International Journal of Agricultural Management and Development
Available online on: www.oiccpress.com/ijamad
ISSN: 2159-5852 (Print)
ISSN:2159-5860 (Online)

Orignial Articles DOI: 10.71877/ijamad.2024.8316

Life Cycle Assessment and Cumulative Exergy Demand Analysis of Animal Feed Production from Sugarcane Bagasse: A Case Study

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Received: 11 Nov 2023
Accepted: 23 May 2024

ABSTRACT

Sugarcane bagasse is a byproduct of the sugar industry and has the potential to be used as a feedstock for animal feed production. This study aims to assess the environmental and resource efficiency of animal feed production from sugarcane bagasse using life cycle assessment (LCA) and exergy analysis. The LCA will evaluate the environmental impacts of the entire life cycle of animal feed production, including the cultivation of sugarcane, transportation, processing, and distribution. The exergy analysis will quantify the resource efficiency of the feed production process by assessing the quality of energy and materials inputs and outputs. The findings reveal that feed production has a measurable impact on human health, indicated by a value of 0.30 DALY. In terms of ecosystem quality, feed production emissions have a relatively small impact, with a value of 0.0005 species.yr, indicating a limited effect on the diversity or stability of species within ecosystems. The energy consumption of 93602.34 MJ per ton indeed indicates a significant dependence on non-renewable fuel sources, i.e., fossil fuels. These results show that there is a need to improve energy efficiency and optimal use of energy resources in the actual production process.

Keywords:
Animal feed, cumulative exergy demand, life cycle assessment, sugarcane bagasse.

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INTRODUCTION

Strong actions to mitigate climate change, including the use of renewable resources and the strengthening of the global market for bio-based resources, have been strongly accelerated. Various assessments, including energy, economic and environmental assessments, have shown that biomass-based resources are able to effectively replace the functions of fossil fuels (Khatri & Pandit, 2022). The livestock industry has developed significantly since the end of the 20th century, and the importance of animal diet was recognized as an important factor affecting their health, performance and well-being (Samadi et al., 2016). With a global annual demand of over 1 billion metric tons of animal feed, the animal feed industry is always on the lookout for feed ingredients that are more cost-effective, nutritious and widely available (Guo et al., 2022). The production of animal feed from sugarcane bagasse is an important process in the animal husbandry industry, where sugarcane waste is used as the main material for the preparation of animal feed (Alokika et al., 2021). Sugarcane bagasse is a substance that is produced as waste after extracting sugar juice from sugarcane. Since sugarcane bagasse has a high nutritional and energy value, its use in the preparation of animal feed can help preserve the environment in addition to increasing productivity (Kaewhom, 2020). Sugarcane bagasse is a rich source of cellulose (32–45%), hemicellulose (20–32%) and lignin (17–32%), 1.0–9.0% ash and some extractives. Huge amount of the generation of sugarcane bagasse has been a great (Parameswaran, 2009). This diversification of bagasse uses could play a prominent role in alleviating fossil fuel dependence without increasing environmental burdens. Some factors affecting the bioconversion of bagasse, namely substrate digestibility and protein productivity, have been discussed by (Nigam, 1990). Investigating the possibility of producing animal feed from sugarcane bagasse was processed using Pleurotus florida. In laboratory conditions, the results showed that the amount of dry matter, neutral detergent fibers and acid detergent fibers have a significant effect on processed sugarcane bagasse and the amount of crude protein (Mahmood et al., 2019). The results of this study indicate that treated bagasse can be used as an alternative grass source for feeding ruminants.

Around 534 million tonnes of bagasse production were estimated from 1.91 billion tonnes of sugarcane in 2018 worldwide. Using sugarcane bagasse as the main ingredient in the preparation of animal feed can reduce the use of natural resources such as plants and legumes in the production of animal feed. Also, this practice reduces the production of wastes and residues from the sugar industry and thus reduces environmental pollution (Bordonal et al., 2018). Life cycle assessment (LCA) is a very important tool for the analysis of a process/system from its cradle to grave. This technique is very useful in the estimation of energy usage and environmental load by a product/system (Chauhan et al., 2011). The potential for significant variability in animal feed production from sugarcane bagasse impacts suggests the need for LCAs of sugarcane systems to consider ranges for key variables. The key variables and important influences identified in this work can guide data collection priorities for future assessment of animal feed production from sugarcane bagasse and possibly other Iranian cropping systems. To further develop LCA as a useful predictive tool for Iranian agricultural systems, further development and testing of impact assessment models for eutrophication, toxicity, and depletion of land and water resources appropriate for Iran is needed.

