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Examining the mechanisms of short-term solubilization of ground food waste for high-rate anaerobic digestion

Ryan E. Graunke, Ann C. Wilkie*

Soil and Water Science Department, University of Florida-IFAS, P.O. Box 110960, Gainesville, FL 32611-0960, USA

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ABSTRACT

Optimizing short-term solubilization is essential for high-rate anaerobic digestion of food waste. The purpose of this study was to measure the short-term kinetics of food waste solubilization and understand what mechanisms are responsible for driving food waste solubilization. Two solubilization assays were conducted to measure the solubilization of mechanically processed food waste. Three methods of mechanical grinding were utilized: an in-sink food disposer and a manual meat grinder with either small or medium size plate openings. A control assay was conducted to measure the release of endogenous soluble material into an aqueous medium. An enzyme assay was conducted to examine short-term food waste hydrolysis. The assays were diluted and buffered to prevent product and pH inhibition, respectively, and allow maximum solubilization to occur. Percent solubilization was calculated as the soluble chemical oxygen demand (COD) fraction of total COD. Data from the two assays were used to calculate the kinetics of endogenous solubilization and enzymatic hydrolysis. Regardless of grinding method, food waste was 27% solubilized within 1 h through endogenous solubilization. Enzymatic hydrolysis was responsible for an additional 29–31% solubilization by 4 h. This study showed that ground food waste was approximately 60% solubilized within 4 h under optimal conditions.

1. Introduction

In the United States, food waste is a significant component of municipal solid waste and the vast majority of food waste is currently landfilled. In 2011, more than 36 million tons of food waste was disposed in the United States, or 21% of municipal solid waste, only 4% of which was diverted from landfills (USEPA, 2013). There are increasing efforts across the U.S. and Europe to divert food waste from landfills for beneficial use. One potential solution is anaerobic digestion, which creates biofuel and biofertilizer from food waste (Wilkie, 2008). Utilizing high-rate anaerobic digestion technology, such as fixed-film digestion, could improve the efficiency of anaerobic digestion of food waste. However, a significant hurdle to overcome in high-rate anaerobic digestion of food waste is optimizing the solubilization step (Wang et al., 2006; Liu et al., 2008). Various pretreatment methods, including thermal, freezing/thawing, enzymatic, and mechanical, are proposed as a solution for increasing the solubilization of food waste and, therefore, the rate and extent of food waste anaerobic digestion. In order to examine the efficacy of pretreatment, it is first necessary to understand the mechanisms through which food waste solubilizes.

Organic matter in food waste can be represented as total chemical oxygen demand (TCOD), which can be divided into two primary fractions: water-soluble organic material and particulate organic material. Food waste contains endogenous intracellular and extracellular water-soluble organic material, as measured by soluble chemical oxygen demand (SCOD). In the present study, SCOD is any organic matter that can pass through a 0.45 μm filter. Particulate organic material, as measured by particulate chemical oxygen demand (PCOD), is any larger organic material that cannot pass through the filter. The relative proportions of SCOD and PCOD in food waste depend on the individual components of the food waste. Components with high sugar contents, such as fruits, generally have a higher proportion of SCOD, due to the ready solubility of simple sugars such as glucose and fructose. More fibrous components tend to have higher PCOD. In raw foods, SCOD is typically intracellular, such as cytoplasm contained within cell walls and cell membranes, while PCOD is comprised of the cell walls and cell membranes or larger intracellular structures, such as plastids. Some cooked or processed food waste components, such as bread and

Abbreviations: CODsf, The soluble fraction of total chemical oxygen demand; *CODesf*, *CODsf* in the endogenous solubilization (control) assay; *CODhsf*, *CODsf* in the hydrolytic enzyme solubilization assay due only to enzymatic hydrolysis.

* Corresponding author. Tel.: +1 352 392 8699; fax: +1 352 392 7008.
E-mail address: acwilkie@ufl.edu (A.C. Wilkie).

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cheese, are acellular as the cells have been disrupted and extruded during processing. In these processed foods, the SCOD is extracellular and is readily released when placed in water.

Solubilization is a critically important step in anaerobic digestion because the microbial consortia require organic matter in a soluble form for cellular assimilation. The rate at which particulate material is solubilized can determine the overall kinetics of anaerobic digestion and the overall vitality of the microbial consortia. Because anaerobic digestion necessitates acidogenesis of neutral solubilized compounds, there must be sufficient alkalinity in the digester to buffer the free organic acid intermediates. The rate and extent to which organic matter is solubilized and subsequently fermented into organic acids determines the alkalinity requirement of the digester. Thus, solubilization kinetics may dictate the required digester volume and the amount of base required for pH control. A pretreatment reactor for solubilization and/or acidification in a two-phase system may be beneficial in optimizing anaerobic digestion depending on the solubilization kinetics of the feedstock (Wang et al., 2006; Liu et al., 2008). Solubilization kinetics are also impacted when considering effluent recycling since the enzymes and microorganisms in the effluent may facilitate solubilization (Lü et al., 2008).

