Source separation increases methane yields for waste-to-energy applications in the personal care product industry

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HIGHLIGHTS

- High-carbon industrial wastewaters are well suited to waste-to-energy applications.
- Some wastes contain inhibitors, which can impair methane yields.
- Methane production was contrasted among waste sources in the PCP industry.
- Colorants reduce methane production and must be separated.
- Waste-to-energy is feasible with source separation and anaerobic–aerobic reactors.

GRAPHICAL ABSTRACT

Enhancing industrial waste-to-energy potential by source separation.
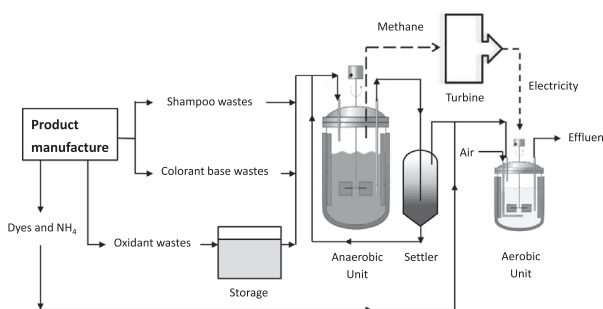
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ABSTRACT

High-carbon industrial wastewaters are attractive for anaerobic biological waste-to-energy treatment approaches. However, some waste streams, such as those from the personal care product industry (PCP), also can contain inhibitory compounds that impair biogas production (methane; CH_4), reducing potential energy recovery. Here we show how source separation of PCP wastes can increase gross CH_4 production by shunting inhibitory streams around the methanogenic treatment step. Methane production was compared between shampoo and hair colorant liquid wastes as sources for waste-to-energy applications. Methane yields were five times greater for comparable COD shampoo versus colorant wastes in batch reactors ($\sim$250 versus $\sim$50 ml CH_4/mg COD), suggesting colorant waste constituents impair methanogenesis, although anaerobic treatment reduced the toxicity of both wastes (i.e., *Daphnia magna* IC50 tolerance values increased from 0.23 ± 0.07 and 0.17 ± 0.04%v/v to 38.0 ± 2.0 and 15.3 ± 8.9%v/v, respectively). To understand methanogenesis inhibition, the colorant waste was separated into sub-streams associated with different production operations and assayed individually, and CH_4 production almost tripled when dye and oxidant levels were reduced. To explain CH_4 yields, qPCR was used to quantify eubacteria and five methanogen groups among reactors. Colorant-fed units always had lower microbial abundances than shampoo-fed units, but *Methanosarcinaceae* levels were especially low in the low CH_4 reactors. Further, these acetoclasts and hydrogenotrophic *Methanobacteriales* significantly correlated with CH_4 yields across all reactors ($r^2 = 0.46$, $p = 0.02$ and $r^2 = 0.68$, $p = 0.003$, respectively).

Waste-to-energy opportunities clearly exist for PCP wastes, although source separation is required to maximise gross CH$_4$ yields.

1. Introduction

Industrial wastes vary dramatically in composition, depending on the chemicals and processes used in product manufacture. This variability sometimes makes the application of biological waste-to-energy approaches difficult because some industrial processes have constituents inhibitory to key biodegradation reactions, such as methanogenesis. Historically such "tricky" wastes have been treated using physico-chemical methods, either as stand-alone processes or as pre-treatment steps [1]. However, such methods can be costly, usually do not produce useful by-products and can generate excess solids that require extra disposal, making such options less attractive. As a result, alternate strategies are needed for the treatment of industrial wastes that contain degradation inhibitors to make wastes more amenable to biological waste-to-energy processes.

One solution is waste source separation. Industrial waste collection systems receive wastes from numerous factory operations, but they are often combined for processing in one common treatment plant. However, if one could separate inhibitory sub-streams and shunt them around key biological treatment units (e.g., anaerobic reactors), the whole waste handling system might become more sustainable. This is especially true for industries with high-carbon waste streams that could produce combustible biogas (i.e., methane; CH$_4$) through methanogenic processes [2]. The key question is what level of source separation is needed to improve gross CH$_4$ production from industrial wastes that contain inhibitors; i.e., can source separation increase CH$_4$ yields to make waste-to-energy options economic, achieve targeted energy reductions and produce less toxic effluents [3]?

