dashboard, but was not flagged when analyzing the microbial electron transfer shift from baseline data.

These results highlight that the probe operates as an indicator of the real-time VA/PA ratio and may be utilized as an early warning system for operators to test system parameters and make process changes to prevent upsets.

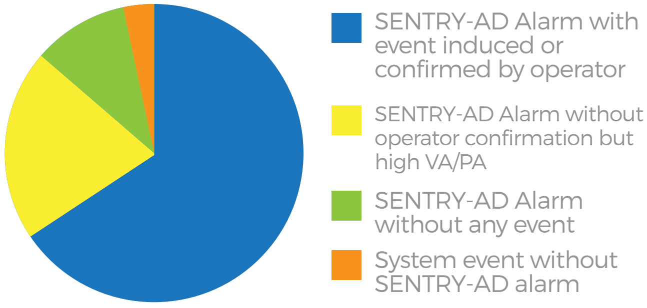

Figure 3: Characterization of events where the SENTRY-AD probe would send an alert to the operator .

1.1 Real-time, imbalance identification: Temperature

Figure 4 shows the response of microbial electron transfer, OLR, biogas production, and VA/PA ratio during an operator induced temperature fluctuation event. On May 26th, the reactor temperature decreased from 38˚ C to 36˚ C and remained stable until May 31st when it began to increase again, eventually spiking to 40˚ C on June 1st, before returning to a stable 36˚ C. The OLR, biogas production, and VA/PA ratio were all stable from May 22nd to June 1st. Despite the VA/PA ratio being over 0.3 for this time, the system was running smoothly. The SENTRY-AD alarmed with events 4-8 as marked on Figure 4 during this time. The instantious data collection of the SENTRY-AD can clearly show system changes that are unable to be picked up with daily tests.

As a result of the increase in temperature to 40˚ C on June 1st, the microbial electron transfer and VA/PA ratio spiked triggering the operators to drastically lower the OLR by 68.7% until the system stabilized. All paramaters on the graph responded to the drop in OLR with reductions in microbial electron transfer, VA/PA ratio and biogas production (Figure 4 at point 9). The dramatic decrease in biogas production prior to the corrective OLR reduction is a strong indication for the need for an alternate method of identifying system imbalances. If small changes can be made earlier to prevent an upset, biogas production would remain high and stable.

