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Environmental profile of sweet sorghum bioethanol in the province of Tucumán (Argentina)

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Abstract

Objectives The objective of this study is to evaluate the environmental profile of bioethanol production from sweet sorghum (*Sorghum bicolor* (L.) Moench) in the province of Tucumán (Argentina).

Methods The study is carried out using the life cycle assessment (LCA) methodology. The evaluated system includes the cultivation of sorghum, its transportation to the sugar mill, and the production of anhydrous ethanol. For the inventory, data recorded in field/industry activities is preferably used, supplemented by specialized publications and the Ecoinvent v3 database. The ReCiPe 2016 impact evaluation model is used to obtain the environmental profile.

Results and discussion The results show that the environmental contribution of the sorghum agricultural phase dominates all impact categories, mainly due to the use of some agrochemicals and fossil fuels. The normalization of these results highlights freshwater ecotoxicity as the most relevant category. The sensitivity analysis reveals that this category depends almost linearly on the leaching-runoff factors of the pesticides, among which chlorpyrifos prevails.

Conclusions This study unveils the hotspots in sorghum bioethanol production, which will be used to improve the agronomic management of the crop and processing. The incorporation of sorghum as a feedstock in the existing cane-based sugar-alcohol industry allows for a significant reduction of the global warming potential, opening opportunities for future research on the subject. Therefore, the cultivation/processing of sweet sorghum is a promising alternative to reduce the environmental impact of ethanol from other sugarcane-producing regions.

Keywords Environmental footprint · Biofuels · Energy crops · Life cycle assessment

1 Introduction

Government agencies around the world have developed initiatives and policies to encourage the production and use of biofuels that could contribute to multiple sustainability goals (REN21 2021). Biofuels are an important strategy to achieve a reduction of greenhouse gas (GHG) emissions, promote the rural economy, improve energy security, and increase energy efficiency (Le Feuvre 2019).

World biofuel production, mainly ethanol and biodiesel, is concentrated in the USA, Brazil, and the European Union (EU). The USA and Brazil are leaders in ethanol production, mainly based on corn and sugarcane, respectively. Other big producers are China, India, Canada, and Thailand.

Argentina ranks seventh in world ethanol production (REN21 2020), managing to expand its bioenergy production and use in order to diversify its energy matrix. Two national laws (26,093/06 and then 27,640/21) allowed for the integration of bioethanol into the sugar industry chain while supplementing gasoline with a minimum bioethanol content of 5%. Currently, this blending mandate is 12%, and it is expected to continue increasing, reaching up to 27.5% (as it is in Brazil) for Otto engines without modifications. The bioethanol produced by the Argentine industry in 2020 was 808,725 million m^3: 47.6% from sugarcane and 52.4% from corn (SGE 2020).

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Sugarcane (*Saccharum officinarum*) and sweet sorghum (*Sorghum bicolor* (L.) Moench) are two energy crops with the highest potential for biomass production: 60–90 t ha^{-1} and 50–80 t ha^{-1}, respectively. In the case of sweet sorghum, the amount of ethanol per hectare (obtained by juice fermentation) reaches values of 2500 L/ha, i.e., 50% of the ethanol produced from sugarcane. Other studies that even consider the possibility of producing second-generation ethanol from sorghum have shown production levels between 3200 and 5220 L/ha (Ahmad Dar et al. 2018).

Sugarcane cropping in Argentina is located in the northwestern provinces of the country. Currently, 23 sugar mills are active and 15 are located in the province of Tucumán (CAA 2020), where the area planted with sugarcane is almost 276,400 ha (Fandos et al. 2021). This industry is one of the main socio-economic activities in Tucumán, generating employment, especially at harvest time.

Sweet sorghum is a crop with high photosynthetic efficiency and high productivity that can be grown in Tucumán due to the agroecological conditions of the region. It can be used in non-competitive rural areas, where no traditional crops are grown, and close to sugarcane mills. Moreover, it has characteristics that allow its industrial processing using the same equipment as sugarcane, which guarantees profitability. The possibility of integrating these two crops is feasible because of the following characteristics of sorghum (Romero et al. 2012): (i) efficient conversion of solar energy into biomass (C4 photosynthetic mechanism); (ii) short growth cycle (3–4 months); (iii) efficient water consumption (tolerant to drought and to moderate soil salinity); (iv) ability to be grown in rotation with soybean; and (v) high content of total fermentable sugars (14–20%) and fiber (14–18%).

This crop can increase the feedstock availability for bioethanol production, perfectly complementing the food and energy production of the already established sugarcane value chain. This is locally demonstrated during the execution of Project "Biosorgo," a public–private partnership where technical development aspects at a commercial scale have been conducted during four years. The main outcome is to determine feedstock availability early in the season before the start of the sugarcane harvest. In addition, as with sugarcane, renewable electrical energy can be produced from the high amount of residual biomass remaining after sorghum harvest (agricultural residues) and processing (bagasse), without modifications in standard equipment and processes, both in the field and in sugarcane mills. These advantages would help sugar and ethanol companies to reduce costs and fuel consumption. Special attention was given to sustainability during the field and industry stage, minimizing the use of inputs (Tonatto et al. 2019). In this context, it is of interest to evaluate the environmental impact of sorghum-based ethanol to measure its influence on the environmental performance of sugarcane-based ethanol.

There are many reports on the environmental impact of the production of ethanol from sweet sorghum, mainly in China and the USA, but also in Mexico, India, Brazil, Greece, and Italy. Various studies evaluate conversion technologies, energy balance, GHG emissions, and the economic performance of this bioethanol (Zhang et al. 2010; Tao et al. 2011; Liang et al. 2012; Li et al. 2013; Yu et al. 2014). Some studies analyze the life cycle potential environmental impacts of sweet sorghum bioethanol considering different technologies (Wang et al. 2014; Olukoya et al. 2015; Ding et al. 2017; Morrissey et al. 2021; Aguilar-Sánchez et al. 2018). In Argentina, publications on this subject are scarce in spite of being sorghum a traditional crop in some regions of the country with studies on animal and human nutrition and bioenergy (De Bernardi 2019; Giorda and Ortiz 2012; Giorda and Alegre 2015; Romero et al. 2010, 2012; Tonatto et al. 2019). At present, there are only local reports of estimations of the environmental profile of sweet sorghum limited to the agricultural stage (Garolera De Nucci et al. 2020).

The objective of this work is to evaluate the environmental profile of sweet sorghum bioethanol production in the province of Tucumán, using the life cycle assessment (LCA) methodology considering several impact categories such as acidification, depletion of fossil resources, eutrophication, among others, and not only the impact associated with GHG emissions. The aforementioned studies are not comparable to the case of Argentina since they analyze geographically specific situations and practices.

2 Methods

2.1 Goal and scope of the study

The objective of this study is to evaluate the environmental profile of sweet sorghum bioethanol production in the province of Tucumán. A "cradle-to-gate" approach is used, accounting for the inputs and outputs from feedstock (sweet sorghum growing) to anhydrous ethanol production at the distillery gate. The limits of the system under study are shown in Fig. 1 and include sorghum cropping, transportation to the sugarcane mill, and anhydrous alcohol production. Likewise, the system includes the production and transportation processes of the different inputs and fuel used. The geographical scope and the data are representative of Tucumán, corresponding to the period 2016/2017. The temporal scope is 218 days (120 days for the crop cycle and 98 days for processing), and the functional unit (FU) is 1 t of sorghum-based bioethanol. This production is the amount required for a standard medium car to travel a distance of $15.2\cdot10^3$ km.

