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Seasonal characterization of sugarcane vinasse: Assessing environmental impacts from fertirrigation and the bioenergy recovery potential through biodigestion

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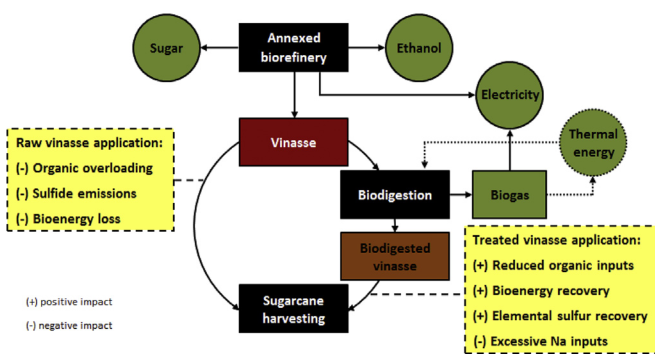
HIGHLIGHTS

- Vinasse streams were characterized throughout the sugarcane harvest period.
- The fate of vinasse through fertirrigation and anaerobic digestion was assessed.
- The organic polluting load could be reduced by 80% through two-phase biodigestion.
- Over 300 thousand inhabitants could be supplied with biogas electricity.
- Sodium accumulation would severely limit the land disposal of biodigested vinasse.

GRAPHICAL ABSTRACT



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ABSTRACT

Sugarcane vinasse has been widely used as a soil fertilizer in the Brazilian sucro-alcohol industry for recycling potassium and water. However, the potential negative effects from long-term soil fertirrigation represent a major drawback regarding this practice, whereas the application of biodigestion represents an efficient method for reducing the polluting organic load and recovering bioenergy from vinasse. Regardless of the predicted use for vinasse, an understanding of the potential of each option is imperative, as the seasonal alterations in the inorganic/organic fractions of vinasse directly affect its management. In this context, this study presents a detailed compositional characterization of sugarcane vinasse from a large-scale Brazilian biorefinery throughout the 2014/2015 harvest to assess the environmental effects (due to fertirrigation) and to estimate the biogas energetic potential. Calculated inputs of organic matter into soils due to vinasse land application were equivalent to the polluting load of populations (117–257 inhab ha^{-1}) at least 2-fold greater than the largest Brazilian capital cities (78–70 inhab ha^{-1}). Two-phase biodigestion could efficiently reduce the polluting load of vinasse (23–52 inhab ha^{-1}) and eliminate the negative effects from direct sulfide emissions in the environment. However, a high risk of soil sodification could result from using high doses of Na-based alkalizing compounds in biodigestion plants. Finally, the optimized recovery of bioenergy through biogas (13.3–26.7 MW as electricity) could supply populations as large as 305 thousand inhabitants, so that over 30% of the surplus electricity produced by the studied biorefinery could be obtained from biogas. Overall, applying biodigestion in the treatment of vinasse provides important environmental and energetic gains. However, the benefits of reducing the polluting organic load of vinasse through bioenergy recovery may lose their effect depending on the alkalizing strategy, indicating that the proper use of chemicals in full-scale biodigestion plants is imperative to attain process sustainability.

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Nomenclature

$[K]_{soil}$	concentration of potassium in the soil
$[K]_{vinasse}$	concentration of potassium in vinasse
$[NaHCO_3]$	sodium bicarbonate dose
[NaOH]	sodium hydroxide dose
AD	anaerobic digestion
AOL_{soil}	applied organic load into the soil
BOD	biochemical oxygen demand
BOD_{sewage}	BOD of sewage
$BOD_{vinasse}$	BOD of vinasse
CEC	cation exchange capacity
COD	chemical oxygen demand
COD_{sewage}	COD of sewage
$COD_{vinasse}$	COD of vinasse
CR	sewage-to-water return coefficient
EP	energetic potential of biogas
EqPop	equivalent population
ER_{COD}	COD removal in biodigestion
GHG	greenhouse gas
HP	harvesting period
HSW	high-strength wastewater
HY	hydrogen yield
ICE	internal combustion engine
LHV_{CH4}	lower heating value of methane
LHV_{H2}	lower heating value of hydrogen
M_{HS-}	molar mass of sulfide
M_{SO4}	molar mass of sulfate
MTC	million tons of sugarcane
MY	methane yield
Na_{vin}^{biod}	concentration of sodium in the biodigested vinasse
Na_{vin}^{raw}	concentration of sodium in raw vinasse
PCC_{water}	per capita water consumption
pHPR	potential hydrogen production rate
pMPR	potential methane production rate
pSE	potential sulfide emission
SAR	sodium adsorption ratio
S-COD	soluble COD (0.45 μm-filtered samples)
TC	tons of sugarcane
T-COD	total COD (unfiltered samples)
TKN	total Kjeldahl nitrogen
TOC	total organic carbon
TRS	total reducing sugar
VFA	volatile fatty acids
VFR	vinasse flow rate
VinAR	vinasse application rate
η	energy conversion factor

