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Life cycle analysis of ethanol obtained from lignocellulosic biomass: A case study of a native perennial grass from Argentina

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ABSTRACT

The increasing concentrations of greenhouse gases (GHG) are the main cause of climate change. The scientific community agree that transition to renewable energies will play a key role as a mitigation strategy for this problem. In this work, an abundant biomass resource of central-eastern zone of Argentina is evaluated: rangelands of the Submeridional Lowlands dominated by *Spartina argentinensis* (espartillo). Bioethanol production from this species would not change the current land use; it has been assessed using a consequential Life Cycle Analysis (LCA) methodology. LCA was carried out with comparative objectives with the fuel to replace (gasoline). The functional unit was defined as "The production and use of 1 MJ of liquid fuel". Two impact categories were considered: (i) Climate Change and (ii) Energy Use through global warming potential and energy return on investment (EROI), respectively. Gasoline's GHG emissions were 96.9 g of CO_{2eq} per MJ while the bioethanol obtained from espartillo was carbon negative in most scenarios. The EROI of gasoline had a value of 0.7 while bioethanol presented a range of 0.7 to 1.8. This LCA was realized with a consequential approach except for the by-products of fermentation at the biorefinery which were not considered to be used for any activity due to not having real data of such by-product; hence the obtained figures could be improved if these by-products were able to replace another product. The energy self-sufficiency of the plant and the avoided fires in rangelands are key factors to improve the environmental performance of bioethanol.

1. Introduction

The global demand for energy has increased notably since the mid-19th century, following the Industrial Revolution, due to the growing consumption of fossil fuels, mainly coal, oil and natural gas. This caused level negative environmental impacts, such as the increase in concentration of greenhouse gases (GHG), which IPCC (2023) claims are the responsible for global warming.

Given the evident environmental impacts of fossil fuel consumption, there has been a growing recognition of the need for a transition to renewable energy sources. The transition to renewables aligns with international climate agreements, such as the Paris Agreement, which seeks to limit global warming to well below 2 degrees Celsius above pre-industrial levels. Achieving these climate targets necessitates a fundamental shift away from fossil fuels and toward sustainable, low-carbon energy sources (UNFCCC, 2015).

Among the various renewable energy options, biofuels have garnered considerable attention because they have the potential to offer cleaner and more sustainable alternatives to traditional fossil fuels (REN21, 2021). Commitments from several countries (Argentina among them) have been signed in 2021 within the framework of the conference of parties (COP26) held in Glasgow, in which the objective for 2050 is to reach the zero value of net carbon emissions, also defined as carbon neutrality (Lennan and Morgera, 2022).

The accomplishment of these commitments would imply emitting in one year the amount of carbon that the planet is capable of absorbing from the atmosphere in that period. Although these objectives are necessary to raise awareness among the population and commit to political decisions, the increasing trends in CO_2eq emissions in recent decades seem difficult to reverse by the year 2050.

Primary energy demand is above 600 EJ since 2019 with only 54 EJ provided by bioenergy (United Nations, 2022) and it is estimated that primary energy demand will rise to 800 EJ by 2050 (Ahmad and Zhang, 2020; Moriarty and Honnery, 2012). In a literature review, Popp et al. (2014) reported that by 2050 the potential for obtaining primary bioenergy will range between 50 and 1500 EJ.

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Based on this wide range, the authors propose 200 to 500 EJ as an achievable value for 2050 under sustainable production conditions. Even the most pessimistic scenario (200 EJ) is auspicious given that 25 % of the global demand for primary energy would be covered from bioenergy; In the optimistic scenario (500 EJ) bioenergy would cover more than 60 % of primary energy demand by 2050.

Biofuels whose raw materials are food sources called first generation biofuels. They are highly questioned since its utilization for energy production, could hinder their accessibility by a large sector of the world population. There is a consensus that utilizing food crops for energy production could potentially exacerbate issues related to global food security, limiting accessibility to essential food resources for a significant portion of the global population (Bahel et al., 2013; Lucotte, 2016; Paris, 2018).

The notable increases in the production of first-generation biofuels have generated great concern because the main sources of biomass used as raw materials are agricultural commodities such as corn and sugar cane for ethanol or rapeseed and soybean oil for biodiesel (Bracco, 2016). Rajagopal et al. (2007) make an ethical proposal when considering what would happen if all the production of wheat, corn, sorghum, sugar cane, among others, were used to produce bioethanol: less than 60 % of the energy consumed globally by the fuel to be replaced. These results revealed the infeasibility of mitigating climate change with first generation biofuels.

In response to the challenges posed by first-generation biofuels, the pursuit of second-generation biofuels has gained attention among the society and research community. These biofuels are derived from lignocellulosic materials, such as specific energy crops and C4 photosynthetic rangeland grasses (Sosa et al., 2019). The appeal of second-generation biofuels lies in their potential to address the food-fuel-environment trilemma while offering a sustainable and environmentally responsible energy source (Tilman et al., 2009).

Rangelands are one of the main land cover types of ice-free areas and are estimated to globally cover 18.5 million km^2 (Godde et al., 2020). In Argentina, the 2018 national agricultural census reported 0.71 million km^2 occupied by rangelands (INDEC, 2021), while Fernández and Busso (2017) claimed that only the area occupied by arid and semi-arid rangelands in Argentina would around 2 million km^2.