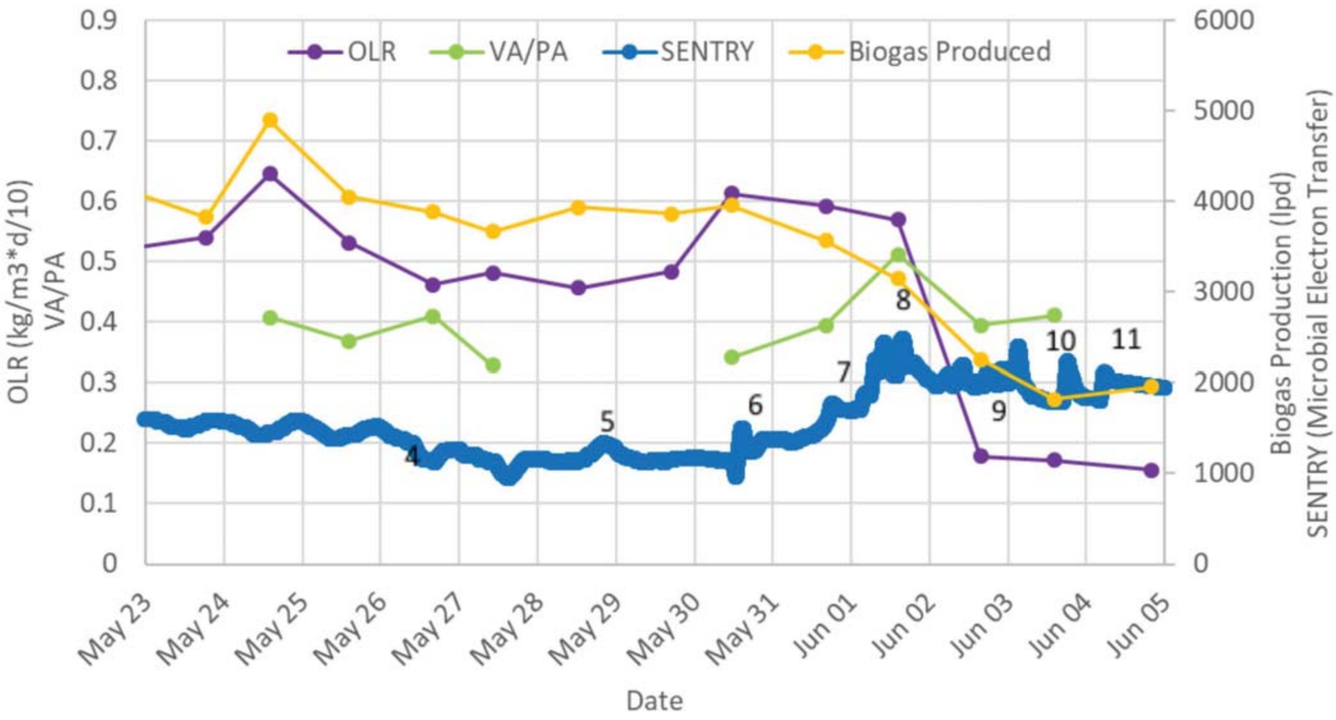

Figure 4 Correlation of SENTRY-AD data with standard chemical parameters during a temperature induced imablance event

1.2 Real-time, imbalance identification: Organic loading

The system had a scheduled membrane cleaning on August 8th which is shown by point 16-17 in Figure 5. The microbial electron transfer and biogas production both significantly decreased immediately following the cleaning. The cleaning event is followed by 4 days with zero organic loading, or no feed for either the AD or the SENTRY-AD probe. On August 12th feeding of the reactor resumed at point 20 in Figure 5. August 18th began a second halt in organic loading with resumption of feeding on August 24th shown by point 22-23 and 24-25 respectively. There are multiple points on these events as the fluctuation in microbial electron transfer occurred over several days. All of these events were picked up as imbalance events by the SENTRY-AD probe, and statistical alerts were generated.

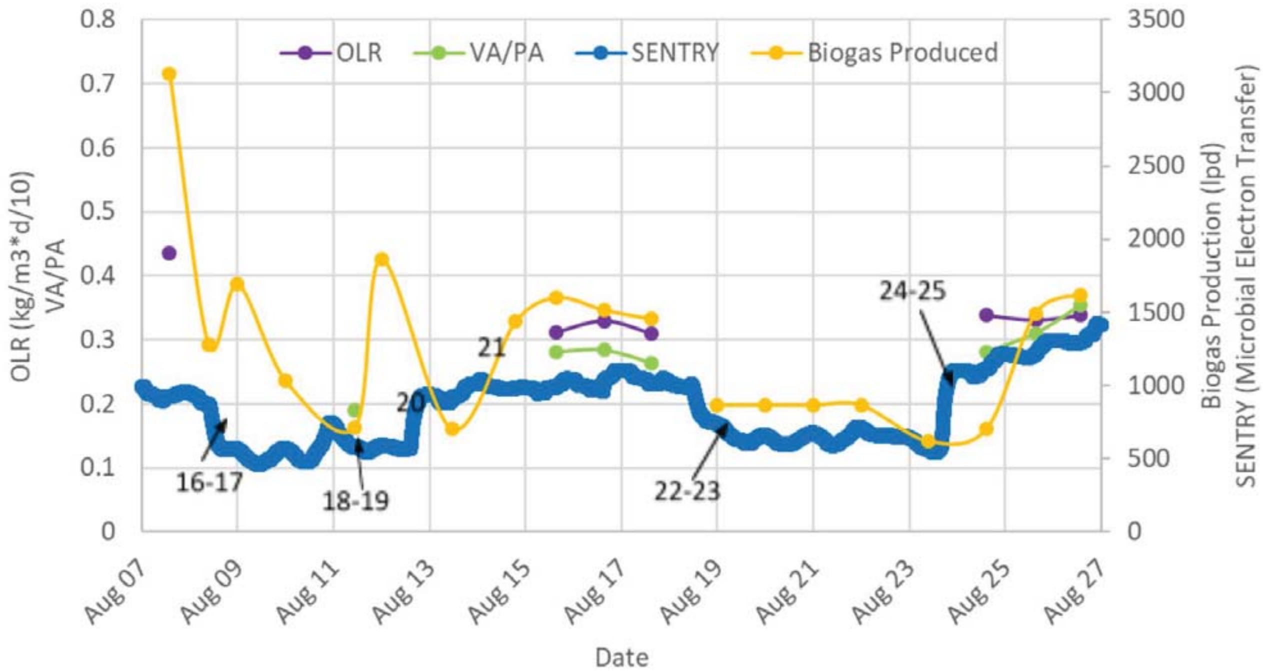

Figure 5: Changes in Microbial Electron Transfer recorded by SENTRY-AD during membrane cleaning and two system starvation events

