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Research Article

Assessing sugarcane production sustainability in Mozambique: integrating the SustenAgro Index approach with the Entropy Weight Method

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Abstract

Paper aims: Assess the sustainability of sugarcane production in Sofala Province, Mozambique, using the SustenAgro Index approach and the Entropy Weight Method.

Originality: This paper provides several original contributions. First it enhances our understanding about the sustainability of sugarcane production in Mozambique, a topic that has been few studied. Second, it proposes a robust and comprehensive sustainability assessment framework based on the SustenAgro Index tailored to Mozambique. Finally, an innovative solution using an entropy approach is employed to determine the weights of criteria.

Research method: An intentional sample of 30 sugarcane producers from the districts of Nhamatanda and Búzi was selected. The sustainability indicators and dimensions were weighted using the entropy method, and the sustainability index was determined using the SustenAgro Index approach.

Main findings: Sugarcane production systems present positive sustainability scores. The social dimension has highest contribution to the sustainability index, followed by the economic and environmental dimension. Inefficient water management and the considerable distance between production fields and the sugar factory, significantly impacts the sustainability of sugarcane production.

Implications for theory and practice: This article presents a reliable framework for assessing sustainability in sugarcane production, leading policymakers and stakeholders to prioritize critical factors in designing policies and interventions.

Keywords

Sustainability index. Sugarcane. SustenAgro approach. Sofala province. Entropy.

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Conflict of Interest
The authors have no conflict of interest to declare.

Ethical Statement
This study was exempt from ethical review under United States Office for Human Research Protection guidelines, as it involves consulting sugarcane farmers' performance of sustainability indicators for sugarcane production and not any activity directly affecting their well-being. The participants' identities were hidden. However, they were informed about the objective of the study, voluntarily signed the Informed Consent Form to participate and authorize the publication of the data.

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1. Introduction

Sugarcane plantations are among the fastest-growing agricultural systems in the world. According to the BM (Banco de Moçambique, 2022), between 2000 and 2020, this crop represented approximately 21% of global agricultural production, generated significant income in more than 100 countries and served as an essential source of employment. The author highlights that in Mozambique, sugarcane is considered one of the most promising industries, employing more than 31,000 permanent and seasonal workers. Sofala province, situated in central Mozambique, is a leading region for sugarcane production and hosts the highest number of sugar factories in the country. Its prominence is attributed to fertile soils and abundant water resources from the Zambezi, Púngue, and Búzi river valleys, with four of the nation's eight factories located in the province.

However, despite the positive contributions of sugarcane production, the industry faces significant challenges due to its environmental impacts. As noted by Bonfils (2021), García-Bustamante et al. (2018), the World Wildlife Fund (2015), and Li & Li (2024), these impacts can be categorized into several key areas: (i) greenhouse gas emissions caused by the intensive use of agrochemicals and artificial fertilizers, and practice of burning sugarcane leaves in certain regions; (ii) soil degradation resulting from monoculture practices, which reduce soil fertility over time, leading to lower productivity and soil erosion; (iii) high water demand for irrigation, which puts substantial strain on local water resources; (iv) pollution of freshwater ecosystems due to runoff from fertilizers and pesticides used in sugarcane fields; and (v) biodiversity loss driven by deforestation.

The cultivation of this crop also carries socio-economic risks to farmers and the population, such as increased inequity in the rural sector, low wages, reduced land available for food crops, land and resource expropriation, water scarcity for local communities, displacement of local populations, exploitation of workers and economic vulnerability (Coelho & Goldemberg, 2019; Mehdi et al., 2024), thus jeopardizing the sustainability of this important sector.

Sugarcane production is a multidisciplinary field encompassing a variety of interconnected factors and stakeholders, including agronomic, environmental, economic, social, and technological innovations, as well as regulatory frameworks and supply chain management (Doloriel, 2014; Hildbrand & Bodhanya, 2014; Kaggwa et al., 2017). These elements underscore the complexity of sugarcane production and the importance of collaboration among diverse experts to effectively address its challenges and capitalize on its opportunities.