Exergy is one of the important indicators in the environmental assessment of animal feed production from sugarcane bagasse. Exergy refers to the amount of energy required to produce a unit of animal feed from sugarcane bagasse. Examining this index can help companies to choose the best methods and processes in terms of energy consumption, thereby reducing exergy and increasing productivity (Naseri et al., 2020). Cumulative energy and exergy consumption, cumulative degree of perfection, and renewability index for sugarcane production were 66,500 MJ ha-^{1}, 82,561 MJ ha-^{1}, 6.21, and 0.86, respectively, and these values were 48,267 MJ ha-^{1}, 67,984 MJ ha-^{1}, 165,831 MJ ha-^{1}, 6.42, and 0.84 for sugar beet production, respectively (Asakereh et al., 2023).

The production of animal feed is a crucial global industry that plays a vital role in meeting society's food needs. As the world population grows and the demand for more food increases, it is increasingly important to optimize animal feed production processes and minimize their environmental impact. One modern approach to this is the use of fermentation of sugarcane residues, which reduces resource wastage and improves energy efficiency. This innovation has the potential to enhance energy efficiency and minimize the environmental impact of animal feed production. The aim of the study is to conduct a LCA and exergy analysis of the production of animal feed from sugarcane bagasse. This involves evaluating the environmental impacts and resource efficiency of the entire process, from the cultivation of sugarcane to the production of animal feed. The study aims to identify areas for improvement and optimization in order to minimize environmental impacts and maximize resource efficiency in the production of animal feed from sugarcane bagasse.

METODOLOGY

Study area

Shuaibieh animal feed production Company is a downstream industry of the large sugarcane development industry in Iran. It utilizes discarded sugarcane remains to produce valuable food for livestock, creating employment and income opportunities. The factory can supply 40 percent of the livestock's food quota, preventing overgrazing and pasture destruction. By using sugarcane by-products such as sorghum, bagasse, straw bagasse, and molasses, the company can produce 100,000 tons of animal feed annually. Interviews with the company provide valuable information for analysis, as face-to-face interviews allow for non-verbal communication and quick feedback. However, this type of interview requires more time, money, and physical presence (Agraib et al., 2023).

LCA analysis

LCA is a methodical evaluation of a product or service that considers its entire life cycle, from production to disposal. This comprehensive assessment encompasses production, transportation, use, and disposal of the product or service (Santoyo-Castelazo et al., 2023). LCA assists companies and organizations in evaluating the environmental, economic, and social effects of their products or services and implementing necessary enhancements. This evaluation also aids in reducing resource and energy usage, as well as refining production processes and supply chains. Additionally, LCA provides consumers with valuable insights into a product or service's impact on the environment and society, enabling them to make more informed decisions (Nunes et al., 2023). Ultimately, LCA can lead to enhancements in products or services, cost savings, decreased resource and energy usage, and environmental preservation, ultimately aiding organizations and consumers in making more informed choices (Amezcua-Allieri et al., 2019):

In line with the life cycle perspective, the company should implement the following measures: Implementing suitable controls to ensure that environmental considerations are integrated into the design and development process for the product or service at each stage of its life cycle, Identifying environmental requirements to deliver products and services as needed, Communicating relevant environmental requirements to external providers, including contractors, Establishing controls to effectively address environmental needs in the design and development process of the proposed product or service at each stage of its life cycle, Identifying environmental requirements to deliver products and services effectively, Sharing industry-related environmental information with external suppliers, including contractors (Maga et al., 2019).