Livestock is the main productive activity in these ecosystems where fire is a common management practice every one to three years (Levine, 1991). Likewise, the removal by burning stimulates the regrowth of higher forage quality both in digestibility and in protein content (Massa et al., 2016). In Argentine, fire has been used in the last two decades to remove native woody and herbaceous biomass in order to facilitate the cultivation of crop and forage species (Cavallero et al., 2023). Livestock management operations are also facilitated by the fact that cattle usually group in recently burned areas (Sitters and Di Stefano, 2020).

Although GHG emitted by burning is biogenic, only the CO_2 emitted should not be accounted in the carbon balance, since its emissions are offset by carbon sequestration that occurs during the growth of burned vegetation. The rest of the GHG produced must be accounted in assessments of the “climate change” impact category (Harald Aalde et al., 2006).

Previous research evaluated how much power energy could be produced if the biomass burned annually were derived to power production employing available technologies (Verón et al., 2012). They found that an average of 8.3 ± 5.9 EJ per year during the 2003-2010 period was burned on a global scale which represented approximately 40 % of global electricity consumption. In the case of Argentina, the average electricity consumption could be met by burnt biomass if it could be derived to power production and a surplus of power could be obtained as well.

Spartina argentinensis Parodi (=*Sporobolus spartinus* (Trin.) P.M. Peterson & Saarela), is a perennial native grass, with C4 photosynthetic metabolism and is the dominant species in a wide region of about 30,000 km^2 in central Argentina, named “Bajos Submeridionales” (“Submeridional Lowlands”). Its low forage aptitude and the difficulty of replacing it by other species, determines that cattle production has low productivity. The responses of *S. argentinensis* to disturbances such as fire and harvest have been well studied from an ecological point of view (Feldman and Lewis, 2005).

Life Cycle Assessment (LCA) is an impact assessment tool, globally recognized and increasingly used in recent years, and is considered the main methodology to objectively evaluate the environmental impacts associated with a product-system. An LCA analyses the environmental aspects and potential impacts throughout the life cycle of a product or activity, considering all the consecutive and interrelated stages from the acquisition of raw materials or their generation from natural resources, through the processing and production of the product, its distribution, use and finally its final disposal or end of life. When all these stages are considered, it is considered to be a “cradle to grave” LCA (de Bruijn et al., 2002).

The LCA allows determining the environmental profile of a product, service, process or activity, allowing the comparison between products or technologies that fulfil the same function, determining which is the most benign from an environmental point of view. The complexity of said analysis requires a protocol to which all LCA studies must comply: the standards set by the International Organization for Standardization (ISO, 2006a, 2006b).

The impacts of cutting and removing *S. argentinensis* biomass on soil carbon, arthropod, and vegetation communities was analysed concluding that it did not produce significant changes between the control treatments without cutting and removal regardless of the harvests frequency (Sosa et al., 2019). Jozami et al. (2022) analyzed the production of i) electricity from gasification and; ii) residential heat through the combustion of pellets from *S. argentinensis*.

Other authors have evaluated the possibilities of obtaining second generation bioenergy from grasslands of different species in general (Bourke et al., 2013; Ferchaud et al., 2016; Jakob et al., 2009; Pugesgaard et al., 2014), and from *S. argentinensis* related species such as *S. alterniflora* and *S. pectinata* in particular (Araujo et al., 2019; Dong et al., 2007; Friesen et al., 2015; Guo et al., 2015; Li and Qiu, 2011; Sosa et al., 2019).

Against this backdrop, this study takes a closer look at the potential for second-generation bioethanol production from native grasslands, with a particular focus on the *Spartina argentinensis* species. These grasslands, occupying substantial areas in Argentina, represent a promising bioenergy resource. Its bioenergetic exploitation would promote work and services within this region.

The objective of this work was to evaluate the global warming potential, the cumulative energy demand (CED) and the Energy Return on Investments (EROI) of obtaining and using energy from native grasslands using as model systems the communities of *S. argentinensis* to produce bioethanol. We aim to introduce a novel approach to ethanol production using lignocellulosic biomass from a native perennial grass in Argentina and to assess its environmental impacts.

By doing so, this study contributes to our understanding of the feasibility of harnessing native grasslands for clean energy production, shedding light on the broader implications for addressing climate change and meeting energy demands in an environmentally responsible manner. This research addresses a significant gap in the literature by conducting the first LCA for *S. argentinensis* as a source of bioethanol, making it a novel contribution to the field.

2. Materials and methods

The bioenergetic system was modelled using primary information when it was available and bibliographic data for those processes for which own data could not be obtained. The data for the inventory were processed using Microsoft Excel and the software (Faculty License) SimaPro 9.0.0.35 (PRé sustainability B.V., 2019). The life cycle assessment was completed following the ISO 14040 and 14044 standards (ISO, 2006c, 2006b). The LCA was carried out with a cradle to the grave and consequential perspective, that is, from the extraction of the raw material to the final disposal of the product. The environmental loads of the co-products of each system were accounted by expanding the system, thus avoided products and process emissions were subtracted from the assessed system emission (Fig. 1).