Daily pattern identification:

As part of the statistical processing, the data obtained from SENTRY-AD was examined for periodic trends. The AD was operated with the intention to have a consistent operation; however, the aggregated SENTRY-AD data identified daily periodicity as graphically represented in Figure 6. The SENTRY-AD data was sinusoidal in nature, with a maxima achieved at 9pm and minima at 10 am and a range of 6.3%. Despite notifying the operational staff, there was no provided explanation for this inherent pattern. Due to the limited complementary data, it is impossible to know how the fluctuation in exoelectrogenic metabolic is tied with AD reactor performance. Nonetheless, it identifies that the biology of the system is not operating as stable as believed by the operators and there is the potential to improve system. Additionally, the granularity of SENTRY-AD data greatly enhances operators' ability to allocate resources for the determination and implementation of courses of action, such as adjusting: temperature, lighting, feeding, etc., that will lead towards a stable and more optimal process.

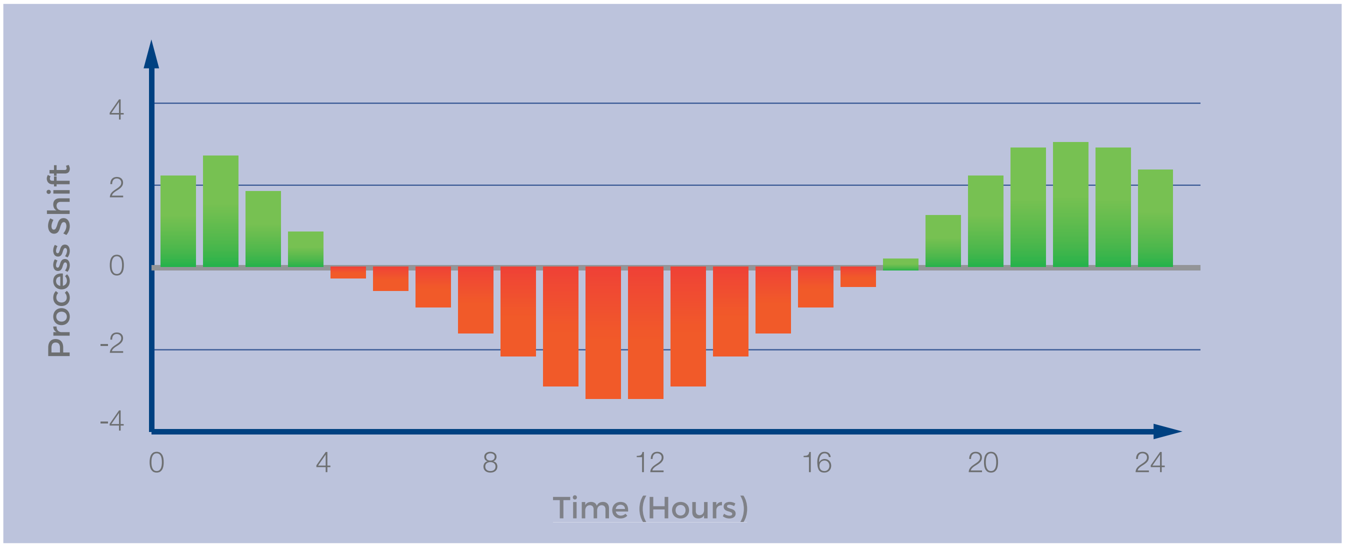

Figure 6: Daily pattern generated by the SENTRY-AD data predicts statistically significant variation in daily performance of the AD system.

2. Long-term pattern identification and Pearson correlation

Visual inspection of the full data (Figure 2) shows shift in SENTRY-AD response after August 8th. The data population in the two periods, before and after August 8th, were pooled, graphed and statistically tested. Using the student's T test, the means before August 8th for all four parameters tested were discovered to be statically different from their mean after August 8th with 99% confidence ($P<0.01$). The average current between the earlier and latter populations was reduced by 55%, while OLR was reduced by 37%, biogas production was reduced by 48%, and the VA/PA ratio increased by 21%.