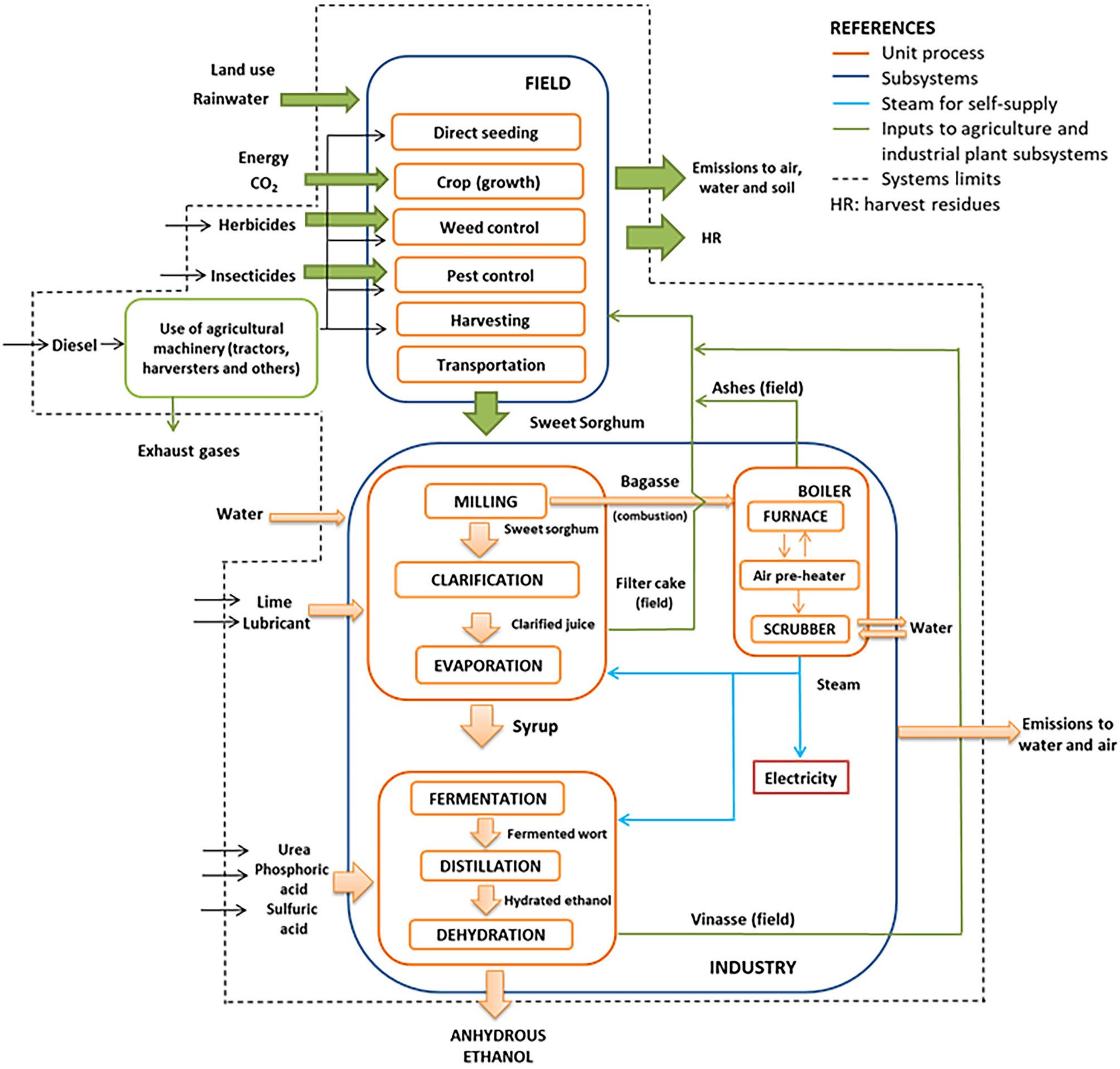


Fig. 1 Schematic of the life cycle system boundaries for sweet sorghum-based bioethanol

The overall system has been divided into two subsystems: FIELD and INDUSTRY. FIELD considers the cropping system of sweet sorghum (Argensil 165 Bio hybrid) in the SE of the province of Tucumán. It includes sowing operations, pre-emergent and post-emergent herbicides production and application, pest control (insecticides), and the mechanized green harvest of the crop. Neither fertilizers nor irrigation water is applied. The proposed agronomic management is a result of the goals of Project "Biosorgo," generating a sweet sorghum crop management as sustainable as possible. It is known that synthetic fertilizers affect the footprint and energy balance of crops, and this aspect is especially relevant to energy crops (Tonatto et al. 2019). Based on site-specific soil analysis, it is confirmed that the selected location does not have P and K deficiencies, while N might be required in certain situations and expected yield. Previous local research determined that an important amount of the extracted nutrients is returned to the soil by harvest residues: 48% of N, 37% of P, and 85% of K (Fontanetto and Keller 2008). After harvesting, residues containing leaves and plant tops (HR) are considered to be used as a trash blanket covering the soil surface; therefore, HR is a by-product of the subsystem. A fraction of this residue (50%) is used as cover in the field, and the rest leaves the system to be used for energy purposes.

Therefore, 50% of the HR is considered as an outflow of the subsystem (co-product). The tasks associated with the production of sorghum seed are dismissed since matter, and energy inputs and outputs are negligible when compared to other field operations. For agricultural operations, the use of diesel (fossil origin) and the manufacture of machinery is included. A 14-row planter powered by a 140-HP tractor and a 130-HP self-propelled sprayer are used. The harvesting system is mechanized and combines a sugarcane harvester (337 HP) with complementary equipment (two tractors and two sugarcane dump wagons). It has to be noted that modern and efficient machinery (high field capacity) is used in all field operations, and only extremely necessary operations are used trying to reduce fuel use as much as possible. When agricultural operations are studied, mechanized harvest is the main diesel-consuming task (106.6 L/ha). Other operations such as planting (4.5 L/ha) and agrochemical applications (1.6 L/ha) are of lower incidence in the total amount used (116.26 L/ha). Transportation of the feedstock to the mill is also a determinant (12 L/truck), considering a distance of 30 km to the mill and a load capacity of 30 t. The agrochemicals used are glyphosate, 2,4-D, atrazine, metolachlor, chlorpyrifos, alphamethrin, thiodicarbamate, and adjuvants. The cycle of this summer crop is 120 days and has an estimated yield of 29.6 t/ha (referred to as millable stalks). Sowing takes place between December and January and harvests between April and May. After harvesting, the sorghum stalks are transported to the sugar mill located 15 km away from the field.