Considering that the driving force of bioenergies is climate change mitigation and energy security, the following impact categories were assessed: (i) climate change, using global warming potential (GWP) with a 100-year time horizon as indicator (Goedkoop et al., 2009), and (ii) energy use with CED LHV (Pré Consultants) and EROI as indicators.

A Sankey diagram was done using "The Sankey Diagram Generator" website from primary energy in field to the FU employing the biorefinery data of Luo et al. (2009).

The objective of the system was to produce energy for vehicular transport so the functional unit (FU) was defines as follow: to produce 1 MJ of liquid vehicular fuel including its combustion. This FU allows the comparison of the bioenergetic fuel with the conventional fossil fuel to replace. The actual scenario was modelled by editing the following dataset obtained from ecoinvent in Simapro: "Transport, passenger car, medium size, petrol, EURO 5 {RER}| transport, passenger car, medium size, petrol, EURO 5 | Conseq, U" due to the fact that there are not available gasoline dataset in Argentina. Road and Car processes were erased for the edited proccess. The product system can be seen in Fig. 1. A yield of 241 L ethanol Mg^{-1} of dry matter was considered, which represents 60 % of the potential yield (Jozami et al., 2013).

The industrial stage data were adapted based on bibliography citations (Jungbluth et al., 2007; Kumar and Murthy, 2012; Luo et al., 2009). It was only considered for the reference of Luo et al., (2009) to use the solid waste from the biorefinery for producing the electricity and heat required by the industrial stage, since the inventory is clearly presented in that publication.

The biorefinery dataset of Jungbluth et al. (2007), is a consequential analysis that considers the production of ethanol, and two avoided products: fibres and proteins obtained from the solid waste of grass bioethanol production. It does not propose the use of self-sufficient energy for the fermentation plant. However, we have not considered these avoided products as the fermentation of *S. argentinensis* has not been accomplished at a pilot scale, so the solid waste could not be analysed. Although Kumar and Murthy (2012) do propose the use of co-produced electrical and thermal energy, these co-products were not considered for that case because they were not clearly detailed in that publication.

The inventory is detailed in Table 1 using Luo et al. (2009) biorefinery data. All the diesel required at field for anthill rupture, grass mowing, hay raking, and haying was measured and transformed to the following dataset from ecoinvent "dataset Machine operation - diesel - ≥ 18.64 kw and < 74.57 kw - high load factor" (Wernet et al., 2016). The value in hours for each field labour was calculated to consume an equivalent quantity of diesel measured at field.

The environmental burden of avoided processes (electricity injected to grid and rangeland burning) are detailed in table 2. The emission factors considered for burning of savanna and grasslands are those reported in (IPCC, 2006).

3. Results and discussion

3.1. Energy flow

Fig. 2 depicts the energy flow from primary energy at farm to final energy in bioethanol. Only 29 % of energy in biomass (bales at field) is stored in the obtained energy carrier (bioethanol). Even though the solid wastes met the industrial requirements, an important quantity of surplus energy could still be used which is shown in red colour in the Sankey diagram. If this energy were used to produce power and or heat, CED,

