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Sugarcane vinasse processing: Toward a status shift from waste to valuable resource. A review

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ABSTRACT

The foreseeable increase of bioethanol production by distilleries will inevitably lead to an important increase in production of the associated effluent, namely vinasse. Due to its high pollution load, characterized by high chemical oxygen demand, high salt content and heavy dark color, the depollution of this effluent is mandatory before release into nature. In this work, we reviewed the literature on the main physicochemical and biological treatments of sugarcane vinasse and emphasised on the technological valuation of vinasse that allows to shift the status of the effluent from waste to valuable resource. The membrane systems seem to offer the best depollution option but they are subjected to strong technical limitations. Several alternative processes have been proposed, but they generally fail to treat the entire organic load of waste when used in stand-alone technology, while generating higher investment costs in the treatment process. The biological processes turn out to be particularly promising as they are able to produce interesting metabolites from living cells. Among them, production of biogas through anaerobic digestion is by far the most developed and economically viable process for treatment of vinasse. However a few works, also using vinasse as a growth medium, have been published on development of innovative technics to produce single cell products such as lipids, proteins, organic acids, alcohols or enzymes. In the medium term, technologies to produce third generation biodiesel are developing to complement and compete with fuels derived from petroleum. Finally, the development of hydrogen production processes from vinasse is emerging, thus preparing us for a long-term decarbonised economy.

1. Introduction

The gradual replacement of fossil fuels with biofuels is generating growing interest in a transition to a more friendly economy. Bioethanol offers numerous advantages for this use. The fuel can be produced worldwide, using a large variety of feedstock, including sugar beets, sugarcane, molasses, corn, rice, dairy product or cellulosic material [1]. It is also considered renewable thanks to its biological origin. Finally, its environmental impact is lower than fossil gasoline [2]. As such, bioethanol production is expected to keep growing for the next decade to reach 134 billion liters in 2024 [3] with biggest producers expected to be United States, Brazil, European Union and China (Fig. 1).

Vinasse, also known as Distillery spent wash (DSW), distillery stillage or distillery slop is an aqueous waste generated by the distillation of alcoholic must during the ethanol production process (Fig. 2; [4–6]). The sugarcane-ethanol industry generally releases on average 156 L of stillage and 250 kg of bagasse per ton of sugarcane and produced 12 L of alcohol and 94 kg of sugar [7], thus representing 13 L of stillage per liter of alcohol produced. The production of this effluent is expected to rise with the production of ethanol and a perspective of 1742 billion liters produced in 2024 is expected based on this ratio.

Vinasse is an acidic stream (pH 3.5-5), high in organic load as represented by high chemical oxygen demand (COD) (up to 140 g/L), with a dark brown color because of the presence of melanoidins [8] and an unpleasant odour. It contains nutrients such as nitrogen (up to 4.2 g/L), phosphorus (up to 3.0 g/L) or potassium (up to 17.5 g/L). As shown in Table 1, the characteristics of the vinasse depends on the raw material used.

The first management system for this effluent was the discharge in water bodies. The impact of this practice was assessed by histopathology of liver in tilapia [9]. Fishes were exposed to different dilutions of stillage from 1% to 10% in laboratory bioassays. The vinasse

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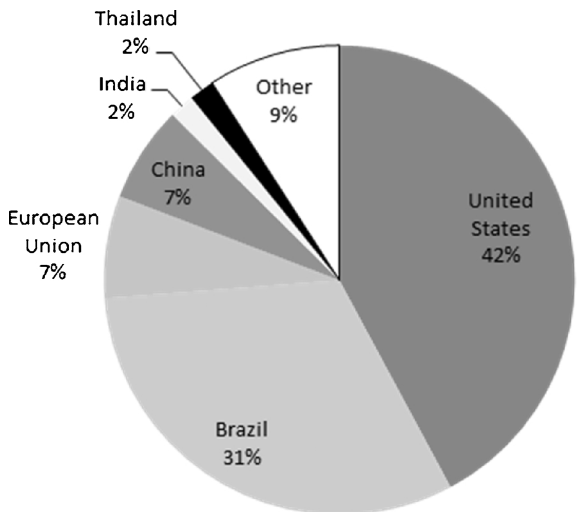

Fig. 1. Global perspectives of bioethanol-producing countries in 2024. Source: OECD/FAO (2015), "OECD-FAO Agricultural Outlook", OECD Agriculture statistics (database), https://doi.org/10.1787/agr-outl-data-en

treated fishes exhibited severe tissue disorganization depending on the concentration applied leading to the conclusion that vinasse has a dose-dependent toxic and cytotoxic potential in water bodies. When it is spread into the nature, the effluent can cause proliferation of microorganisms and consumption of the dissolved oxygen in water, leading to death of aquatic animals and plants and contaminating sources of potable water [10–12]. These environmental problems lead several countries to adopt regulations about effluent discharge, aiming at reducing the environmental impact and minimizing the direct contact of raw vinasse with water bodies.