Due to its important role in providing food and raw materials for industries and the intensive use of natural resources, there is a growing interest in assessing the sustainability of agricultural production systems (Mili & Martínez-Vega, 2019). Sustainable agriculture is recognized as essential for achieving the Sustainable Development Goals (Trigo et al., 2022), however, assessing it, particularly in the case of sugarcane production, is very complex due its multidisciplinary nature (Bartzas & Komnitsas, 2020).

The literature provides several assessment frameworks to assess sustainability (Chopin et al., 2021). The triple bottom line became the most acceptable framework (Cinelli et al., 2014; De Luca et al., 2017; Elkington, 1994), since it considers simultaneously the interconnected economic, environmental and social dimensions of sustainability (Sala, 2020). In this framework, each dimension is represented by different attributes or criteria and trade-offs between them can be assessed (Sinisterra-Solís et al., 2024). Therefore, according to Cruz et al. (2018) ensure the sustainability of production systems, it is critical to strike a balance between economic, social, and environmental aspects to mitigate the negative impacts of the activity and integrate methodologies that consistently express the theories and structures developed to assess sustainability.

The present study aims to evaluate the sustainability of sugarcane production in Mozambique's Sofala province using a composite indicator based on the SustenAgro Index complemented by an entropy approach to determine the weights of the sustainability dimensions and their indicators. Additionally, a regression analysis was conducted to assess the influence of farmers' socioeconomic characteristics. The results of this study may serve as a benchmark for sugarcane farmers and sugar mills, enabling them to make well-informed decisions and improve operations for increased sustainability. Furthermore, the results provide information for decision-makers in the public sector, which aids in developing policies that promote a sustainable sugarcane production system and align with broader sustainability objectives. Crucially, this study also furnishes significant data for scholars, including a concise overview of the present level of sustainability in sugarcane crop production in the region, which facilitates the identification of obstacles and emphasize the areas that need additional exploration in future studies.

2. Methodology

This study uses an integrated approach of the SustenAgro Index with the Entropy Weight Method to assess sugarcane production sustainability in Mozambique's Sofala province. The research was conducted in six stages: (i) identification and selection of the sugarcane sustainability indicators; (ii) weight indicators and dimensions using an Entropy method; (iii) collection of data about the performance of sustainability indicators and socio-economic characteristics from 30 sugarcane farmers using a questionnaire; (iv) calculation of the sustainability index based on the SutenAgro Index; (v) assessment of the contribution of each dimension to the sustainability index; and (vi) assessment of the influence of the farmers' socio-economic characteristics on the sustainability index.

2.1. Assessment framework of sugarcane production sustainability

The sustainability of sugarcane production was assessed using an adapted approach of the SustenAgro Sustainability Index, as outlined by (Jesus et al., 2019). This index is part of the broader SustenAgro Decision Support System framework developed by Embrapa in Brazil. It assesses the sustainability of sugarcane production and processing systems using social, environmental, and economic indicators. The primary goal of the SustenAgro system is to provide a self-evaluation tool for improving the efficiency and sustainability of production units that do not undergo formal certification processes, which has proven to be effective for the sugarcane production system (Jesus et al., 2019). Therefore, the sustainability levels of the sugarcane production systems were determined considering the following steps: i) grouping indicators according to sustainability dimensions; ii) weighting indicators and dimensions; iii) assessing the values of indicators; and iv) calculation of the composite indexes, namely the sustainability index.

i) Grouping indicators according to sustainability dimensions

The 38 indicators selected from 68 initial indicators and validated by ten experts of Sofala province through the two rounds of the Delphi method in the previous study were grouped according to their environmental (9), economic (16), and social (13) dimensions (see Table 1).