Personal care product (PCP) manufacturing is one industry that produces high-carbon wastes that contain inhibitory and conditionally toxic compounds. This industry traditionally has used physico-chemical and aerobic biological methods for liquid waste treatment [4,5]. However, physico-chemical methods generate large amounts of solids that require disposal, and aerobic treatment is very energy intensive due to high organic loadings and high oxygen demands (CODs range from 2000 to >25,000 mg-COD/L). As such, the PCP industry is considering anaerobic–aerobic sequenced biological treatment methods because they can reduce energy costs [6], and potentially achieve safe and acceptable effluent quality [7–9]. Unfortunately, PCP wastes can contain oxidants, dyes and ammonia from hair colorant product manufacture, which can potentially inhibit methanogenic microorganisms. However, if one source separated and directly passed inhibitory sub-streams directly to a second-stage aerobic unit, more efficient CH$_4$ production would be possible. Ahammad et al. [6] recently showed that anaerobic–aerobic sequence reactor systems effectively treat PCP wastes and save up to 68% in energy consumption, although COD-to-CH$_4$ yields from anaerobic units was not high. In fact, anaerobic–aerobic sequenced reactors have been conditionally effective in previous domestic and industrial waste treatment applications [10–13], but optimal biogas production is often not achieved [7]. However, if source separation was used, anaerobic–aerobic sequence reactor designs could be co-optimised relative to carbon removal and energy minimization, potentially making the whole treatment system energy-positive.

Here we examined source separation for enhancing CH$_4$ production from shampoo and colorant wastes in the PCP industry

as an example for other industrial applications. Batch reactors were operated treating synthetic shampoo and colorant wastes to determine baseline CH$_4$ production yields, biodegradation potentials, secondary nutrient needs and effluent toxicities associated with each waste type. Colorant wastes then were "de-constructed" into separable components according to manufacturing process and similar degradation assays were performed. Finally, quantitative PCR (qPCR) was employed to quantify eubacteria and different methanogens in the reactors to gain a deeper understanding of microbial communities associated with optimal CH$_4$ yields. Methane production yields almost tripled when wastes were separated, confirming source separation combined with anaerobic–aerobic sequence reactors have great potential for industrial waste treatment applications.

2. Materials and methods

2.1. Waste streams

The simulated shampoo and colorant wastes were prepared by combining individual product ingredients typically used in PCP manufacturing processes, which have been reported previously [14]. Characteristics of the two primary wastes are summarised in Table 1, which also provides nutrient ratios and general biochemical composition data for the wastes. All analyses were performed according to Ahammad et al. [6,15] and standard methods [16]. Nutrient ratios and biochemical composition are important because our secondary goal was to assess the value of nitrogen (N) and-or phosphorus (P) additions for enhancing the anaerobic biodegradability of each waste. The simulated wastes used here were intentionally lower strength than many PCP factories because preliminary tests showed the negative influence of some constituents was amplified in batch reactors, which was atypical of full-scale systems.

2.2. Experimental setup and inoculum

Screw-cap, air-tight 500-mL glass batch reactors (Neubor, Germany) were used to compare the anaerobic degradation potential and CH$_4$ production yields for the colorant and shampoo wastes with and without N and P additions. Each waste mix was assessed in triplicate with each reactor containing 200-ml waste and 75-ml microbial inoculum ($n = 60$). The sludge inoculum was obtained from an anaerobic pilot plant maintained at a PCP factory in Poland; therefore the sludge had been previously exposed to a

Table 1
Characteristics of synthetic PCP wastewaters used in study.

Parameter	Shampoo	Color
COD (mg/l)	1100	1860
TKN (mg/l)	4.2	13.3
Phosphate (mg/l)	1.5	5.5
Nitrate (mg/l)	0.3	BDL
Sulphate (mg/l)	1.07	4.13
C:N:P (by mass)	2249:9:1	1037:7:1
Carbohydrate (mg/l glucose equivalent)	7.6 ± 0.2[a]	17.6 ± 0.05
Protein (mg/l BSA equivalent)	15.8 ± 0.15	34.8 ± 0.45
Lipid (mg/l)	787.9 ± 2.2	736.8 ± 1.0