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Trends in global warming and human health impacts related to Brazilian sugarcane ethanol production considering black carbon emissions

Marcelo Galdos [a,*], Otávio Cavalett [a], Joaquim E.A. Seabra [a,b], Luiz Augusto Horta Nogueira [c], Antonio Bonomi [a]

[a] Brazilian Bioethanol Science and Technology Laboratory (CTBE) – CNPEM, Rua Giuseppe Máximo Scolfaro, 10.000, Polo II de Alta Tecnologia, P.O. Box 6170, Campinas, Sao Paulo 13083-970, Brazil

[b] Faculdade de Engenharia Mecânica, UNICAMP, Rua Mendeleyev, 200, Cidade Universitária "Zeferino Vaz", Campinas, São Paulo 13083-860, Brazil

[c] Instituto de Recursos Naturais, Universidade Federal de Itajubá, Campus Universitário Pinheirinho, Itajubá, Minas Gerais 37500-050, Brazil

HIGHLIGHTS

- Black carbon should be included in environmental assessments of biofuel production.
- Phasing out burning will reduce the impacts of sugarcane ethanol production.
- Increasing the amount of ethanol produced per unit of area potentially reduces its impacts.

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ABSTRACT

Sugarcane produced in Brazil has several environmental advantages. However, burning residues, which leads to GHG and black carbon (BC) emissions, has been used to facilitate manual harvest. BC emissions have a net warming effect and cause health problems. Mechanized harvest without burning is gradually replacing manually harvested burned sugarcane. Global warming potential (GWP) and human health indicators of sugarcane ethanol production in Brazil, in the pre-mechanization (100% burned), current (~50% burned) and future (100% without burning) scenarios, were calculated. In the past, the GWP of ethanol production was 1.1 kg CO_2 eq L^{-1} and BC emissions were 32.6 kg CO_2 eq L^{-1}. The human health impact in disability adjusted life years (DALY) was 3.16E−05 DALY L^{-1} ethanol. The current ethanol production process has a GWP 46% smaller, while BC emissions are seven times smaller than before mechanization started. The human health impact is currently 7.72E−06 DALY L^{-1}. In the future, with complete mechanization and the integration of first and second generation ethanol, the expected GWP emissions will be 70% smaller, and BC emissions will be 216 times smaller than when all sugarcane was harvested with burning. These results show that ethanol production in Brazil is improving in terms of global warming and human health aspects. Other upstream aspects of ethanol production such as direct and indirect land use change, and downstream impacts such as the emissions of acetaldehydes were not considered in this study, which focused on a major technological shift in residue management in the agricultural phase of sugarcane ethanol production. A broader assessment of the sustainability of ethanol must account for those issues, as well as economic and social aspects. Sugarcane-derived ethanol produced in Brazil has been considered one of the most sustainable biofuels options, but it is essential to identify and promote practices and policies that further improve its production, such as the phase out of pre-harvest sugarcane burning and the increase in ethanol yield per unit of area.

1. Introduction

Sugarcane is an attractive feedstock for bioethanol production, considering both an energy output:input ratio of approximately 9:1 and greenhouse gas (GHG) emission reductions compared to fossil fuels of close to 80% [1,2]. However, pre-harvest burning of dry leaves and tops (trash) has been a common practice to facilitate manual harvest and transport operations. Burning leads to emissions of GHGs besides the release of soot into the atmosphere. Black carbon (BC) is a major component of soot, resulting from the incomplete combustion of fossil fuels, biofuels and biomass. It has been estimated that total global emissions of BC are approximately 8 Tg C year, with 4.6 from fossil fuels and the remaining

* Corresponding author.
E-mail address: marcelo.galdos@bioetanol.org.br (M. Galdos).

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from open biomass burning [3]. Black carbon scatters and absorbs portions of incoming solar rays, but also absorbs radiation from the diffuse upward rays of scattered sunlight [4]. The net effect is a warming of the atmosphere. It has been suggested that BC is the second most important component of global warming after CO_2 in terms of direct forcing [5]. Therefore, it has global warming impacts, besides posing human health hazards.

Due to environmental and economic reasons, there are ongoing burning phase out programs in the main sugarcane-growing regions in Brazil, with the gradual replacement of manual harvest with burning by mechanized harvest without burning. Slope of terrain is one of the limiting factors for harvesting sugarcane mechanically. In São Paulo State, the largest sugarcane producer, pre-harvest burning is expected to cease in all areas suitable for mechanical harvest by 2021 by state law number 11241 approved in 2002, but a voluntary sugarcane industry program has set 2014 as a target year for phasing out pre-harvest burning in those areas. Minas Gerais state, the second largest sugarcane producer, has also implemented a sugarcane burning phase-out program. Furthermore, all new sugarcane-ethanol operations currently being established in Brazil, including in new areas in the Center-West region, are required by law to implement harvest without burning. In addition of the pressure for phasing out burning though legislation, the reduction in burning is also driven by other factors such as the lack of manual labor, increased labor costs, and voluntary certification schemes. Therefore, there is a clear trend for country-wide phase out of pre-harvest burning, both in new and traditional sugarcane areas.