ii) Weighting Indicators and dimensions

This study applied the Weight of Entropy Method (EWM) to assign weights to indicators and dimensions, contrasting with the SustenAgro Index's traditional approach, which relies on expert opinion for indicator weights and assigns equal weight to each sustainability dimension (environmental, social, and economic). The use of EWM is justified by the need for an objective approach to assigning weights based on each indicator's degree of differentiation (Bao et al. (2020). As Bao et al. (2020) note, this method minimizes human bias by accounting for the informational content of each indicator. Juan and Pengjuan (2021) assert that the EWM offers an accurate weighting approach, while Wang et al. (2020) emphasize its ease of implementation and flexibility, accommodating stakeholders who may not prefer equal weighting across indicators. The Entropy method is versatile, allowing for the evaluation of sustainability across economic, environmental and social dimensions. Şahin (2021) argues that the method is objective, as it relies on inherent data variability rather than subjective judgment, and can be applied to various data types . Feng et al. (2019) emphasize that EWM measures the disorder or uncertainty within a system, helping to identify which dimensions exhibit the most variability and, therefore, have the greatest impact on the overall assessment. In this case, indicators weights are determined in Equations 1 to 3 based on experts' assessments, obtained using a Likert scale. The initial stage of this approach entails standardizing the measured values of the i-th index in the j-th case, denoted as p_{ij}, using the equation proposed by Gorgij et al. (2017) and Li et al. (2012), as follows:

$$P_{ij} = \frac{x_{ij}}{\sum_{j=1}^{n} x_{ij}} \quad (1)$$

According to Dong et al. (2018), in the EWM, the entropy value E_i of the i-th index is represented as:

$$E_i = -\frac{\sum_{j=1}^{n} P_{ij} * lnP_{ij}}{lnn} \quad (2)$$

EWM's entropy value (E_i) varies from 0 to 1. According to Amiri et al. (2014) and Liu et al. (2010), the calculation of the weight (w_i) is given by the formula:

Table 1. Distribution of indicators by the sustainability dimensions and their thresholds.

	Indicators	Description	Value
	Environmental dimension		
N1	Water quality measurement	Yes	(+1)
		No	(-1)
N2	Existence of a water management and collection system	Yes	(+1)
		No	(-1)
N3	Measuring the amount of water in the irrigation system	Yes	(+1)
		No	(-1)
N4	Measuring the amount of water used in the production process	Yes	(+1)
		No	(-1)
N5	Water availability throughout the production cycle	Yes	(+1)
		No	(-1)
N6	Use of sugar cane varieties adapted to local soil and climate conditions	Yes	(+1)
		No	(-1)
N7	Rational use of inputs	Yes	(+1)
		No	(-1)
N8	Existence of a suitable place to deposit waste	Yes	(+1)
		No	(-1)
N9	Compliance with regulations for the transportation, conservation, sale and appropriate disposal of pesticide waste and containers	Yes	(+1)
		No	(-1)
	Economic dimension		
E1	Return on investment (years)	<2.5	(+1)
		2.5	(0)
		>2.5	(-1)
E2	Profit	Very high	(+1)
		High	(0)
		Low	(-1)
E3	Productivity	High	(+1)
		Low	(-1)
E4	Production (Ton)	>2000	(+1)
		1000 – 2000	(0)
		<1000	(-1)
E5	Investment in technologies	Yes	(+1)
		No	(-1)
E6	Existence of a production expansion plan	Yes	(+1)
		No	(-1)
E7	Sugarcane yield (Ton/ha)	>60	(+1)
		50 – 60	(0)
		<50	(-1)
E8	Sugarcane price (*MT/Ton)	3000	(+1)
		<3000	(-1)
E9	Existence of plantation planning	Yes	(+1)
		No	(-1)
E10	Existence of harvest planning	Yes	(+1)
		No	(-1)
E11	Existence of transportation of sugarcane from the field to the factory	Yes	(+1)
		No	(-1)
E12	Consideration of the relationship between investment in machinery, production and return on investment	Yes	(+1)
		No	(-1)
E13	Type of cultivation practices	Manual	(+1)
		Semi-Mechanized	(0)
		Mechanized	(-1)
E14	Production assessment based on market size and price	Yes	(+1)
		No	(-1)
E15	Sharing production risks between Farmers and the factory	Yes	(+1)
		No	(-1)
E16	Percentage of sucrose	High	(+1)
		Low	(-1)

*MT – Metical (Mozambican Currency).

Table 1. Continued...