The INDUSTRY subsystem (sweet sorghum processing) comprises the production of anhydrous ethanol (99% vol.) for fuel purposes using concentrated sweet sorghum juice. The considered stages of the process are milling of the stalks, juice clarification and concentration (by evaporation), alcoholic fermentation, and subsequent distillation and dehydration. The bagasse, fibrous residue obtained after the juice extraction, is used as fuel for a biomass boiler, generating heat and power for the self-sufficiency of the mill. No production of surplus electrical energy is considered. The resulting ashes from bagasse combustion and the filter cake (residue from the juice clarification process with a high organic and inorganic matter content) are disposed of in the field. The clarified juice is concentrated by evaporation to a concentrated juice of 65% weight of solids. It is then diluted in water, and the necessary nutrients, urea and phosphoric acid (sources of N and P), are added so that the yeast (*Saccharomyces cerevisiae*) ferments sugars into ethanol and CO_2 in open-air fermenters. A two-column system is used for the distillation stage: a distilling and a rectifying one. The ethanol 96% vol produced by distillation is dehydrated through molecular sieves to obtain fuel-grade anhydrous ethanol (purity greater than 99.6%). All the anhydrous alcohols are devoted to fuel use. Vinasses, the main liquid residue of the distillation process, are disposed of in the field as a source of nutrients and soil amendment. Pumping, transportation, and dilution of vinasses for its application in the field have been included in the study. Industrial processing takes place between April and May during 45 days at a sugar mill in Tucumán. The daily milling capacity is 8000 t of sweet sorghum.

2.2 Life cycle inventory analysis

The data used for the inventories were mostly collected directly from the field, mill, and distillery, through in situ measurements, interviews with experts, and also with researchers from Estación Experimental Agroindustrial Obispo Colombres (EEAOC), a public institution devoted to regional agroindustry research. Primary data provided by field experiences carried out by the authors during 2016/2017 were prioritized. Data from the industrial stage were adjusted through laboratory analysis and mass and energy balances. This information was used, for instance, to estimate GHG emissions in the mill's boilers. The system boundaries include the impact associated with the production of all necessary inputs (e.g., agrochemicals and fuel). Secondary data comes from various sources: interviews with experts and specific publications and international datasets such as Ecoinvent v3 (Swiss Center for Life Cycle Inventories 2015), from which similar processes were adapted when local information was not available.

Data of inputs and outputs of the FIELD and INDUSTRY subsystems are included in Tables 1 and 2, respectively. It is important to note that the FIELD subsystem is a multifunctional system (millable sweet sorghum stalks and HR). Therefore, a mass criterion for the allocation of the environmental loads of each product is adopted (Table 1), resulting in allocation factors of 70.6% for sweet sorghum stems and 29.3% for HR. Regarding the CO_2 intake by the crop and the energy accumulated in the biomass (based on its lower calorific value), they are taken from Jungbluth et al. (2007). The air emissions include those due to the complete combustion of fossil diesel taken from Ecoinvent v3. The European guidelines for emissions distribution of pesticides to environmental compartments (90% to the agricultural soil, 9% to air, and 1% to water) (EC 2018) are used. The emission factors for these compounds are estimated considering specific chemical properties (AERU 2022), environmental conditions, and agricultural practices (Dijkman et al. 2012; Franke et al. 2013).

In the INDUSTRY subsystem, emissions into the air (CO_2, CO, NO, SO_2, and particulate matter) resulting from the combustion of sorghum bagasse at the chimney outlet are calculated from their elemental composition of carbon, nitrogen, and sulfur. It is assumed that none of the gasses is retained by the water in the scrubbers. The emissions produced in the fermentation stage (CO_2 and ethanol) are determined through material balances. The components of the untreated vinasses disposed of in the field are considered as emissions to the soil.

Table 1 Inventory for the FIELD subsystem (reference flow: 1 t sorghum)

Inputs	Unit	Value	Outputs	Unit	Value		Unit	Value
From nature			***Products***			***Emissions to water***		
CO_2	t	0.86	Sweet sorghum stalks	t	1	Suspended solids	kg	0.040
Energy	MJ	9256.76	Harvest residues (HR)	t	0.42	Chemical oxygen demand	kg	0.034
Rainwater	m^3	214.86				Biological oxygen demand (BOD_5)	kg	0.034
Land occupation	$m^2 \cdot a$	111.07	***Emissions to air***[a]			Oils, unspecified	kg	0.013
			CO_2, fossil	kg	10.744	Carboxylic acids, unspecified	kg	$9.0 \cdot 10^{-4}$
From the technosphere			Nitrogen oxides	kg	0.106	Hydrocarbons, aromatic	kg	$1.1 \cdot 10^{-4}$
Agrochemicals			Carbon monoxide, fossil	kg	0.023	Glyphosate	kg	$4.2 \cdot 10^{-4}$
Glyphosate	kg	0.081	SO_2	kg	0.023	2,4-D	kg	$2.5 \cdot 10^{-4}$
2,4-D	kg	0.032	Particulates, < 2.5 um	kg	0.014	Atrazine	kg	$9.9 \cdot 10^{-4}$
Atrazine	kg	0.101	Particulates, > 10 um	kg	$5.42 \cdot 10^{-4}$	Metolachlor	kg	$2.8 \cdot 10^{-4}$
Metolachlor	kg	0.029	Particulates, > 2.5 um and < 10 um	kg	$1.75 \cdot 10^{-4}$	Chlorpyrifos	kg	$1.1 \cdot 10^{-4}$
Adjuvant	kg	$1.7 \cdot 10^{-3}$	Methane, fossil	kg	0.011	Thiodicarb	kg	$2.0 \cdot 10^{-4}$
Chlorpyrifos	kg	0.013	Non-methane volatile organics	kg	$8.50 \cdot 10^{-3}$			
Vegetable oil	kg	0.031	N_2O	kg	$4.50 \cdot 10^{-4}$	***Emissions to soil***		
Alphamethrin	kg	$8.0 \cdot 10^{-4}$	Pentane	kg	$2.16 \cdot 10^{-4}$	Oils, unspecified	kg	0.014
Thiodicarb	kg	$4.1 \cdot 10^{-3}$	Propane	kg	$1.75 \cdot 10^{-4}$	Zinc	kg	$1.7 \cdot 10^{-3}$
Ethoxylated fatty alcohol	kg	$4.0 \cdot 10^{-4}$	Butane	kg	$1.74 \cdot 10^{-4}$	Iron	kg	$2.3 \cdot 10^{-4}$
Water	kg	0.153	Atrazine	kg	$8.94 \cdot 10^{-4}$	Aluminum	kg	$1.1 \cdot 10^{-4}$
			Glyphosate	kg	$3.8 \cdot 10^{-3}$	Glyphosate	kg	0.038
Diesel			2,4-D	kg	$2.2 \cdot 10^{-3}$	2,4-D	kg	0,022
Agricultural operations	L	3,928	Metolachlor	kg	$2.6 \cdot 10^{-3}$	Atrazine	kg	0,089
Inputs transport	L	$7.9 \cdot 10^{-3}$	Chlorpyrifos	kg	$1.0 \cdot 10^{-3}$	Metolachlor	kg	0,026
Sorghum transport to the mill	L	0,405	Thiodicarb	kg	$1.8 \cdot 10^{-4}$	Chlorpyrifos	kg	0,010
			Alphamethrin	kg	$3{,}8 \cdot 10^{-5}$	Thiodicarb	kg	$1.8 \cdot 10^{-3}$
Use of agricultural machinery						Alphamethrin	kg	$3.8 \cdot 10^{-4}$
Sowing	ha	0,034						
Agrochemical application	ha	0,034						
Harvest	ha	0,034						

Only values greater than $1 \cdot 10^{-4}$ kg are shown

[a] For diesel combustion, emissions are taken from Ecoinvent v3 (diesel, burned in agricultural machinery, market for diesel)

3 Results and discussion

3.1 Life cycle environmental impact assessment

The life cycle impact assessment method selected for this study is the ReCiPe 2016 model (Huijbregts et al. 2017). For impact evaluation, 14 impact categories taken from the ReCiPe Midpoint model are used. Moreover, global normalization factors from ReCiPe are used to normalize the midpoint characterization results, considering 2010 as the reference year. SimaPro® v9 Main emissions in(PRéSustainability 2020) is used as a software tool to carry out life cycle modeling and calculations.