The main use of vinasse is as a fertilizer through irrigation of fields [7,13]. The risks of fertilization are principally associated with the build-up of nutrients in the soil including soil salinization and over-fertilization, leading to salt leaching to groundwater, increasing soil instability or eutrophication of water bodies. Other impacts on the ground include contamination with toxic metals such as zinc, copper or barium amongst other metals quantified in Table 2, permanent soil and water resources acidification, interference in the process of photosynthesis due to the high color and turbidity of stillage or clogging of soil pores by organic overload, thus decreasing oxygen transfert and microbial activity, as well as stimulating the generation of unpleasant odors due to the anaerobic degradation of organic loads [14].

The application of vinasse in the field also has negative effect on invertebrate present in the soil. Avoidance behavior was observed on earthworms (*Eisenia andrei*) and collembolans (*Folsomia candida*) and lower reproduction of these two species along with enchytraeids (*Enchytraeus crypticus*) and mites (*Hypoaspis aculeifer*) was highlighted which was attributed to the high salt content and especially the high potassium concentrations [15].

Ethanol is regarded as an alternative to fossil fuels thanks to its lower greenhouse gas emission compared to gasoline [2]. Effluents count for a part of the emissions of the ethanol sector. The vinasse management system impact the overall greenhouse gases emissions at the field application level [16,17] and during its storage and transportation before application to the field [13–18]. Transportation of vinasse in open channel and disposal in the field as a fertilizer is the main method used in Brazil for discharge of the spent wash. CH_4 and N_2O emissions all along the disposal system were followed because of their potential as greenhouse gases and it was found that CH_4 count for 98% of the total emissions during transport but was consumed once applied to the soil. However, the N_2O emissions occurred mainly after irrigation of the field.

Vinasse, because of its high organic, salt and heavy metal contents and its large production volume, represents a great challenge to natural environment, from water bodies to atmospheric greenhouse gases through soil contamination. Consequently, depolluting processes should be applied before discharge in the environment.

The scope of this work was to assess the advances on the knowledge on treatment and usage of vinasse reported in the literature in the last 20 years. In a first part, treatments and outcomes applied to vinasse were reviewed, encompassing physicochemical and biological treatments. Then, the question of the status of vinasse as a waste or a resource is addressed through examples of its usage as agricultural amendment, substrate for biomass and valuable molecule production and as raw material for energetic purposes.

2. Physicochemical and biological treatments of vinasse

Given that many issues have been raised by the use of vinasse in direct application on the ground, several works were published with the goal to reduce both the quantity and the polluting load of the liquid effluent. Physicochemical or biological management process can be used for this purpose. Physicochemical process for the treatment of vinasse are based on separation of the organic charge from the water or on the use of strong oxidizing agent for degradation of the chemical pollutants, thus reducing the volume of stillage to treat or the amount of pollutant in the effluent whereas biological methods are used in milder conditions of temperature and pressure with no addition of chemicals.

2.1. Volume reduction

The first challenge associated with vinasse management is its production volume. The corn ethanol industry has already managed this problem by concentrating the organic charge through drying processes, leading to the valorization of the dried residue for animal feeding purpose [4]. However, energy requirement associated with evaporation of the water content is energetically high and economically disadvantageous.

2.2. Recirculation

As a waste from distilleries, vinasse could be advantageously recycled directly into the ethanol production process as a tap water replacement [19–22]. Recycling of the whole stillage into fermentation medium leads to a higher concentration of dry matter after 14 cycles from 9.6% to 24%. This process enabled a 66% decrease in nutrients addition, 46.2% in fresh water and 50% in sulfuric acid requirement [19].

Further stillage volume reduction is possible by replacing tap water with recirculating stillage after distillation and solid separation [20] or using post-methanated effluents [21] without influence on the ethanol yield and fermentation time.

The resulting concentrated effluent reduced energy requirement for vinasse drying but did not eliminate the evaporation step and liquids emissions into the environment. Further physical, chemical or biological post-treatments are then required to reduce the polluting characteristics of the ultimate effluent after recycling of the vinasse.

2.3. Membrane system

Filtration systems in wastewater treatment use membranes to concentrate the suspended solids from a slurry in a concentrate stream and to release the depolluted water in the permeate stream. Several technologies including microfiltration, nanofiltration or reverse osmosis offer different cut-off limits depending on the molecular weight of the particles to strip out from the water. It can be considered as an intermediate operation to separate solutes or as a final depolluting step before discharging of the water. As a final step, this operation is