	Indicators	Description	Value
	Social dimension		
S1	Alignment of working conditions with current law	Yes	(+1)
		No	(-1)
S2	Access to appropriate protective equipment	Yes	(+1)
		No	(-1)
S3	Formalization of employment (%)	>90	(+1)
		80 - 90	(0)
		80<	(-1)
S4	Presence of child labor	No	(+1)
		Yes	(-1)
S5	Occurrence of accidents in the previous year	No	(+1)
		Yes	(-1)
S6	Existence of worker training programs	Yes	(+1)
		No	(-1)
S7	Existence of action to promote the well-being of the local community	Yes	(+1)
		No	(-1)
S8	Existence of routine training in workplace safety	Yes	(+1)
		No	(-1)
S9	Salary satisfaction	Yes	(+1)
		No	(-1)
S10	Respect for gender equality at work	Yes	(+1)
		No	(-1)
S11	Compliance with average working hours per week (hours)	<40	(+1)
		40	(0)
		>40	(-1)
S12	Job generation (number of jobs)	>50	(+1)
		20 – 50	(0)
		<20	(-1)
S13	Land conflict	Yes	(-1)
		No	(+1)

*MT – Metical (Mozambican Currency).

$$w_i = -\frac{1-E_i}{\sum_{i=1}^{I}\left(1-E_i\right)} \tag{3}$$

iii) Assigning values to each indicator

In this stage, we defined the sustainability threshold values for the indicators identified according to the approach of Jesus et al. (2019) and Zorzo (2015), who assigned values between -1 and +1 to the indicators, with -1 corresponding to less sustainable and +1 to more sustainable. According to Guo et al. (2015), Pavlovskaia (2014) and Schwartz (2012), this scale has several advantages: it is easy to understand and interpret; allows for straightforward comparison between different indicators and practices; and ensures a balanced assessment by considering both positive and negative impacts.

iv) Calculation of the Sustainability Index

The SustenAgro Index was chosen as reference for the calculation of the sustainability index because it addresses all three dimensions of sustainability - social, environmental, and economic. Specifically developed for the sugarcane industry, it is highly relevant and accurate for this crop, considering the distinct challenges and opportunities in the production of sugarcane (Jesus et al., 2019; Voora et al., 2023). Previous studies have demonstrated its practicality and effectiveness in evaluating the sustainability of sugarcane production system. Sustainability Index (SI) for each farmer was calculated using the Equation 4:

$$SI = \sum_{n=1}^{N} w_n * v_n * w_N + \sum_{s=1}^{S} w_s * v_s * w_S + \sum_{e=1}^{E} w_e * v_e * w_E \tag{4}$$

where:

n to N is the set of indicators in the environmental dimension;

s to S is the set of indicators in the social dimension;

e to E is the set of indicators in the economic dimension;

w_n, w_s and w_e are the weights of each individual environmental, social and economic indicators;

v_n, v_s and v_e are the values of each individual environmental, social and economic indicators;

w_N, w_S and w_E are the weights of the environmental, social and economic dimensions.

To analyze variations in the *SI* and classify it at the appropriate level, the Sustainability Index was normalized (*SI'*) to a scale from −100 to +100 in Equation 5. This was then evaluated using the "sustainability traffic light", a tool that visualizes results with a color-coded system, indicating the performance of different sustainability indicators (see Table 2).

Table 2. Sustainability semaphore indicating variations in sustainability level.

-100 to -60	-60 to -20	-20 to 20	20 to 60	60 to 100
Lower sustainability	Negative changes	Not relevant changes	Positive changes	Higher sustainability

Source: Adapted from Jesus et al. (2019).

$$SI' = \frac{100-(-100)}{SImax - SImin} * (SI - SImin) + (-100) \quad (5)$$

2.2. Description of study area

The present study was conducted in the province of Sofala, Mozambique. It focused on sugarcane farmers from two districts within the province: Nhamatanda and Buzi, both of which supply sugarcane to the Mafambisse sugar factory. Sofala Province, located in central-eastern Mozambique, spans an area of 68,018 square kilometers. Sofala benefits from favorable agroecological conditions and a strategic geographic location for sugar production (Banco de Moçambique, 2022), influencing the establishment of the four sugar factories currently operating there. This province was selected because it hosts 50.12% of the country's sugar factories. The Mafambisse sugar factory was chosen due to its unique position as the only factory in Sofala Province that produces sugarcane on its own fields and purchases sugarcane from individual farmers under contract. Currently, it collaborates with 37 farmers, including both individuals and associates.