3.2 Midpoint indicators

Figure 2 shows the composition of the environmental impact associated with the production of 1 t of sweet sorghum-based bioethanol in Tucumán (Argentina). The abscissa axis shows 14 impact categories selected from the ReCiPe 2016 Midpoint model. In the ordinate axis, the contribution of the involved processes to each category is expressed as a percentage. Different colors represent the different processes that directly take place in the production of anhydrous ethanol: feedstock (sweet sorghum) production, inputs production (lime, phosphoric acid, sulfuric acid, urea, lubricants), and the production of ethanol itself.

Table 2 Inventory for the INDUSTRY subsystem (reference flow: 1 t of sorghum bioethanol)

INPUTS	Unit	Value	OUTPUTS	Unit	Value
Raw materials			***Products***		
Sweet sorghum stalks	t	13.8	Bioethanol	t	1
From the technosphere			***Emissions to air***[a]		
$Ca(OH)_2$ (lime)	t	0.01	*Boiler*		
Lubricants (oils)	t	$3.1 \cdot 10^{-4}$	CO_2	t	2.665
Urea	t	$6.8 \cdot 10^{-4}$	CO	t	$4.0 \cdot 10^{-3}$
Sulfuric acid 96%	t	0.026	NO	t	$1.8 \cdot 10^{-4}$
Phosphoric acid 85%	t	$3.9 \cdot 10^{-4}$	SO_2	t	$3.0 \cdot 10^{-4}$
			Particulate matter >2,5µm, <10µm	t	$3.0 \cdot 10^{-3}$
			Fermentation		
			CO_2	t	0.957
			Ethanol	t	$6.0 \cdot 10^{-3}$
			Emissions to water[b]		
			Scrubber		
			DBO_5	t	0.036
			Total solids	t	0.036
			Calcium	t	$1.7 \cdot 10^{-3}$
			Magnesium	t	$5.0 \cdot 10^{-4}$
			Sodium	t	$5.0 \cdot 10^{-4}$
			Potassium	t	$1.0 \cdot 10^{-4}$
			Particulated matter (< 10µm)	t	0.072
			Emissions to soil[c]		
			Phosphorus	t	$5.2 \cdot 10^{-4}$
			Calcium	t	0.011
			Magnesium	t	$2.6 \cdot 10^{-3}$
			Sodium	t	$2.0 \cdot 10^{-3}$
			Potassium	t	$1.1 \cdot 10^{-4}$
			Nitrate	t	$1.0 \cdot 10^{-4}$

[a] Bagasse combustion: computed from local measurements. Fermentation: mass balances

[b] Substances contained in the water leaving the scrubbers for bagasse flue gas washing

[c] Calculated from the components of the untreated vinasses

The environmental contribution of sweet sorghum production prevails in all categories. If analyzed in detail, this is caused mainly by the use of agrochemicals (herbicides and insecticides) and the fossil fuel used as part of the crop management system (Fig. 3). The largest contributions of the FIELD subsystem are observed in the following categories: land occupation (LO), freshwater ecotoxicity (FET), and human toxicity (non-cancer) (HTnc) with almost 100%, followed by ozone layer depletion (OD), terrestrial ecotoxicity (TE), and global warming (GW), with 96%, 93%, and 91%, respectively. In GW, GHG emissions account for 172 kg of CO_2eq/t of ethanol, of which 156 kg CO_2eq/t comes from sorghum production in the field.

The intrinsic impact of ethanol production in the distillery is evident in the following categories: eutrophication of fresh water (FE), formation of photochemical oxidants at the ecosystem level (EPOF), formation of photochemical oxidants at the human health level (HPOF), terrestrial acidification (TA), and particle formation (PMF), with a contribution of 80%, 49%, 40%, 30%, and 20%, respectively (Fig. 2). In all of them, the main cause is the emission of NO from the combustion of bagasse in boilers. The evaporation of ethanol in the open-air fermentation tanks also contributes to EPOF and HPOF. FE is determined by the phosphorus content from the disposal of vinasses in soils and in TA and PMF due to the emission of SO_2 and NO during the combustion of bagasse. It should be noted that this study does not reflect with full certainty the environmental impact produced by fertigation with vinasses (as this impact is not evaluated through field trials), an aspect that should be specifically addressed to obtain a complete picture of bioethanol sustainability. Different studies refer to sorghum vinasse treatment, use, and impacts, but they are too case dependent on being included with sufficient certainty in our study. For example, Mijangos-Cortés et al. (2014) studied the use of sweet sorghum raw and treated vinasse (with and without dilution)