The aim of this work was to evaluate the potential environmental benefit of phasing out pre-harvest burning of sugarcane crop residues in Brazil, focusing on global warming and human health impacts considering also BC emissions. A brief discussion of other emissions associated with ethanol as well as other technologies currently under development aside from ethanol vehicles was included to provide a broader view of the subject. We have calculated global warming potential and human health indicators of sugarcane ethanol production in Brazil in three periods: pre-mechanization (100% burned), present ($\sim$58% burned) and future (100% mechanically harvested without burning). Additionally, effects of pre-harvesting burning on the present sugarcane production system and alternatives of introduction of second generation ethanol production are explored and discussed separately in detail.

2. Materials and methods

2.1. Life cycle assessment

The approach to evaluate the environmental impacts in this study was Life Cycle Assessment (LCA). This is a well known method for determining the environmental impact of a product (good or service) during its entire life cycle or, as in the case of this study, from production of raw materials, transport of inputs and feedstock to industrial processing in a biorefinery. The method consists of four main steps: goal and scope definition, inventory analysis, impact assessment and interpretation [6–8].

In goal and scope definition the intended application of the study, system boundaries, functional unit and the level of detail to be considered are defined. In this study system boundaries are defined as cradle-to-gate and include all raw materials and emissions of sugarcane cultivation, transport and industrial processing but the transport, usage and discard of the products are not included. The most relevant processes and emissions were included in the LCA, as illustrated in Fig. 1, in accordance with recent LCA biofuel literature [9–12]. The functional unit considered is one liter of anhydrous ethanol.

Life cycle inventory (LCI) is the methodological step where an overview is given of the environmental interventions (energy use, resource extraction or emission to an environmental compartment) caused by or required for the processes within the boundaries of the studied system.

Impact assessment examines the environmental burdens of the emissions and resource use quantified in the inventory analysis. The software package SimaPro® [13] which has been widely applied as a tool for the environmental impact assessment, was used in this study. The global warming potential (GWP) was evaluated using the IPCC's fourth assessment report [14] for a time horizon of 100 years, and greenhouse gases and particulate matter emissions were converted into CO_2 equivalent. The global warming impact of black carbon was evaluated [15], expressed in kg CO_2 equivalent per kg of particulate emission. The human health impacts [respiratory (i.e. organics, inorganics); carcinogens, climate change (i.e. disease, displacement), radiation effects (i.e. cancer), ozone layer depletion (i.e. cancer, cataract)] was estimated as disability adjusted life years (DALY) using the Ecoindicator 99 life cycle impact assessment method [16].

The identification of significant issues, conclusions and recommendations are made in the interpretation step. According to LCA methodology, allocation is required for multi-output processes. In this study economic allocation based on the market value of the process outputs (ethanol and electricity) was applied.

2.2. Black carbon emissions

This assessment included particulate material emissions from the combustion of crop residues in the agricultural phase of ethanol production, from burning bagasse and crop residues on plant furnaces, as well as emissions from the combustion of liquid fuels in agricultural operations and transport. Specific emissions factors for both for biomass burning [4] and for combustion of fossil fuel [17] are listed in the Supplementary material. No distinction was made between particulate matter sizes – both PM2.5 and PM10 were included in the calculations. The global warming potential of black carbon is approximately 2000 for 20 years, 500 for 100 years and 200 for 500 years [15]. This assessment of sugarcane ethanol production was conducted considering a 100-year time horizon. It has been suggested [18] that fossil fuel soot has an even higher 100-year GWP potential (840–1280), since it has a higher composition of black carbon in relation to organic carbon, which increases its potential to absorb radiation. There are also attempts to present distinct surface temperature response per unit emission (STRE) values, which are similar to GWP values, for fossil-fuel soot and biofuels soot [19]. However, due to the current limited number of studies presenting separate GWP values, the same GWP was used for both biomass and fossil fuel soot in this study.

2.3. Scenarios

The "Present" scenario represents an average technological picture for the Center-South region of Brazil tacking the year 2010 as a basis. The inventory was based on extensive compilation of data from literature, experts' advice and also field work.

The "Past" scenario represents the technology used for ethanol production in the beginning of the 1980s (beginning of the ProAlcohol program). The inventory was based in the work of Nogueira [20], one of the first comprehensive studies of the energy balance for ethanol production in Brazil.

The "Future" scenario is based on the data for new technologies that are likely to be introduced in the sugarcane sector in Brazil in the next 10–20 years. The consideration used for the inventory is based on projections for future agricultural practices possible to be implemented and expert knowledge in the area.