2.3. Sample selection

The study's target group consisted of active sugarcane farmers participating in the 2023 agricultural campaign. An intentional sampling method to select these farmers was employed. According to Lauretto et al. (2012), intentional sampling is a type of non-probabilistic sampling in which the researcher plays a significant role in choosing the elements of the population that will form the sample. This method requires the researcher to be well-informed about the characteristics of the target group. As a result, the study identified 30 farmers as eligible and available for participation.

2.4. Data collection

Data collection was carried out using a questionnaire structured in two sections. The first addressed the socioeconomic characteristics of farmers, including affiliation, gender, age, education level, farm size, household size, and years of agricultural experience. These variables were selected from studies by Nwaiwu et al. (2013), Afrous & Abdollahzadeh (2011) and Sharifzadeh & Abdollahzadeh (2017). The second section comprised a set of 38 appropriate and priority indicators to assess the sustainability of sugarcane production, selected by ten experts from the government, the private sector, and academia specializing in sugarcane production, environmental management, and sustainability in Sofala province, using two rounds of the Delphi method. Three technicians from agricultural extension services assisted in applying the questionnaire with 30 farmers in February and March 2024. Each farmer was engaged for 20 and 25 minutes to complete the questionnaire, and the collected data were handled with strict anonymity and confidentiality.

2.5. Data analysis

The data were analyzed using descriptive statistics tools (mean, frequency and percentage) to assess the distribution of sugarcane farmers based on their socioeconomic characteristics and sustainability levels. An ANOVA test was applied to compare the average environmental, social, and economic contributions to the SI. Additionally, regression analysis was employed to examine the influence of farmers' socioeconomic characteristics on the SI of sugarcane production. These tests were performed using SPSS Version20 software, with significance level at 0.05.

3. Results

This section presents the findings. The first part focuses on describing the farmer's characteristics, followed by an analysis of the performance of the sustainability dimensions, the calculation of the SI and the final determination of the sustainability levels. Additionally, the influence of farmers' characteristics on the SI is tested.

3.1. Characteristics of farmers

Of the 30 farmers interviewed, 86.7% were male, while only 13.3% were female. Most farmers (56.7%) are members of the Buzi Sugarcane Growers Association, located in the Búzi district; whereas 23.3% belong to the Mudagrower Association; and 3.3% are part of the Muda Macequesse Association, both situated in the Nhamatanda district. The remaining 16.7% are independent farmers, not affiliated with any association, also located in the Nhamatanda district.

The average age of farmers is 55.73 years, with an average of 16.27 years of agricultural experience. In terms of education, 50% have completed secondary education, while 30% have attained higher education. The average production area is 58.52 hectares. Farmer families range from 2 to 12 members, with an average family size of 5.6 members.

3.2. Description of indicators by sustainability dimensions

3.2.1. Environmental indicators

In the environmental dimension, nine indicators were used in the study. The results show that none of the interviewed farmers measure the water quality used for irrigation (N1) or have a system in place to monitor the quantity of water used (N3 and N4). Furthermore, 73.3% of farmers lack a management system for capturing irrigation water from the primary source (N2).

Despite the low performance on water-related indicators, all farmers use sugarcane varieties that are well-suited to their region's climate and soil (N6), comply with transport and conservation regulations (N9), and 80% report having uninterrupted water availability during the production cycle (N5), which is essential for agricultural production. Moreover, more than half of the farmers (53.3%) rely on estimates to measure the amount of inputs needed for their fields (N7), such as one bag of 50 kg per hectare, while 56.7% do not have a suitable location for disposing of waste and product containers used in the field (N8).