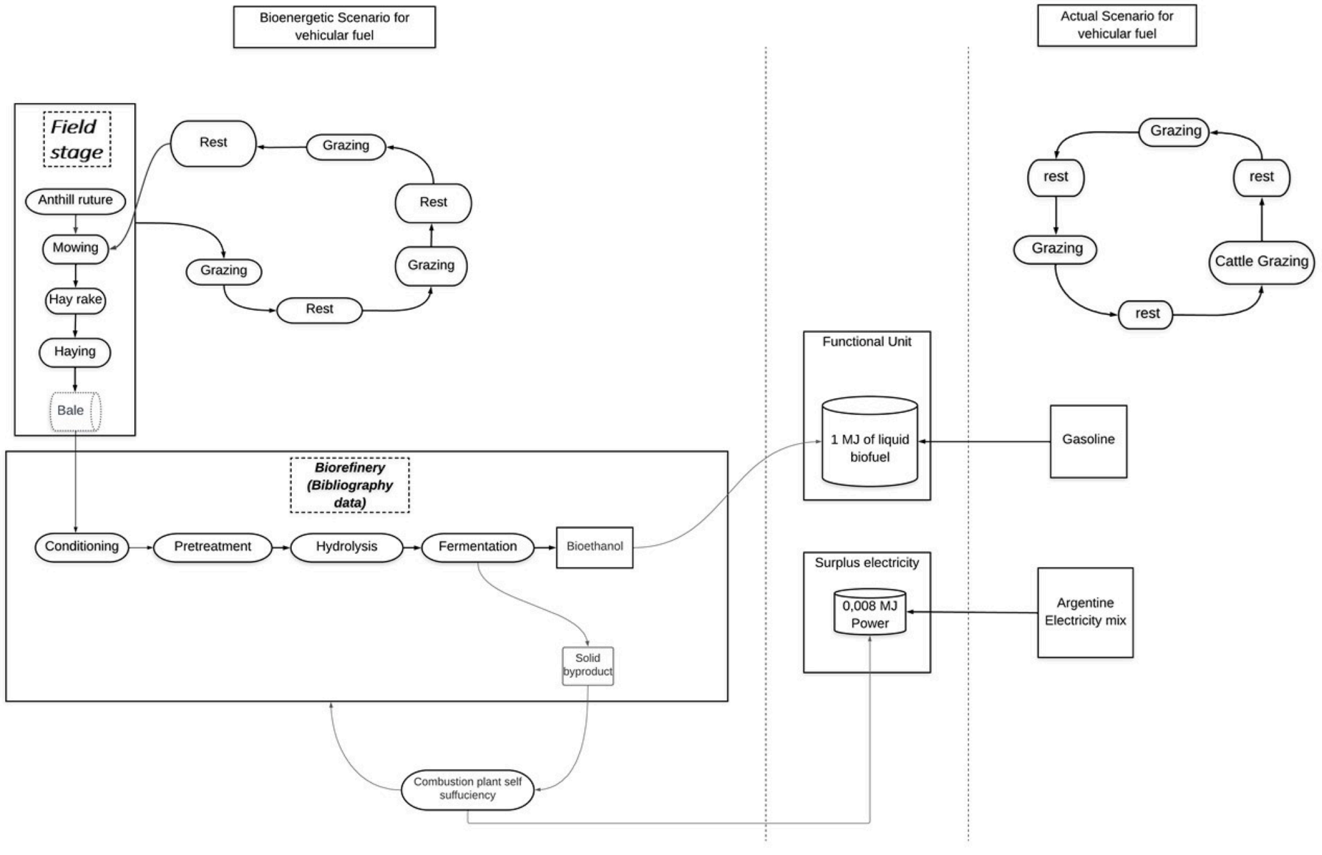

Fig. 1. Limits of the unit system comparing bioenergetic with the current system for the production of liquid fuel gasoline for transportation

Table 1
Inventory of the processes considered in the bioethanol system

Functional Unit	Stage	Reference flow	Process	Value	Unit	Reference
To produce 1 MJ of liquid vehicular fuel including its combustion	8.87E-5 (Mg of Bales)	2,27E-04	Loading and unloading of bales	1.4	Bales	(Wernet *et al.*, 2016)
			Machine operation - diesel - ≥ 18.64 kw and < 74.57 kw - high load factor	0.4	Hours	(Primary data equivalent to the dataset of Wernet *et al.*, 2016)
			Land occupation	2669.5	m^2	Primary data
			Bales transport (30 km)	33.3	Tkm	(Blonk Agri Footprint BV, 2015a, 2015b)
	Industrial (Kg of Bioethanol)	3,72E-02	Biomass handling (Electricity)	285.5	KJ	Luo et al (2009)
			Pretreatment (Sulfuric Acid)	0.1	kg	
			Pretreatment (Lime)	0.1	kg	
			Pretreatment (Electricity)	252.2	KJ	
			Pretreatment (Heat)	5327.2	KJ	
			Enzyme production	0.28	kg	
			Enzyme production (Electricity)	2585.7	KJ	
			Saccharification and cofermentation (Electricity)	247.0	KJ	
			Product recovery (Electricity)	244.9	KJ	
			Product recovery (Heat)	1840.5	KJ	
			Wastewater treatment (Electricity)	214.0	KJ	
			Water cooling (Electricity)	328.5	KJ	
	Distribution		Bioethanol transportation (100 km)	0.004	Tkm	(Blonk Agri Footprint BV, 2015a, 2015b)

Table 2
Avoided processes per MJ of bioethanol considering Luo et al (2009) for biorefinery surplus electricity and IPCC (2006) emission factors for rangeland dry matter burnt.

Process to replace	Values per FU	Unit	Reference
Electricity (Argentina)	8.0	KJ	Luo et al (2009)
Rangeland burnt	0.6	m^2	IPCC (2006)

EROI and GWP of bioethanol obtained from *S. argentinensis* reported later in this research could be all significantly improved.

Ensuring high levels of energy efficiency is a crucial factor for making the process economically viable. In many techno-economic assessments, the generation of steam required for the process involves burning a portion of the solid residue in a steam boiler (Galbe et al., 2007). Leveraging the excess solids offers the potential to generate heat, electricity, or pellets that can be sold to improve the process economics, aligning with the principles of sustainability associated with the circular economy (Ren and Zhang, 2022).

Consequently, the energy demand of the process becomes a critical factor, influencing the amount of solid residue that can contribute to additional income as a solid fuel co-product. Therefore, it is imperative for the process to prioritize energy efficiency within the context of the circular economy (Galbe et al., 2007).

Another topic not covered by this research is the potential use of CO_2 produced by yeasts which is highly pure and can be sold to the beverage industry hence enhancing the energy balance if considered as an avoided process (Sebastião et al., 2016). This consideration could significantly impact in the LCA results as 1 kg of biomass released sugar can potentially produce 0.51 kg of ethanol and 0.49 kg of CO_2 (Arundale et al., 2015).