The first stage of the life cycle assessment involves clearly defining the goal and boundaries of the assessment, including the functional unit, system boundaries, and impact categories to be considered. In the case of Shuaibiya-Khuzestan animal feed production and preparation company, one ton of animal feed from sugarcane bagasse was chosen as the functional unit. The second stage involves compiling a comprehensive inventory of all inputs and outputs associated with the product, process, or service being assessed. This includes raw materials, energy, water, emissions, and waste throughout the entire life cycle. The third stage involves evaluating the potential environmental impacts associated with the inventory items identified in the previous stage. This includes assessing the impacts on resources, human health, ecosystems, and other relevant impact categories (Du et al., 2019). The ReCiPe2016 was selected as the best method. This method has different categories in the middle and end points, which can be seen in Figure 1. LCIA consists of four steps, which are briefly described below.

The data obtained from inventory analysis is classified into different categories based on their expected environmental effects. Characterization involves assigning weights to substances contributing to the same environmental impact, resulting in aggregated results for each impact category in a specific unit of measurement. Normalization relates specific data to a larger data set or situation, such as relating SOx emissions to a country's total SOx emissions. In weighting, numerical factors are used to convert results for different impact categories into points, making it the most subjective stage of LCA based on value judgments rather than scientific evidence. This step allows for the conversion of different criteria into a numerical score, facilitating decision making (Vural Gursel et al., 2021). The last step of the life cycle assessment includes analyzing the results and making conclusions based on the findings. This could involve finding areas for improvement, comparing various options, and sharing the results with stakeholders. These stages are meant to offer a thorough and organized evaluation of the environmental aspects and potential effects of a product, process, or service throughout its life cycle (Ita-Nagy et al., 2020).

Cumulative exergy demand analysis

The Cumulative Exergy Demand (CExD) approach evaluates the overall exergy needed for generating and distributing a specific energy quantity. This method considers all energy inputs and losses across the complete energy supply chain, encompassing extraction, processing, transportation, and conversion (Nabavi-Pelesaraei et al., 2022). CExD analysis offers a thorough assessment of the resource and environmental effects of energy systems by examining not only the direct energy inputs, but also the energy quality and conversion process efficiency. This enables a more precise comparison of various energy sources and technologies, considering their overall exergetic efficiency and environmental impact (Ordikhani et al., 2021). Measuring the total exergy demand of energy systems allows decision-makers to gain a deeper understanding of the actual advantages and disadvantages of various energy options. This enables them to make more knowledgeable decisions regarding energy policy, investment, and technology advancement. This approach can also pinpoint ways to enhance the sustainability and effectiveness of energy systems, and facilitate the shift towards more sustainable and low-exergy-demand energy sources (Ghannadzadeh & Meymivand, 2019). Electricity, water, and wind play vital roles in agricultural production. Fossil fuels like gasoline and diesel power agricultural machinery, while electricity is utilized for irrigation, crop processing, and transportation. Water is essential for field irrigation, and wind energy powers water pumps. Additionally, renewable energies like solar and wind can be harnessed for agricultural purposes. This study examines various forms of energy, including non-renewable, fossil, renewable, potential, primary, biomass, water, metals, and minerals, in the context of agricultural production.