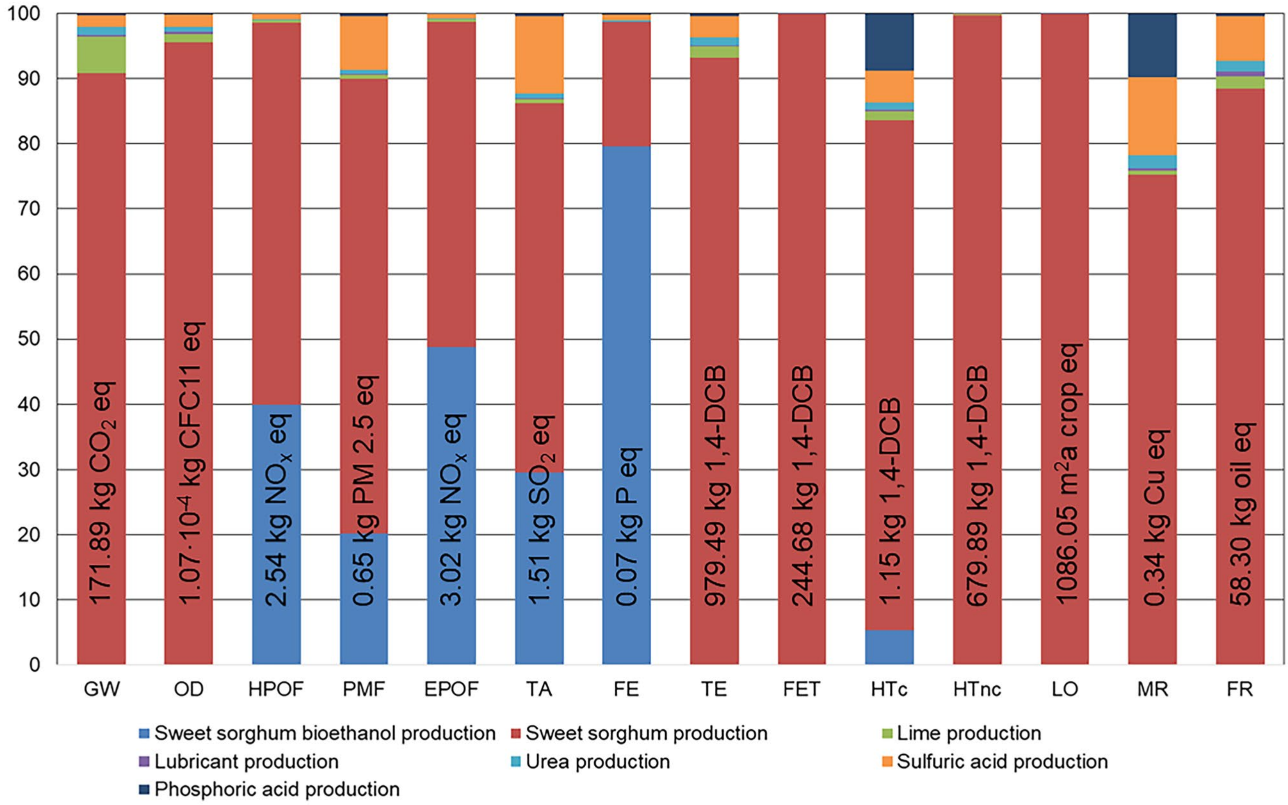


Fig. 2 Environmental profile of sweet sorghum bioethanol referred to 1 t of biofuel (characterization). Values on the *Y*-axis are percentages. Numbers within each column are the absolute value of the impact. On *X*-axis: global warming (GW), ozone depletion (OD), photochemical oxidant formation (human health) (HPOF), fine particulate matter formation (PMF), photochemical oxidant formation (ecosystem quality) (EPOF), terrestrial acidification (TA), freshwater eutrophication (FE), terrestrial ecotoxicity (TE), freshwater ecotoxicity (FET), human toxicity (cancer) (HTc), human toxicity (non-cancer) (HTnc), land occupation (LO), mineral resource scarcity (MR), fossil resource scarcity (FR)

for fertigation during sorghum growing at a lab scale. Raw vinasse was deleterious for germination, while treated vinasse allowed a normal physiological behavior of plants. They claim that treated vinasses retain nitrogen, potassium, and organic matter to healthy levels for the soil. Reinhardt et al. (2014) noted that the fertigation with sorghum vinasse decreases the aquatic eutrophication impact by reducing N fertilizer doses. In this vein, Sotomayor et al. (2018) referred to sugarcane vinasses from Tucumán, which have a certain similarity with those of sorghum. They studied the disposal of sugarcane raw vinasses soils. A pH increase in soil layers and some soil salinity (K^+) was registered. No change was observed in physical properties of the soil. Oliveira Filho et al. (2021) have partial coincidence with the previous study, concluding that vinasses application in the sugarcane production system does not improve soil fertility (lower pH and availability of cationic nutrients), but it has a positive effect on the increase in K^+ availability. Based on these studies, we believe that there could be an improvement in yield and in some impact categories such as freshwater eutrophication, but the burden shifting toward other categories such as water use or fossil resources depletion and global warming should be carefully evaluated.

For their part, Morrissey et al. (2021), using another impact assessment method (TRACI), report that the largest contributors to GW are the industrial stage (35%) due to the use of additional natural gas for heating processes and electricity. That is, sorghum bagasse is not used as fuel in boilers to generate heat and electricity for self-consumption. This is different from our self-sustained industrial process. They also report a contribution of 15% from fossil fuels during the agricultural stage. In the same study, the impact of eutrophication resulted in 78%, caused by sweet sorghum production. (Note that the TRACI method combines marine and freshwater eutrophication in a single impact.)

Other processes that contribute to the environmental impact to a lesser extent are the production of lime (calcium hydroxide), sulfuric acid, phosphoric acid, urea, and lubricants, all consumed in the ethanol production stage. Emissions originated by sulfuric acid production stand out, especially in the following categories: depletion of mineral resources (MR, 12%), TA (12%), and PMF (8%). The

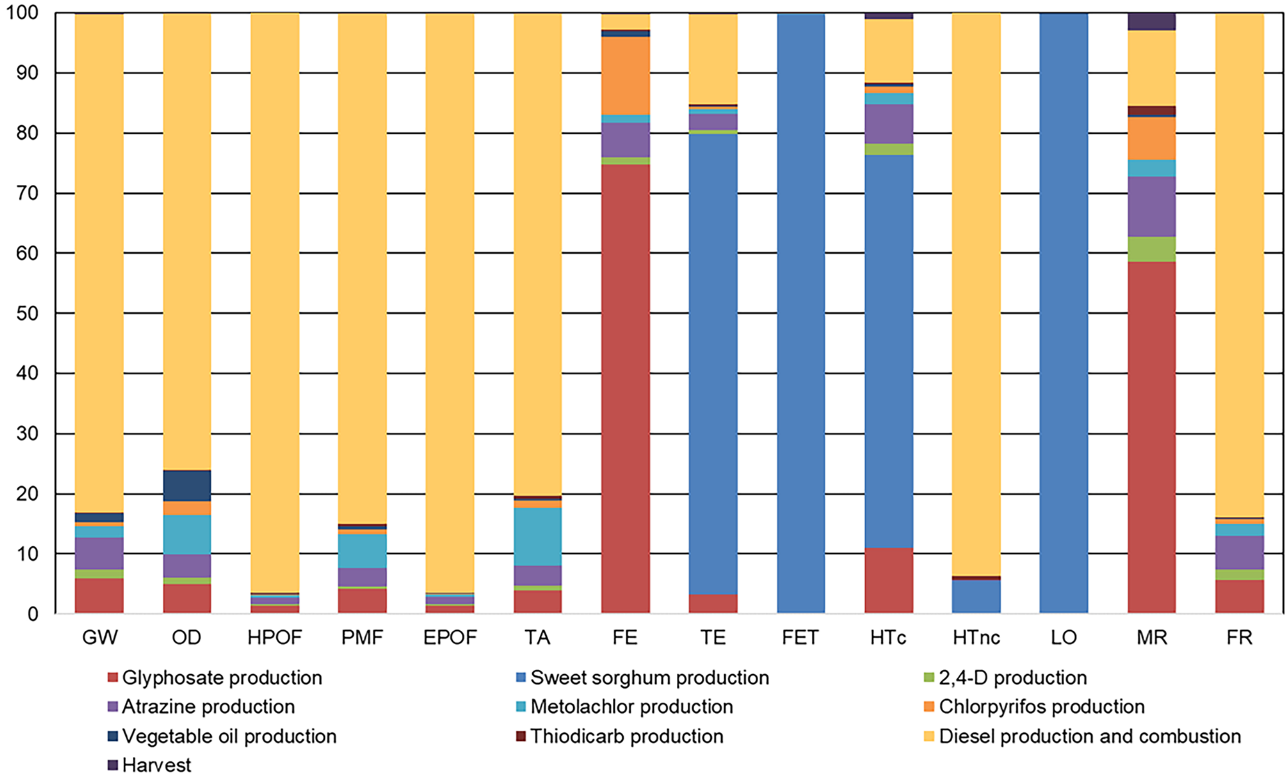


Fig. 3 Environmental profile of sweet sorghum production (FIELD subsystem). Values on the *Y*-axis are percentages. On *X*-axis: global warming (GW), ozone depletion (OD), photochemical oxidant formation – human health (HPOF), fine particulate matter formation (PMF), photochemical oxidant formation – ecosystem quality (EPOF), terrestrial acidification (TA), freshwater eutrophication (FE), terrestrial ecotoxicity (TE), freshwater ecotoxicity (FET), human toxicity (cancer) (HTc), human toxicity (non-cancer) (HTnc), land occupation (LO), mineral resource scarcity (MR), fossil resource depletion (FR)

impact of phosphoric acid production is notable mainly in MR and human toxicity (carcinogenic) (HTc) with a contribution of 10% and 9%, respectively. The main contribution of the lime manufacturing process is to GW (6%), and the main contribution of urea production is to MR (2%). The impact of the production of lubricants is negligible—less than 1%—in all impact categories.