3.2. Global warming potential (GWP)

The CO_2eq emissions for the gasoline reference system accounted for 96.9 g of CO2eq per MJ of gasoline. Well-to-tank emissions accounted for 27 % of this figure, while the remaining 73 % are tank-to-wheel emissions. The data corresponds to emissions from gasoline combustion in Europe because there is no available official inventory of Argentinean gasoline.

Fig. 3 highlight the breakdown of GHG emissions in the obtention of 1 MJ of bioethanol if the heat and power demand of the biorefinery were

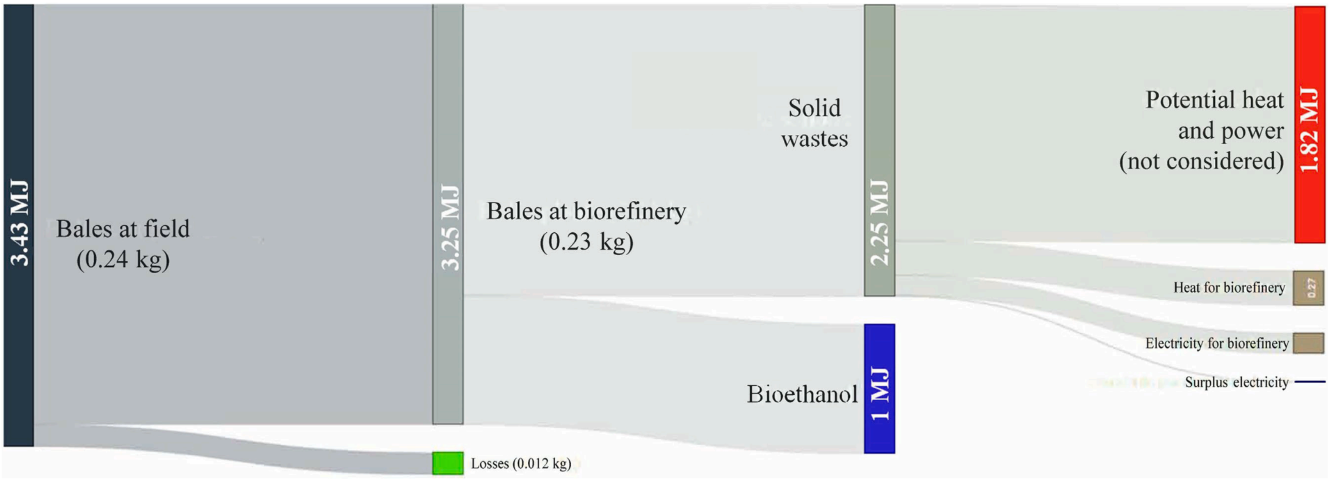

Fig. 2. Sankey diagram of energy flow from primary energy at farm to the FU of 1 MJ of bioethanol. Biorefinery data was considered self supplied according to Luo et al (2009).

obtained from actual Argentinean main sources of energy, mainly derived from fossil fuels and considering the biorefinery energy demand of Luo et al (2009). Even without considering biorefinery energy self-supply, the GHG emissions resulted substantially lower than those of gasoline: 24 g vs 79.5 g of CO_2eq, respectively.

It is important to note that land use would not change by biomass harvesting so the implementation of the bioenergetic scenario assessed in this research would not hinder the negative emission potential due to collateral CO_2 emissions hence positioning *S. argentinensis* as a potential feedstock of bioenergy that could collaborate with carbon capture and sequestration (Babin et al., 2021).

Although the refinery data from Luo et al. (2009) are the ones with highest emissions, as in this reference they consider the plant's energy self-sufficiency, the values are very favourable. If self-sufficiency were obtained in the rest of the references considered, they would reduce GHG emissions notably, with a better carbon footprint when compared with Luo et al. (2009) scenario.

If biorefinery energy demand were met by the combustion of solid by-products as reported by Luo et al (2009) the GWP would reduce considerably as shown in Fig. 4. The CO_2 produced by yeast fermentation is another by-product that could help to reduce the GWP if utilized in industrial processes considered as an avoided process (i.e., dry ice and carbonated beverages) as reported by other researchers (Gnansounou and Dauriat, 2005; Sebastião et al., 2016).

Considering the emissions avoided by the burning of rangelands the system results carbon negative, hence carbon dioxide would be removed from the atmosphere when comparing the actual situation of rangeland burning and gasoline as energy for vehicles with rangeland harvest for bioethanol.

In Fig. 4 we resume all the results using different references for the biorefinery stage. The biorefinery reported in Luo et al (2009) is the one that emits the higher quantity of GHG with 71.4 g of CO_2eq per MJ of bioethanol so if solid byproducts were harnessed in the other reported references to meet the energy demand of the biorefinery, the results should be even better than that obtained for Luo et al (2009) in which the GWP resulted carbon negative (-30.3 g of CO_2eq per MJ of bioethanol).

The avoided soybean meal of the solid waste considered by Jungbluth et al (2007) was not considered in our research as we could not obtain the solid waste of *S. argentinensis* fermentation. If considered, the solid waste from grass bioethanol would replace soybean meal with a value of emission reduction of 497 g of CO2eq avoided per MJ of bioethanol produced. This would make *S. argentinensis* bioethanol carbon balance strongly negative this mitigating even more the global warming.