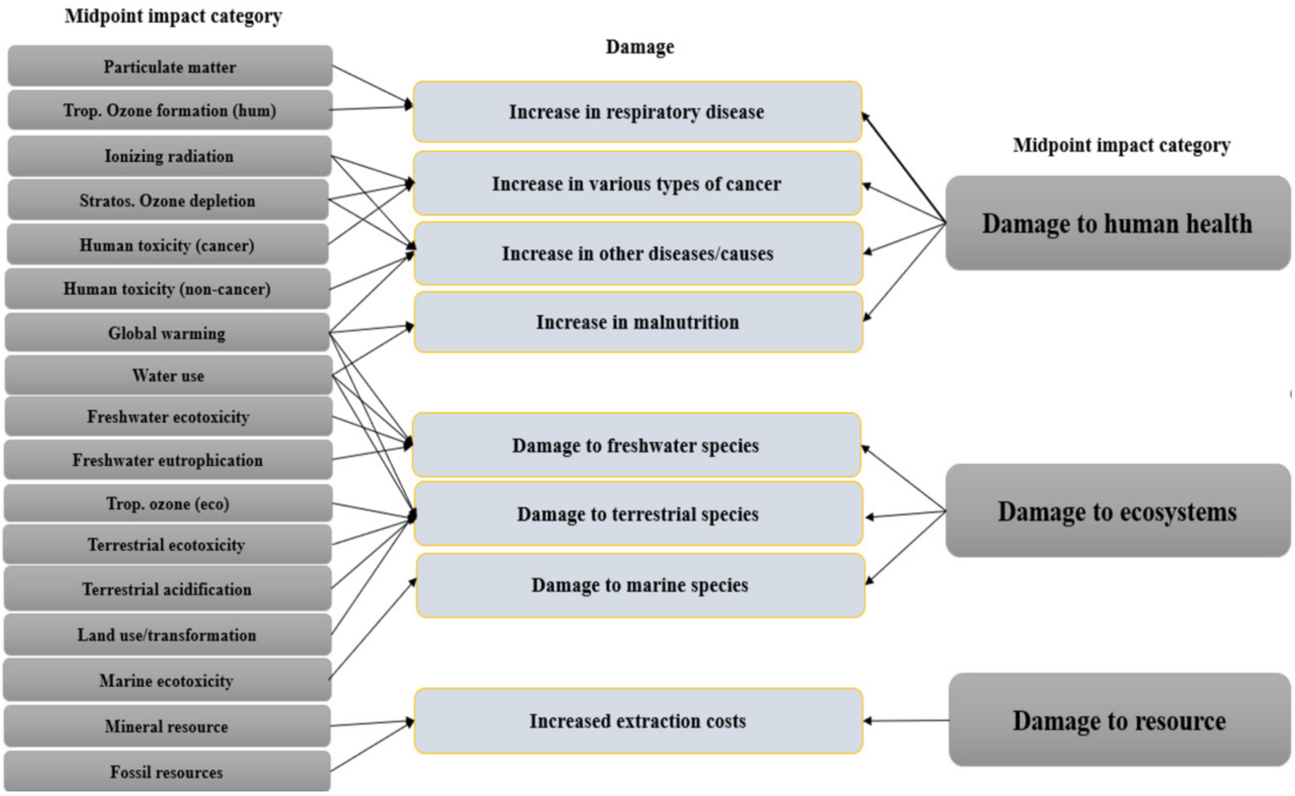

Figure 1. *Midpoints and endpoints of impact category of the ReCiPe2016 method.*

RESULTS

LCA Analysis

The computation of emissions on farms during feed production using sugarcane bagasse is dependent on a range of factors and specific procedures (as outlined in Table 1). A general overview of emissions linked to the production of animal feed from sugarcane bagasse reveals that direct emissions encompass greenhouse gases that are released during the production process. Carbon dioxide (CO_2) emissions may arise from the combustion of fossil fuels for energy generation, and the production of CO_2 from feed production (173.08 kg) is substantial. The relative impact of these emissions can be better understood by considering the production scale (e.g., per ton of feed, per year). Methane (CH_4) emissions may also come about from diesel fuel. A comprehensive LCA would be necessary to accurately estimate the emissions associated with sugarcane bagasse-based animal feed production. This assessment would take into account all stages, from sugarcane cultivation and bagasse extraction to processing. It is worth noting that the emissions can vary depending on multiple factors, such as the location, specific production processes, energy sources, and management practices used within the industry (Weisser, 2007).

The values associated with damage assessments can vary widely based on various methodologies employed and the specific context in which the assessment is conducted. Based on the information provided, the results from the ReCiPe2016 method show the impact of feed production on different endpoints (Table 2). Here is a breakdown of the information you provided: Human health (0.30 DALY): DALY stands for Disability-Adjusted Life Years, which is a measure of the overall disease burden caused by a specific environmental stressor or risk factor. A value of 0.30 DALY indicates that feed production emissions have a measurable impact on human health, though the specific nature and severity of the health effects would require further analysis, Ecosystem quality (0.0005 species.yr): Ecosystem quality refers to the health and functioning of ecosystems. A value of 0.0005 species.yr suggests that feed production emissions have a relatively small impact on the diversity or stability of species within ecosystems. However, it's important to note that maintaining ecosystem quality is crucial for overall ecological balance and long-term sustainability, Resources (647.01 USD2013): The value of 647.01 USD2013 indicates that feed production emissions have a significant impact on resource scarcity. This suggests that resource depletion, such as water and energy usage, associated with feed production is substantial.