Aguilar-Sánchez et al. (2018) analyze several scenarios, one of which is similar to the one evaluated in this study. By using CML 2 baseline 2000 methodology, this scenario has lower impacts in all categories except for eutrophication and terrestrial ecotoxicity due to the production of surplus electricity to be sold to the public network. This energy production allows for decreasing the impacts through burden allocation.

Figure 3 shows the contribution to the environmental impact categories restricted to sweet sorghum production (FIELD subsystem). Emissions due to diesel production and combustion dominate in all categories, markedly in HPOF (96%), EPOF (96%), HTnc (94%), PMF (85%), fossil resources depletion (FR, 84%), GW (83%), TA (80%), and OD (76%), with less than 15% in the remaining categories. Other processes that have to be noted in this environmental profile are herbicides and insecticides production. Glyphosate production has an important share in MR and FE as this process consumes mineral resources (phosphorus rock) as release nutrients (N and P) to the water bodies. Production of atrazine is relevant in MR and HTc, and metolachlor in TA and OD. Regarding insecticides, the production of chlorpyrifos, as in the case of glyphosate, predominates in FE and MR. The contribution of alphamethrin is negligible in all impact categories. Agrochemical application, sowing, and harvesting operations (infrastructure) have a small contribution, particularly in MR and HTc.

The direct impacts of the FIELD subsystem, i.e., those that are not inherited from other processes associated with the FIELD subsystem but are produced by its own emissions and direct resources use, are observed mainly in FET, LU, HTc, TE, and GW impact categories. They have a contribution of 100%, 100%, 83%, 76%, and 68%, respectively, followed by TA and PMF. Figure 4 shows the main emissions that contribute to two selected categories: FET and GW. In FET, the impact is dominated by the presumed leaching of the insecticide chlorpyrifos

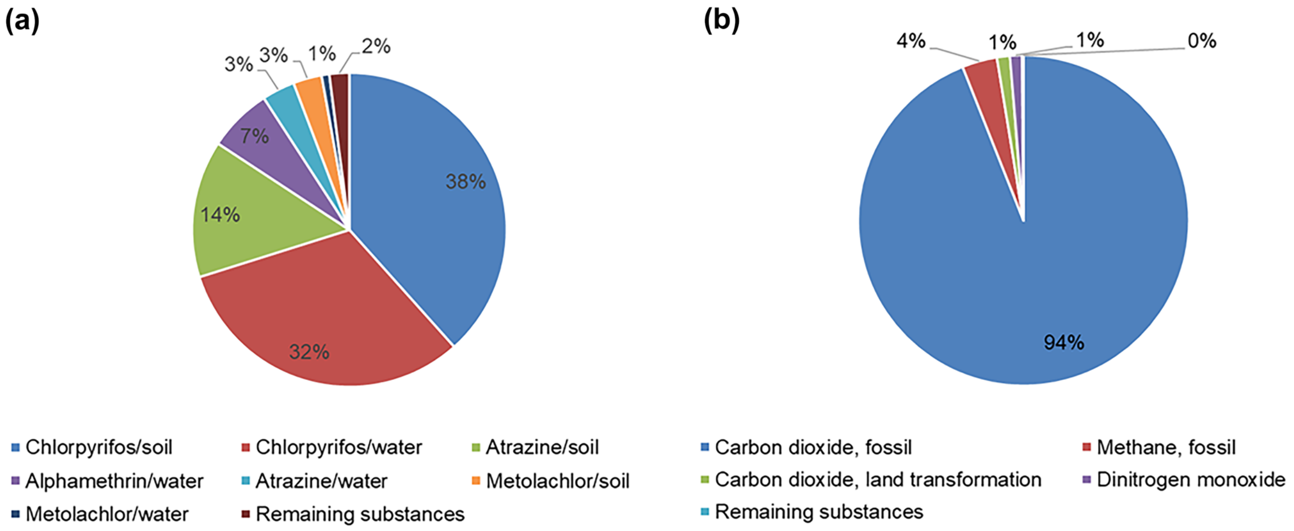


Fig. 4 Main emissions in (**a**) FET and (**b**) GW categories for the FIELD subsystem

(70%), followed by atrazine (17%) and alphamethrin (7%). GHG emissions in GW are determined by fossil CO_2 generated by the combustion of fossil fuels (94%), as in other reported studies (Morrissey et al. 2021).

Figure 5 shows the results of the impact normalization for sweet sorghum-based bioethanol. The *Y*-axis is dimensionless. As seen in Fig. 5a, the highest environmental impact score corresponds to FET. It could be traced that sweet sorghum production (99%) contributes to this category as a result of the herbicides application (atrazine and metolachlor) and the use of chlorpyrifos, an organophosphate insecticide widely used in agriculture. Figure 5b shows those categories that cannot be perceived in Fig. 5a, given the high value of FET. As can be seen, HTnc is remarkable due to the production and combustion of diesel used in sorghum cropping. The particular impact of bioethanol production is notable mainly in the categories TE and HTc, with 0.945 and 0.415, respectively. For Braconnier et al. (2014) and Wang et al. (2014), the category with the greatest impact is eutrophication. This obeys to the use of large amounts of agrochemicals, mainly fertilizers, to obtain high crop yields. In the present work, instead, sorghum is grown without fertilizers, thus producing a high amount of carbohydrates with low input requirements (Romero et al. 2012). Therefore, the dominance of FE is not noticed.

In line with our findings, some studies (Aguilar-Sánchez et al. 2018; Olukoya et al. 2015) claim that sweet sorghum cropping is responsible for the highest emissions in the cultivation stage due to the production and use of agricultural wtation of sweet sorghum from the field to the biofuel production plant.

3.3 Sensitivity analysis

Driven by the results in Fig. 5, a parametric sensitivity analysis was performed to assess the influence of a variation in the emission factors of pesticides on to the FET category.

The emission factors used for the study are estimated from various sources (Franke et al. 2013; EC 2018). Figure 6 shows the results in the FET category (for the FIELD subsystem) after applying variations on the mentioned factors for all the pesticides (glyphosate, 2,4-D, atrazine, metolachlor, chlorpyrifos, thiodicarb, and alphamethrin) released to all three compartments (air, soil, and water). A 9.6% decrease is observed in the category when the original factor is reduced by 10%, and by 19.8% when the reduction is 20%. This remarkable influence on the FET is given by the great contribution of sweet sorghum cropping itself. A sensitivity $S=1$ is obtained, which indicates a linear correlation between the emission factors and the environmental impact analyzed.