The systems assessed in this work emitted between 35 and 90 g of CO_{2eq} for each MJ of bioethanol produced, without considering the avoided fires. These emissions are consistent with those reported by Morales et al. (2015) in an extensive literature review of bioethanol LCA. Avoided GHG emissions of fires are determinant for the carbon balance obtained here so substantial environmental contribution could be obtained considering that the Submeridional Lowland is subjected to frequent fires. In the aforementioned region, up to seventeen fires have been reported in a period of twenty years from 2000 to 2019 (Cavallero et al., 2023).

3.3. *Energy use (EROI and CED)*

The CED of bioethanol using Luo et al (2009) with energy demand of the biorefinery met with solid wastes (Fig. 5). Even though the heat and power is met by the combustion of solid wastes of the fermentation process, the data of this reference show a high CED for the ammonia required for the enzymes production which is consistent with other research (Wiloso et al., 2012).

A resume of all assessed CED and EROI using different biorefinery data for bioethanol obtention and its comparison with gasoline can be appreciated in Fig. 6. Even though both indicators resulted better for bioethanol than for gasoline, differences were not as notable as for GWP. The reason is that avoided fires affect GWP having no effect in CED and EROI. If co products of biorefineries were used in the less energy demanding references (Jungbluth et al., 2007; Kumar and Murthy, 2012) to meet biorefinery heat and power demand, the CED and EROI would probably result more favourable than that of Luo et al (2009).

The EROI obtained in our research resulted consistent with figures reported in the review by Morales et al. (2015) for second-generation bioethanol were most of the EROI resulted greater than 1. However, it resulted well below 3 in all scenarios. This value of 3 is the minimally value to be useful for society as reported by Hall et al. (2014). This EROI figures could be increased in most scenarios to 10 and 14, if 50 % and 90 % of the 1.82 MJ of solid waste shown in Fig. 2 were harnessed for energy obtention, respectively. As in GWP, if avoided processes of Jungbluth et al (2007) biorefinery were considered, its EROI would be 3, 4 as there would be a lot of avoided energy of both grass fibre and soybean meal with 0.8 and 6.7 MJ of avoided energy, respectively.

All the employed data for biorefinery used energy intensive pretreatment. However, the use of biological pretreatments such as wood rot fungi, to degrade lignin, allowing the structural carbohydrates of the cell wall to be hydrolyzed, would significantly reduce energy use and the production of waste derived from the industrial stage. (Liong et al., 2012). For *S. argentinensis*, a biological pretreatment with secretomes from the fungus *Pycnoporus sanguineus* has been evaluated and contrasted with conventional pretreatments, obtaining good performance

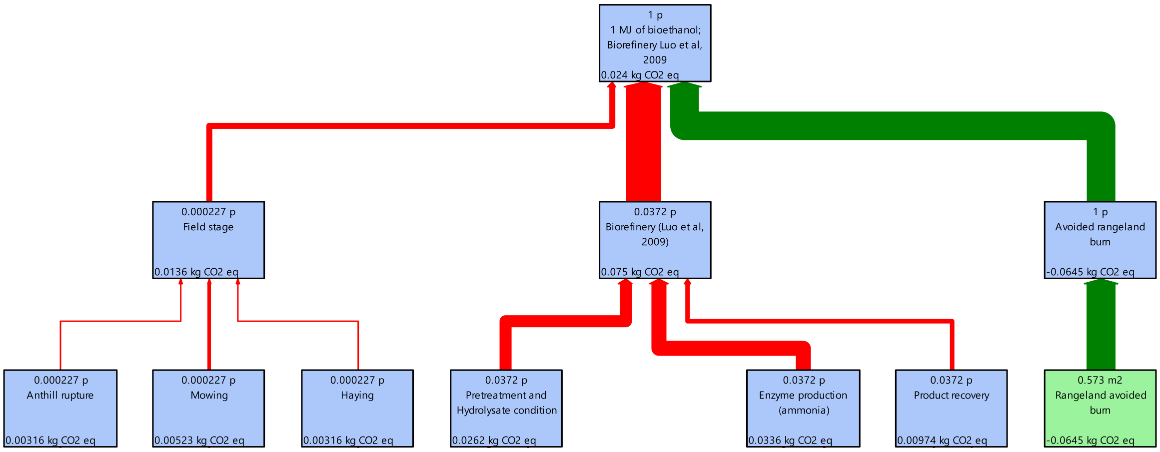

Fig. 3. Network diagram of GWP obtained in Simapro for the obtention of 1 MJ of bioethanol with biorefinery energy demand of Luo et al (2009) obtained from actual main Argentinean heat and power available energy.