The findings illustrate a multifaceted scenario. Although emissions from feed production may not significantly affect ecosystem quality and human health, they do have a significant impact on resource scarcity. This underscores the importance of implementing sustainable practices in feed production to reduce resource usage and safeguard the long-term sustainability of ecosystems (DeClerck et al., 2016). The ReCiPe2016 method is a thorough impact assessment framework that takes into account various environmental endpoints. Although the values you provided shed light on certain endpoints, a more in-depth analysis and consideration of other factors is necessary to fully comprehend the overall sustainability implications of feed production emission (Duru & Therond, 2015).

Figure 2 illustrates the impact of various inputs on environmental emissions, particularly in relation to human health, ecosystem quality, and resource depletion. Electricity, machinery, direct emissions, and equipment significantly contribute to emissions in both human health and ecosystem quality categories, indicating their importance in environmental impacts and potential risks. Electricity also has a significant impact on resource depletion, contributing to over 30 percent of emissions, while natural gas and diesel fuel consumption have the greatest impact on resource scarcity. Understanding these contributions is crucial for identifying areas for improvement and implementing targeted mitigation strategies. It's important to consider the specific context of the study that produced Figure 3, as it may influence the results and their relevance to other situations. Addressing significant contributors such as electricity and fuel consumption can lead to more sustainable practices in feed production (Chowdhury et al., 2023).

CExD Analysis

The outcomes of a Cumulative Exergy Demand (CExD) assessment can differ based on several factors, including geographical location, process specifics, and analysis scope (as shown in Table 3). Nonetheless, sugarcane bagasse, a byproduct of sugarcane processing, is frequently utilized as a bioenergy feedstock or animal feed. In terms of energy, sugarcane bagasse is recognized for its renewable energy potential, thanks to its relatively high cellulose content (Cheng et al., 2024). A reliance on non-renewable, fossil fuel sources is evident with an energy consumption rate of 93602.34 MJ ton-^{1} . This considerable energy consumption can be attributed to various factors, including the use of fossil fuels for machinery, transportation, processing, and other production-related aspects. Primary non-renewable energy forms have the lowest energy consumption rate at 118.28 MJ ton-^{1}

Figure 3 illustrates how each input affects different types of energy consumption. Machinery usage has a positive impact on renewable water energy consumption, while salt consumption has the highest energy consumption in non-renewable fossil and mineral forms. As environmental sustainability becomes increasingly important and the push to reduce greenhouse gas emissions grows, it is essential to find ways to decrease reliance on non-renewable energy sources in sectors like agriculture and animal feed production (Molaee Jafrodi et al., 2022).

Table 1
On-Farm Emissions in Animal Feed Production from Sugarcane Bagasse Based on 1 Ton.

Items	Value
1. Emissions by diesel fuel to air (kg)	
(a). Carbon dioxide (CO_2)	173.08
(b). Sulfur dioxide (SO_2)	0.05
(c). Methane (CH_4)	0.007
(d). Benzene	0.0004
(e). Cadmium (Cd)	5.55E-07
(f). Chromium (Cr)	2.76E-06
(g). Copper (Cu)	9.43E-05
(h). Dinitrogen monoxide (N_2O)	0.006
(i). Nickel (Ni)	3.88E-06
(j). Zink (Zn)	5.55E-05
(k). Benzo (a) pyrene	1.66E-06
(l). Ammonia (NH_3)	0.001
(m). Selenium (Se)	5.55E-07
(n). PAH (polycyclic hydrocarbons)	0.0001
(o). Hydro carbons (HC, as NMVOC)	0.15
(p). Nitrogen oxides (NOx)	2.46
(q). Carbon monoxide (CO)	0.34
(r). Particulates (b2.5 µm)	0.24
2. Emission by human labor to air (kg)	
(a). Carbon dioxide (CO_2)	31.66