Having discovered chlorpyrifos (organophosphate thioate of recognized toxicity) as the most influential of the pesticides in this category, the sensitivity analysis is repeated by varying only the chlorpyrifos emission factor to the three environmental compartments. Table 3 shows the values taken into account for the study, and Fig. 6 includes these results. The sensitivity of FET against the emission factor of chlorpyrifos is $S=0.71$.

No particular analysis has been found in the literature regarding agrochemical emission factors for this system. In Wang et al. (2014), an uncertainty analysis of the data used and of the process conditions regarding energy efficiency and environmental impact scores was carried out. Aguilar-Sánchez et al. (2018) performed a sensitivity analysis of

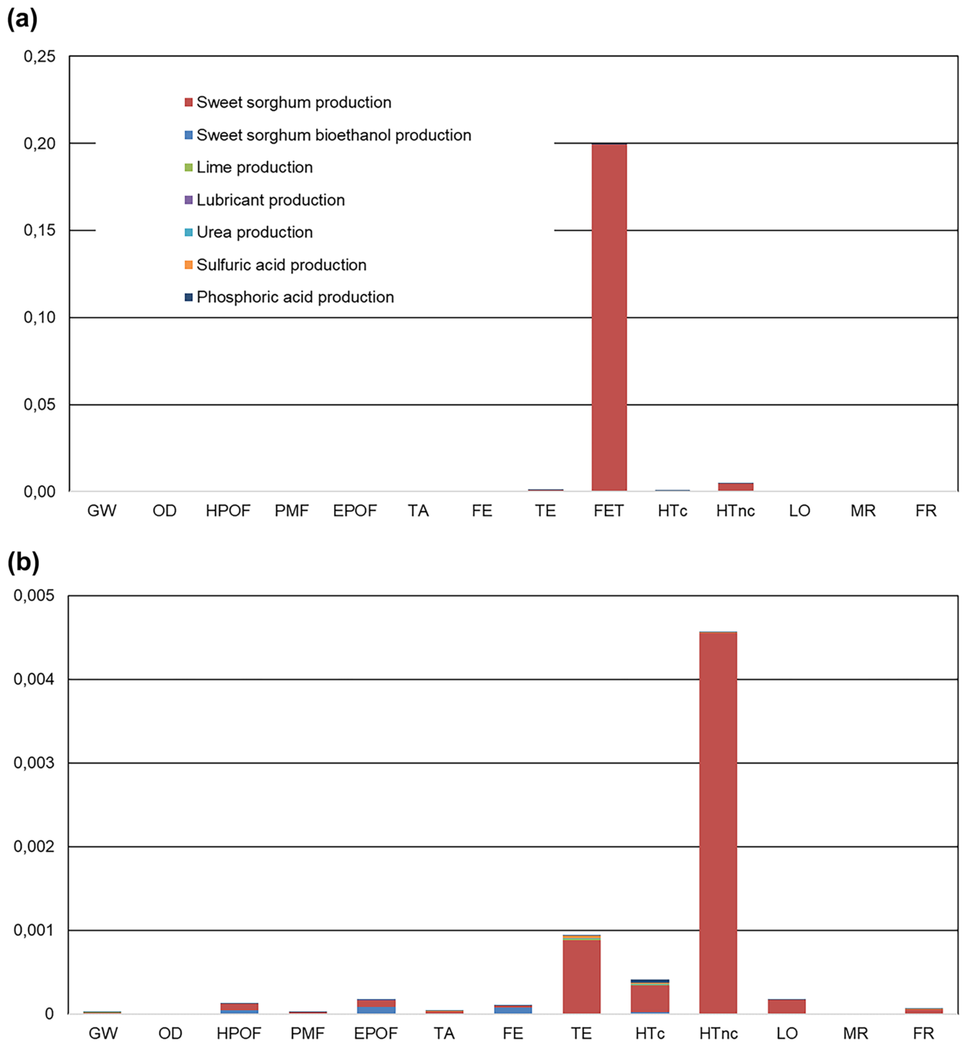


Fig. 5 **a** Environmental profile of 1 kg of sweet sorghum-based bioethanol (normalization). **b** Environmental profile of 1 kg sweet sorghum-based bioethanol (normalization) excluding the FET category. On *X*-axis: global warming (GW), ozone depletion (OD), photochemical oxidant formation – human health (HPOF), fine particulate matter formation (PMF), photochemical oxidant formation – ecosystem quality (EPOF), terrestrial acidification (TA), freshwater eutrophication (FE), terrestrial ecotoxicity (TE), freshwater ecotoxicity (FET), human toxicity (cancer) (HTc), human toxicity (non-cancer) (HTnc), land occupation (LO), mineral resource scarcity (MR), fossil resource depletion (FR)

sweet sorghum impacts under crop yield variations and conclude that the relationship is not linear. Most results found in published research for a similar system to the one presented here are not comparable since they use different impact assessment methods, sources for data, and system boundaries. Furthermore, the choice of the impact evaluation method, as well as the level of the analysis (midpoint vs. endpoint), is invariably a limitation and can lead to disparate results. A sensitivity study on this aspect is an important avenue to pursue for future work.

3.4 Sweet sorghum-sugarcane integration

As mentioned before, some authors claim for a good complementarity between sugarcane and sweet sorghum (Romero et al. 2012; Braconnier 2014), being the present study an opportunity to evaluate this assertion. The idea is to alternate sweet sorghum with other crops (e.g., soybean) in certain lands under edaphic limitations. By doing this, the sugarcane sector can expect to increase its ethanol production without any additional investment for new equipment, as the sorghum stalks are harvested and processed like sugarcane. In addition, sugarcane mills could extend the operating window of their facilities (Braconnier 2014; Mbothu Machandi 2021).

One way to roughly evaluate the benefit of integrated production of ethanol from sweet sorghum and sugarcane is to consider different percentages of the utilization of the sugarcane area during the summer by growing sorghum. Currently, the area cultivated with sugarcane in Tucumán is around 270,000 ha (Fandos et al. 2021).