For particulate feedstocks, such as food waste, solubilization has been considered the rate-limiting step of the entire digestion process (Eastman and Ferguson, 1981; Palmowski and Müller, 2003; Wang et al., 2006; Izumi et al., 2010). The ratio between SCOD and PCOD endogenous to the feedstock is critical for the overall anaerobic digestion kinetics (Prashanth et al., 2006). While SCOD can be readily assimilated by the microbial consortia, PCOD must be hydrolyzed by extracellular hydrolytic enzymes produced by the microbial consortia. There are many factors that limit enzymatic hydrolysis rates. Four principal factors that limit enzymatic hydrolysis are adequate enzyme levels, substrate characteristics (particulate surface area and resistance to degradation), pH inhibition of enzyme activity, and product inhibition of enzyme kinetics. The characteristics of particulate material present in food waste significantly impact the kinetics of enzymatic hydrolysis (Neves et al., 2008). More recalcitrant materials, such as cellulose, structural proteins, and other oligomers of lipids, proteins and/or carbohydrates, have slower hydrolysis kinetics than more easily degradable materials, such as starch. Disruption of the substrate cells and tissues can increase the substrate availability to hydrolytic enzymes (Izumi et al., 2010). Enzymatic hydrolysis can also be limited by pH or product inhibition (Veeken et al., 2000; He et al., 2006). Because acidogenesis tends to lower pH, it is important that acids are either buffered or rapidly converted to CH_4 and CO_2 to maximize hydrolysis and anaerobic digestion kinetics. Although acidification in anaerobic digestion is typically more detrimental to acetogenesis and methanogenesis, an excessively low pH can also reduce enzymatic hydrolysis due to reduced enzyme activity outside of the enzymes' pH optima. This can be potentially problematic in a two-phased anaerobic digestion system with a separate hydrolytic/acidogenic reactor, which tends to operate at a lower pH than the methanogenic reactor. Accumulation of hydrolysis end-products, which can result if acidogenesis is reduced, may also inhibit enzymatic hydrolysis and consequently limit acetogenesis because there are insufficient acid intermediates available to the acetogens. Product inhibition can be overcome with robust microbial consortia that rapidly consume these end-products or by dilution with an aqueous phase, which requires a larger digester volume. Active microbial consortia can also reduce pH inhibition by consuming the products of acidogenesis and preventing acidification.

Optimal anaerobic digestion of food waste relies on balanced microbial consortia. The vitality of the consortia depends on a supply of organic intermediates consistently available supply of organic intermediates for microbial assimilation. The short-term solubilization kinetics determine the amount of soluble organic material that is rapidly available to the acidifying microorganisms and subsequently to the acetogenic and methanogenic microorganisms. Kim et al. (2012) demonstrated that in a thermophilic anaerobic digester fed with food waste and sewage sludge, higher rates of acetogenesis and methanogenesis are supported by higher hydrolytic enzyme activity compared to mesophilic conditions; hence, the rate of hydrolysis can be the driving factor in overall anaerobic digestion kinetics.

The purpose of the present study was to examine the short-term solubilization kinetics of ground food waste and to understand what mechanisms are responsible for driving and limiting short-term solubilization when pH and product inhibition are excluded. Mechanically ground food waste was used in this study to maximize solubilization by rupturing cells and disrupting tissues. In order to measure the relative contribution of endogenous solubilization and enzymatic hydrolysis, two different solubilization assays were conducted. A control assay measured the release of endogenous SCOD by diluting mechanically ground food waste with a buffered aqueous solution. An enzyme assay measured enzymatic hydrolysis of mechanically ground food waste in the presence of excess hydrolytic enzymes in a buffered aqueous medium, such that enzymes were not limiting and the maximum rate of hydrolysis could be achieved. By using identical food waste under identical assay conditions, the kinetics of both endogenous SCOD release and enzymatic hydrolysis could be determined.

Table 1
Composition of standard food waste.

Components	Percent composition (% ww[a])	Percent composition (% of TCOD[b])	Representative organic macromolecule
Apple, Red Delicious	24	11.9	Carbohydrate (sugar, pectin)
Potato, Russet	24	13.7	Carbohydrate (starch)
Beans, red kidney (canned, drained and rinsed)	20	21.2	Protein
Broccoli (florets)	12	4.3	Carbohydrate (cellulose)
Bread, white hamburger bun	12	29.7	Carbohydrate (starch)
Cheese, Sharp Cheddar	8	19.2	Protein, lipid

[a] ww = wet weight.
[b] TCOD = Total chemical oxygen demand.

2. Materials and methods

2.1. Standard food waste

Due to the general heterogeneity of food waste, a standardized food waste was developed for the present study to allow repeatable experiments and directly comparable data. The standard food waste consisted of fresh food waste constituents representing the major macromolecule groups of food waste: carbohydrates, proteins, and fats (Table 1). The constituents were proportioned to simulate actual food waste analogous to that generated from local food service establishments (i.e. restaurants and schools). Fresh food waste was used because it would allow the immediate and short-term solubilization to be measured, unlike actual food waste collected from a food service area, which may have already begun the solubilization process. To ensure that the standard food waste was representative of food waste generated in the community, the physicochemical properties of the standard food waste were compared to the physicochemical parameters of food waste