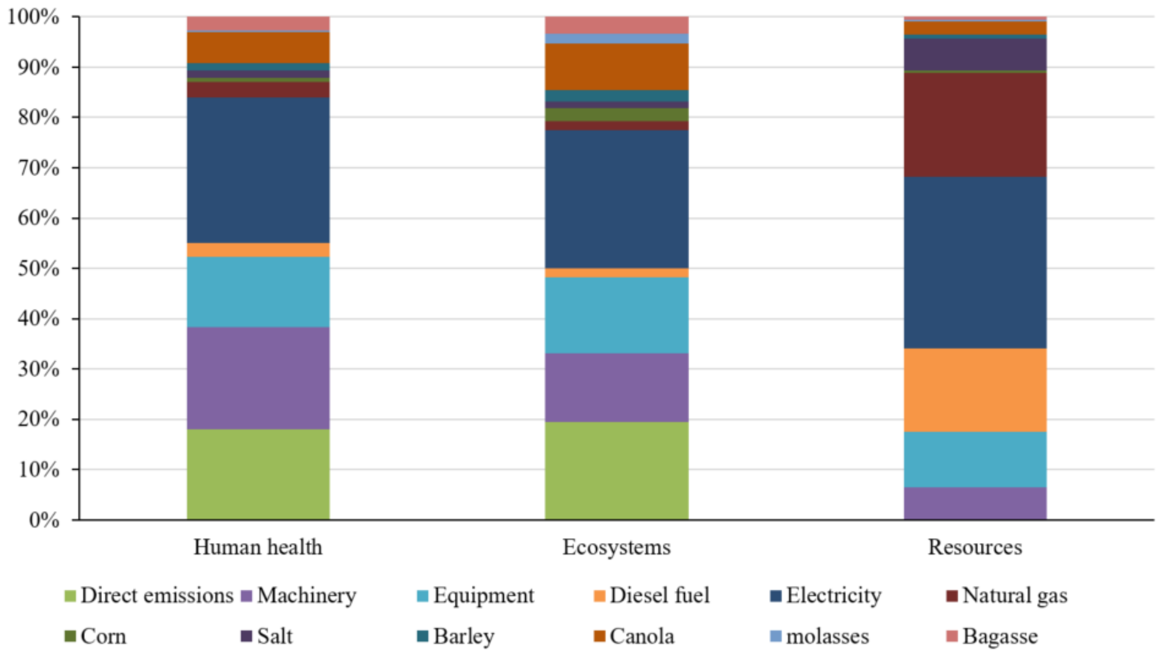

***Figure 1**. Contribution of Different Inputs in the Damages Categories in Animal Feed Production from Sugarcane Bagasse.*

Table 2

Values of the Damage Assessment Per One Ton in Animal Feed Production from Sugarcane Bagasse.

Items	Unit	Value
Human health	DALY [a]	0.30
Ecosystems	species.yr [b]	0.0005
Resources	USD2013	647.01

Table 3

The energy forms result of CExD analysis for one ton in animal feed production from sugarcane bagasse.

Energy form	Unit	Value
Non-renewable, fossil	MJ ton^{-1}	93602.34
Renewable, potential	MJ ton^{-1}	9451.88
Non-renewable, primary	MJ ton^{-1}	118.28
Renewable, biomass	MJ ton^{-1}	2581.77
Renewable, water	MJ ton^{-1}	14513.59
Non-renewable, metals	MJ ton^{-1}	1243.26
Non-renewable, minerals	MJ ton^{-1}	14031.16