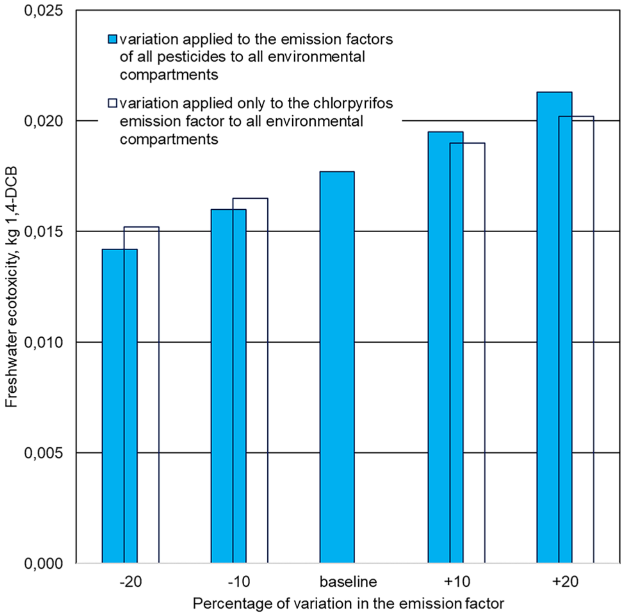


Fig. 6 Variation in freshwater ecotoxicity category, FIELD subsystem (characterization), when variations in the pesticide emission factors occur

The ethanol produced in the region has a GW of 2.75 kg CO_2eq/kg ethanol with a yield of 11.58 kg ethanol/t sugarcane and 75 t sugarcane/ha (Nishihara Hun et al. 2017). Taking into account that the GW obtained in this work is 0.17 kg CO_2eq/kg ethanol with a yield of 33.30 kg ethanol/t sorghum and 29.6 t sorghum/ha, the decrease in GW that could be attained by only cultivating 10% of the area occupied by sugarcane is 9.6%. Figure 7 illustrates the decrease in GW of ethanol for higher volumes of sorghum-based ethanol production. A more exhaustive evaluation that includes other impact categories is anticipated for future work in which a full harmonization of the sugarcane and sorghum systems is imperative.

Table 3 Emissions factors of chlorpyrifos (%, active ingredient)

	To water	To soil	To air
20% increase	1.0000	90.0000	10.0000
10% increase	0.9635	86.7117	8.6712
Baseline	0.8759	78.8288	7.8829
10% decrease	0.7883	70.9459	7.0946
20% decrease	0.7007	63.0630	6.3063

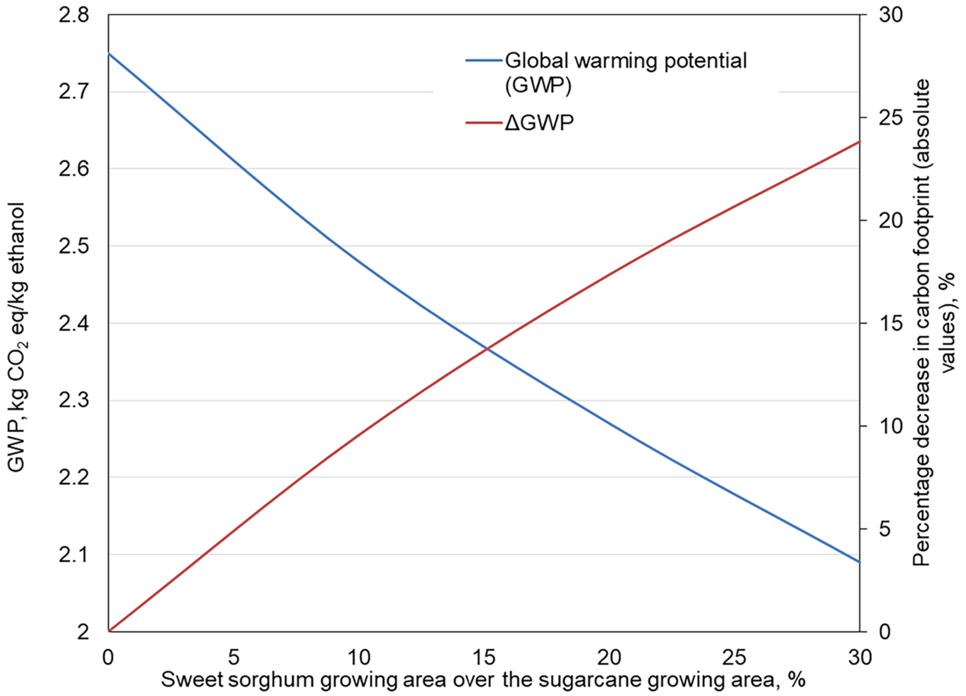
3.5 Other considerations

Even though this is a case study type of research, the particularities of the study can still be extrapolated to a vast area in the northwest of Argentina (NWA). A potential area of 92,000 ha could be planted with sweet sorghum in Tucumán and 145,000 ha in NWA. Previous studies show that sweet sorghum could be grown with soil limitations within the sugarcane planting area. It also has the potential to be adopted as a rotation crop in the soybean cropping system, a well-established crop in the region (Tonatto et al. 2019). In studies carried out in Tucumán, sweet sorghum was tested in lands that are usually underutilized. This means that there is no competition with sugarcane. Instead, complementary growth is foreseen. This is also related to the harvest season of crops: March to May for sorghum and May to October/November for sugarcane. An extended harvest season from a bioenergy standpoint could be generated with no competition for equipment and machinery. Another major beneficial impact of sweet sorghum adoption at a large scale is the contribution of alternative bioenergy sources, avoiding a local displacement of sugar into ethanol. This will allow, at least, a partial conciliation of the food vs. fuel dilemma.

Looking at agronomic management in detail, there is a notable difference between the proposed crop management (as suggested in Project "Biosorgo") and other cases reported internationally. The first one does not include the use of fertilizers for economic and environmental reasons, expecting a lower yield based on this management. The review paper by Zegada-Lizarazu and Monti (2012) reports contradictory results regarding fertilization where different N doses have insignificant differences in fermentable sugar production, and excessive N fertilization levels can reduce the juice quality and, thus, the ethanol yield. The Sweetfuel project considers a fertilizer dose calculated according to nutrient removal and losses, with higher inputs and emissions outweighed by higher outputs of bioethanol and excess power (Reinhardt et al. 2014). While this approach is correct, it is also true that an alternative to reduce GHG emissions is to reduce the use of fertilizers and the associated field emissions as well as other impact categories. This, in turn, will be in balance with a minor nutrient removal of the crop based on a lower yield.

In the end, crop management will have to be discussed at a local and site-specific level, considering advantages and disadvantages that will set the potential of the given crop in a given environment. We believe that our work provides valuable elements so that farmers and industries interested in this crop may enter into this discussion.

Fig. 7 Absolute and percentage decrease in the GW category (carbon footprint) of ethanol in Tucumán due to the increase in the area cultivated with sweet sorghum



4 Conclusion

The environmental profile of sorghum-based ethanol in Tucumán is presented for the first time. This profile enables us to conclude that the environmental contribution of crop growing predominates in all impact categories. The reason for this is the use of herbicides and insecticides, and fossil fuels in this stage. A more contextual impact assessment, at the normalization level, shows freshwater ecotoxicity as the most affected impact category caused by the application of herbicides (atrazine and metolachlor) and an organophosphate insecticide (chlorpyrifos). Results in freshwater ecotoxicity are very sensitive to changes in the emission factor of pesticides, particularly chlorpyrifos. This conclusion strengthens the idea of performing empirical determinations of emission factors to reduce the uncertainty of the results. Another uncertainty source to be addressed in future work is the detailed effect of vinasses and other residues that are recycled to the field.

Finally, inserting the production of sorghum ethanol within the sugarcane ethanol production is a sustainable alternative for the province that will increase production without substantially increasing the environmental impact. Thus, this study is a relevant advance in complementing the existing information about the impact of the sugarcane and alcohol industry in the region, which together constitutes the environmental footprint of bioethanol in the region.

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Data availability All data generated or analyzed during this study are included in this published article.

Declarations

Conflict of interest The authors declare no competing interests.

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