1. Introduction

The fate of vinasse, the primary wastewater from ethanol production, represents one of the main burdens of the sucro-alcohol industry in Brazil. In the mid-1970s, restrictive laws prohibited the direct and indirect discharge of vinasse into water bodies (Fuess and Garcia, 2014; Moraes et al., 2015), which promptly encouraged the land disposal of this high-strength wastewater (HSW) through fertirrigation by recycling nutrients, primarily potassium, and water to the sugarcane fields (Dias et al., 2015). Despite the proven techno-economic feasibility of fertirrigation (Cruz et al., 2013), the continuous long-term land disposal of vinasse into soils has great potential to trigger a series of negative environmental effects (Fuess and Garcia, 2014; Fuess et al., 2017c), such as soil salinization and the subsequent structural destabilization of the terrain, microbial activity losses, and the permanent acidification of soils and water resources. These effects are the direct results of the high inputs of salts and biodegradable organic compounds, particularly organic acids, into the fields.

Anaerobic digestion (AD) or biodigestion may be considered the primary alternative for managing vinasse in sugarcane biorefineries. AD has important advantages over fertirrigation, including a reduction in the polluting organic load of vinasse, the potential recovery of bioenergy from biogas, and the potential for enhancing the profitability of biorefineries through the generation of surplus electricity, based on the burning of biogas in prime movers (Fuess and Garcia, 2015; Fuess et al., 2018; Moraes et al., 2014, 2015). Moreover, the removal of nutrients in AD systems is negligible, which means that the fertilizing potential of *in natura* vinasse is maintained in the biodigested effluents (Moraes et al., 2015; Salomon et al., 2011). Additional technological approaches proposed for the management of vinasse include the cultivation of microbial biomass for the production of protein-rich cells (Pires et al., 2016; Santos et al., 2016), which may also be coupled to the recovery of different bioproducts, such as bioemulsifiers (Colin et al., 2016; Oliveira and Garcia-Cruz, 2013), enzymes (Kahraman and Gurdal, 2002), and lipids (Fernandes et al., 2017). The recycling of vinasse into the fermentation step has also been shown as an efficient destination for this HSW, aiming at the production of fuel ethanol (Navarro et al., 2000) and spirits (Menezes et al., 2013).

Regardless of the chosen use for sugarcane vinasse, it is imperative to understand the potential of each available application through a complete compositional characterization of vinasse, as seasonal alterations in the inorganic and organic fractions of this HSW directly affect the proposed management approaches. With respect to fertirrigation in Brazil, the concentration of nutrients in vinasse, particular that of potassium, defines the application rates into the sugarcane fields (CETESB, 2015), resulting in other environmental impacts from the associated inputs of biodegradable organic matter (the polluting organic load) and other constituents. In turn, biodigestion is directly affected by the biodegradability of the organic fraction from vinasse as well as by the accumulation of specific inhibitory/interfering compounds, such as phenols and sulfate.

In this context, this study aimed to present a detailed compositional characterization of sugarcane vinasse from a large-scale Brazilian biorefinery (with a milling capacity of 9.3×10^6 tons of sugarcane (TC) per harvest) throughout the 2014/2015 harvest, particularly for the year 2014. The organic and inorganic fractions of vinasse were characterized over seven months (May to December), and the compositional data were used to predict the environmental effects (due to fertirrigation) and to estimate the energetic potential of biogas. The impacts of the specific constituents of vinasse, such as sodium and sulfate, were considered in each case. Estimates on the application of biodigestion considered single- and two-phase schemes in an effort to understand how the polluting and energetic potentials of sugarcane vinasse could be affected throughout the harvest by applying different treatment approaches. Full-scale experiences with sugarcane biodigestion are still scarce in the Brazilian sucro-alcohol industry (Fuess et al., 2017a), minimizing field data availability and, consequently, requiring simulation- and estimate-based studies to properly understand the pros and cons of AD. In this sense, the results obtained herein may be used as a reference for the implementation of specific management approaches in biorefineries to prevent negative effects from the use of vinasse as a fertilizer and bioenergy source.

2. Methods

2.1. Sugarcane vinasse sampling and characterization

Sugarcane vinasse samples were regularly collected from an annexed full-scale biorefinery located in the State of São Paulo, Brazil,