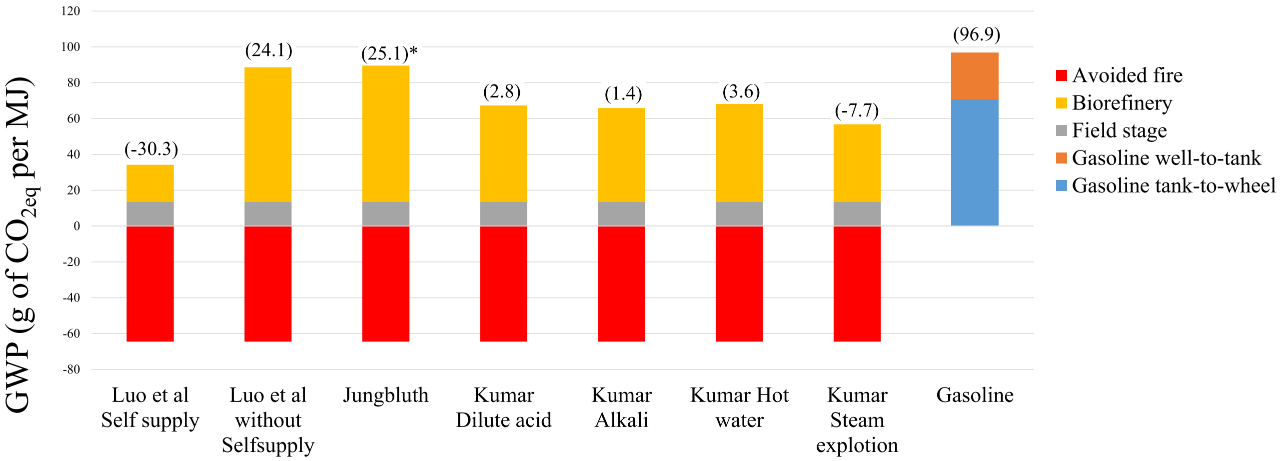

Fig. 4. GWP of 1 MJ of liquid fuel. For bioethanol, biorefinery energy requirements were obtained from different references. Numbers between parenthesis indicates the result of produced emissions minus avoided emissions for each scenario. * The avoided products of Jungbluth et al (2007) were not included here.

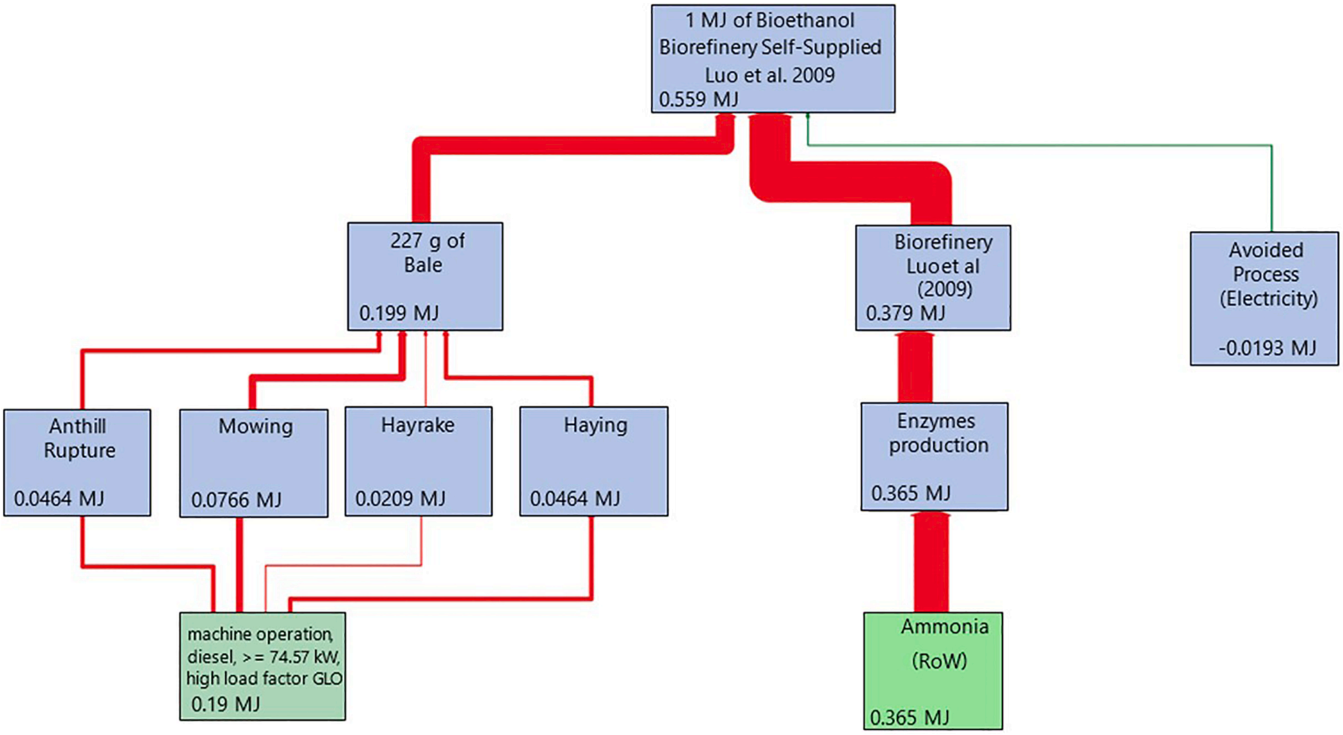

Fig. 5. Network diagram of CED obtained in Simapro for the obtention of 1 MJ of bioethanol with biorefinery energy demand of Luo et al (2009) met from the combustion of the plant solid by-products.

on a laboratory scale (Larran et al., 2015). This pretreatment has also been tested on another C4 grass species, *Panicum prionitis* (Gauna et al., 2018).