The VA/PA ratio on average was higher, but was notably more volatile with greatly increased variability. The box plots showing data for each parameter before and after the membrane are shown in Figure 7 confirm that these time periods were significantly different.

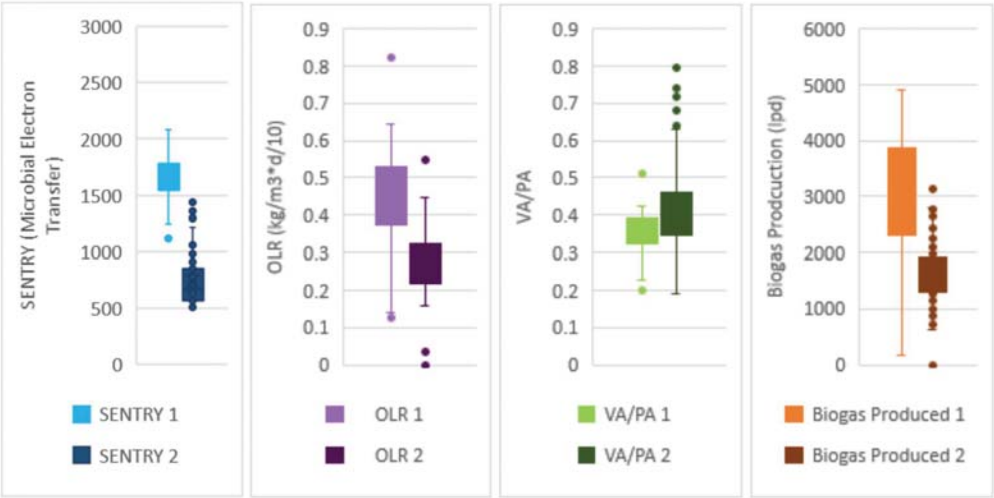

Figure 7: Comparison of pooled sample results before (1) and after (2) the membrane cleaning and starvation event for SENTRY-AD response, OLR, VA/PA and Biogas.

Several operational parameters correlated well with SENTRY-AD performance. All parameters tested daily by the system operators were analyzed for a correlation to the microbial electron transfer. The parameters that correlated strongly with a p value of <0.01 to the current included organic loading rate, biogas production, VA/PA ratio, VA, TA, influent COD concentration, and pH. The SENTRY-AD probe confirmed that the system's performance had decreased to a new steady state, with less biogas production and increased instability as indicated by the higher and more volatile VA/PA ratio.

Conclusion

In the 9-month study SENTRY-AD demonstrated that it can provide: (i) real-time imbalance identification, (ii) pattern identification (periodicity), and (iii) aid in long-term process characterization. SENTRY-AD is a unique solution because it is real-time measurement of biological activity and provides instant and granular data that can be leveraged in facility operation and maintenance.

The response of SENTRY-AD tracked well with the VA/PA ratio, a common ratio used to denote the biological stability of the reactor, but SENTRY-AD has the added benefit of being a continuous measurement, providing instantaneous operator feedback when there is a process intervention required. SENTRY-AD leveraged with programmed statistical alerts on the real-time data, positively identified 19 of 20 known upsets, and in addition flagged 9 events that were likely process imbalances.

The analysis of the historical real-time data identified unknown inherent cyclical daily patterns in the sensor activity exhibiting a range of 6.3%. This suggests that the process had additional room for increased stability, and that there was opportunity for process optimization.

SENTRY-AD provides the novel capability to identify patterns in microbial activity, and then have real-time feedback for operators during optimization.

SENTRY-AD data can be leveraged with other water quality and process data to inform courses of action to improve and optimize the digestion process. In addition, the ability to leverage statistical techniques on the acquired high resolution dataset has huge potential to drive the performance of a system while still maintaining stability. The data, and the deep statistical analysis of it, will improve operators' confidence when troubleshooting operational challenges and making process optimization adjustments.

SENTRY-AD's ability to continuously measure the metabolic activity of the biological community provides a new tool for the correlation of operation and maintenance procedures with reactor response. It has merit as a tool for: reactor protection, improving troubleshooting capacity, and process optimization. With SENTRY-AD installed in the system, operators can 'listen' directly to the bacteria and no longer need to rely solely on experienced interpretation of water quality parameters to ascertain microbial health and appropriate action in their system.

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