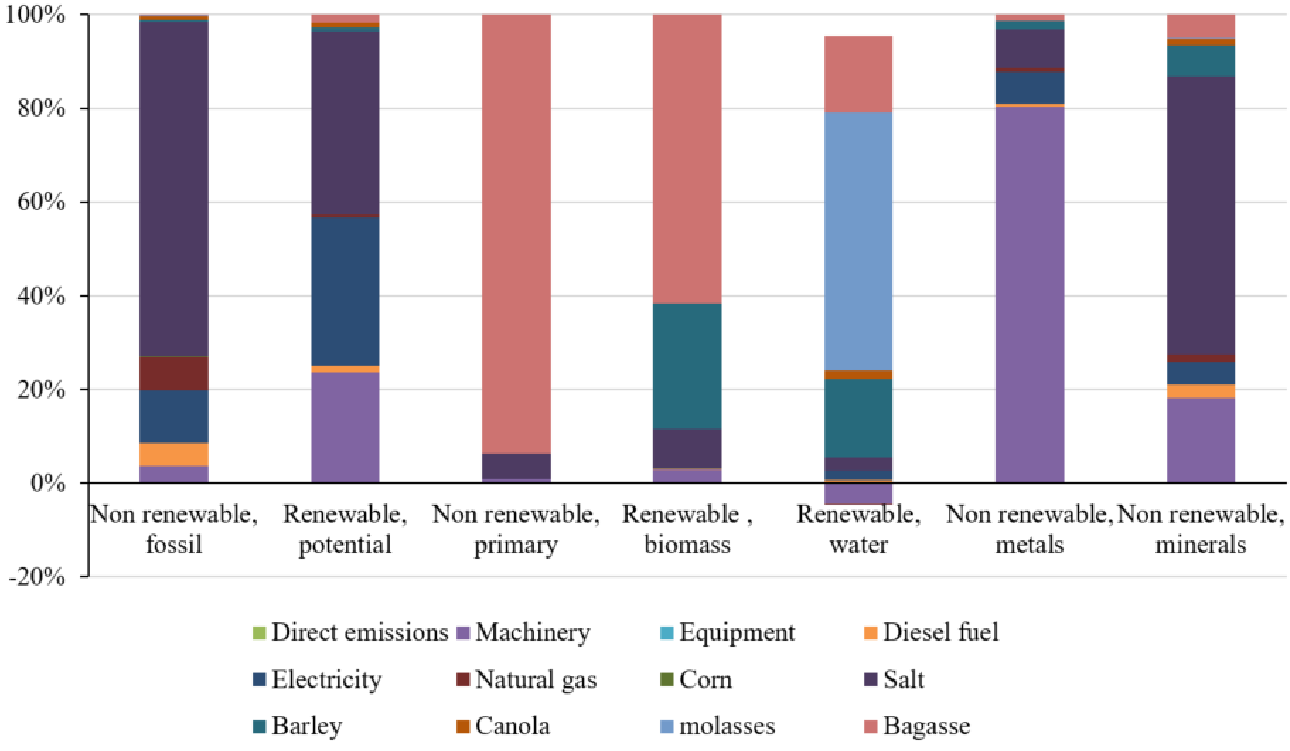

Figure 2*. Contribution of Inputs to Consume Energy Forms in Animal Feed Production from Sugarcane Bagasse.*

CONCLUSIONS

This study offers a thorough examination of the environmental and resource effects of producing animal feed from sugarcane bagasse. The analysis, using LCA and cumulative exergy demand, demonstrates the potential environmental and resource advantages of using sugarcane bagasse for animal feed production. The study emphasizes the significant impact of feed production emissions on resource scarcity, with a value of 647.01 USD2013, indicating considerable resource depletion, particularly in water and energy usage. The results emphasize the need for further research and potential interventions to mitigate the environmental impact of feed production on human health, ecosystem quality, and resource scarcity. The environmental impact of feed production emissions has significant implications for human health, ecosystem quality, and resource scarcity. While the impact on ecosystem quality is relatively small, the impact on human health and resource scarcity is substantial. Additionally, high energy consumption in the production process indicates significant dependence on fossil fuel sources. Further research is necessary to better understand the specific effects on human health and identify potential interventions to mitigate the impact. Efforts to reduce resource depletion, particularly in water and energy usage, are crucial for sustainable feed production. Overall, this study highlights the need for a comprehensive approach to address the environmental impact of feed production emissions and promote sustainable practices in the industry. The findings suggest that this approach could contribute to reducing the environmental impact and resource demand of animal feed production. Further research and implementation of sustainable practices in this area could lead to significant improvements in the sustainability of animal feed production. Overall, this study highlights the importance of considering the life cycle and resource implications of animal feed production and the potential benefits of utilizing alternative feed sources such as sugarcane bagasse.

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How to cite this article:
Azadeh, S., Gholamiparashkoohi, M., Zamani, D., & Firouzi, S. (2024). Life Cycle Assessment and Cumulative Exergy Demand Analysis of Animal Feed Production from Sugarcane Bagasse: A Case Study. *International Journal of Agricultural Management and Development, 14*(3), 293-303. **DOI:** 10.71877/ijamad.2024.8316