4. Conclusions

The results of this work show the environmental suitability of using *S. argentinensis* as a source of bioethanol, due to the reduction in emissions and the lower use of energy compared to gasoline. It is crucial to increase the circularity of the system by self-supplying the plant heat and power requirements to further improve these indicators.

Our study underscores the critical importance of transitioning to renewable energy sources as a mitigation strategy to address climate change, with a specific focus on the native perennial rangelands of the Submeridional Lowlands dominated by *Spartina argentinensis* (espartillo) in central-eastern Argentina.

Through a comprehensive Life Cycle Assessment methodology, this research has provided valuable insights into the potential of bioethanol production from *S. argentinensis* as an environmentally sustainable alternative to gasoline. The findings of this study demonstrate that bioethanol derived from this grass has the potential to be a carbon-negative fuel source, with the avoidance of rangeland burning playing a crucial role in achieving this environmentally beneficial outcome. Additionally, the Energy Return on Investment (EROI) for bioethanol from *S. argentinensis*, though variable, indicates a favourable potential for energy efficiency. Furthermore, no land change would be required for such activity.

It's worth noting that there is room for improvement in the environmental performance of bioethanol production from this biomass. Exploring the utilization of fermentation by-products to replace other

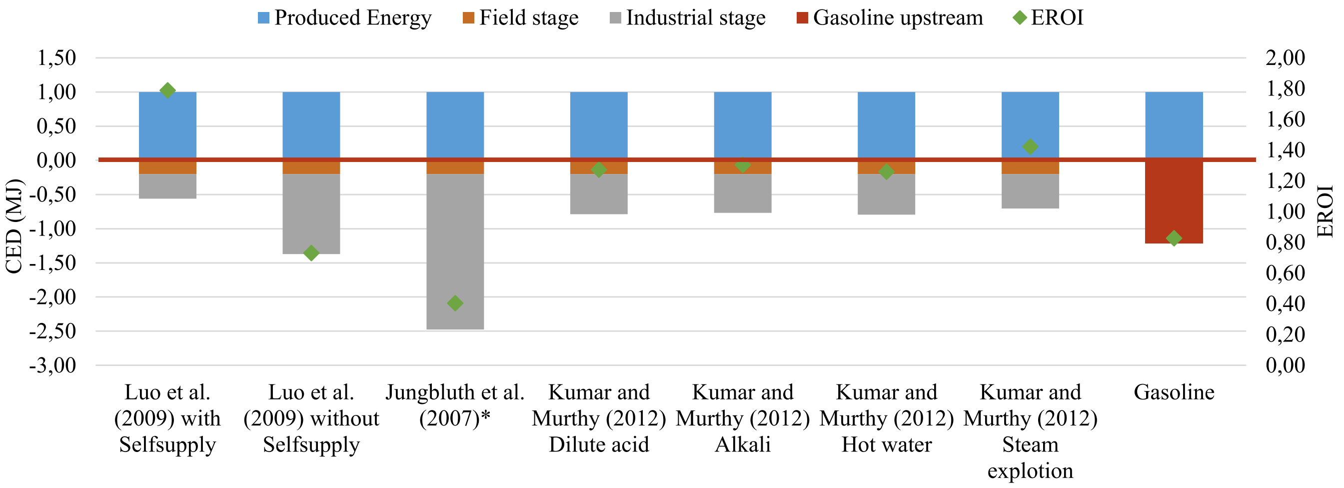

Fig. 6. CED and EROI of bioethanol and gasoline. The EROI is calculated by dividing the positive values (those above the horizontal red line) divided by the required energy (bars below the horizontal red line). *Avoided soybean meal and grass fibre are not considered for Jungbluth et al (2007).

processes or products could yield even more favourable outcomes, aligning with the three R principle of sustainability of circular economy: Reduce, Reuse and Recycle. Moreover, the CO2 produced by yeast fermentation could be a valuable by product for the beverage industry. A way of achieving this may require integration of the biorefinery with other industry that may use such by products obtained from the bioethanol biorefinery in order to improve the circularity of the system.

In summary, this research contributes to the growing body of evidence supporting the transition to renewable energies as the main strategy for addressing climate change. As the first research endeavor addressing the Life Cycle Analysis (LCA) of bioethanol from espartillo, this study highlights its potential to not only reduce greenhouse gas emissions but also promote sustainable land use practices. As we continue to grapple with the challenges of a changing climate, efforts to harness local, renewable resources like espartillo for clean energy production represent a significant step towards a more sustainable and environmentally responsible future.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the authors used Chat gpt in order to improve the translation of some paragraphs originally written in Spanish. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

CRediT authorship contribution statement

Emiliano Jozami: Writing – review & editing, Writing – original draft, Investigation, Conceptualization. **Bárbara M. Civit:** Supervision, Methodology, Conceptualization. **Susana R Feldman:** Writing – review & editing, Writing – original draft, Project administration, Investigation, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Emiliano Jozami reports financial support was provided by Universidad Nacional de Rosario and the Agencia Santafesina de Ciencia, Tecnología e Innovación. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Aknowldegements

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