3.2.2. Economic indicators

With an average yield of 53.29 tons per hectare (E7) and a total production of around 3,293 tons (E4), the economic dimension of the study revealed an average return on investment of 1.67 years. Notably, 73.3% of farmers were able to recover their investment in less than 2.5 years (E1). Additionally, 93.3% of farmers expressed intentions to expand their production area to increase earnings and meet the growing demand for sugarcane from the factory.

3.2.3. Social indicators

Regarding social indicators, only 26.7% of farmers regularly train their workers in the production process and other cultivation techniques (S6). However, training in hygiene and safety at work is more common, with 60% of farmers incorporating it as a routine activity (S8) and being satisfied with the associated salary (S9). Furthermore, 46.7% of farmers have created more than 50 permanent and seasonal jobs in 2023 campaign (S12).

Community development activities or initiatives related to the delivery of basic food baskets to needy families in production areas are carried out by only 20% of farmers (S7). Gender balance on farms is notably low, with only 3.3% of farmers achieving a balance between male and female workers (S10). Working hours exceed 40 hours per week for 50% of the farmers (S11), with 53.3% of these workers being formalized (S3).

Land conflicts with local communities have not been reported by any farmers (S13). Work accidents are rare, with only 3.3% of farmers having experienced one on their farms (S5). Additionally, 73.3% of farmers provide their workers with adequate protective equipment (S2).

3.3. Weights and contributions of individual indicators

The results of the entropy method regarding the weights of the 38 selected indicators revealed that, within the environmental dimension, the indicator 'Measuring the amount of water used in the production process' (N4) had the highest weight (0.2011), followed by indicator N3 'Measuring the amount of water in the irrigation system' (0.1506). In contrast, the indicator for the 'Existence of a suitable place to deposit waste' (N8) had the lowest weight (0.0601). Regarding the economic dimension, the indicators of the 'Existence of transportation of sugarcane from the field to the factory' (E11) and the relationship between investment in machinery, production and return on investment (E12) had the highest weight, with 0.1347 and 0.1244, respectively. The social dimension had the indicator 'Presence of child labor' (S4), with the most significant weight (0.2378), followed by 'Occurrence of accidents in the previous year' (S5, 0.1526) and 'Formalization of employment' (S3) with 0.1028.

In general, the indicators with the highest weight were 'Presence of child labor' (S4, 0.2378), 'Measuring the amount of water used in the production process' (N4, 0.2011), 'Occurrence of accidents in the previous year' (S5, 0.1526), 'Measuring the amount of water in the irrigation system' (N3, 0.1506) and 'Existence of a water management and collection system' (N2, 0.1437), corresponding to environmental and social dimensions (see Table 3).

Table 3. Weight of indicators by dimensions.

Indicators	Weight	Indicators	Weight	Indicators	Weight
Environmental dimension		Economic dimension		Social dimension	
N1	0.0766	E1	0.0115	S1	0.1028
N2	0.1437	E2	0.0549	S2	0.0114
N3	0.1506	E3	0.0496	S3	0.1028
N4	0.2011	E4	0.0549	S4	0.2378
N5	0.0767	E5	0.0144	S5	0.1526
N6	0.0831	E6	0.0476	S6	0.0161
N7	0.1234	E7	0.0456	S7	0.0321
N8	0.0601	E8	0.0496	S8	0.1028
N9	0.0848	E9	0.0908	S9	0.0047
		E10	0.0878	S10	0.0399
		E11	0.1347	S11	0.0235
		E12	0.1244	S12	0.0212
		E13	0.0908	S13	0.1028
		E14	0.0489		
		E15	0.0456		
		E16	0.0489		

Regarding the weights of sustainability dimensions, the results of the entropy method.

Regarding the weights of sustainability dimensions, the results of the entropy method showed a greater weight for the environmental dimension (0.4247), followed by the social and economic dimensions with 0.3833 and 0.1920, respectively. An ANOVA test was conducted to compare the average contributions of the different sustainability dimensions to the sustainability of sugar production. The results indicated a significant difference among the contributions of the environmental, social, and economic dimensions to the SI, with a p-value of less than 0.01 (see Table 4)

Table 4. ANOVA test results on the dimension's contribution to the sustainability index.

	Sum of Squares	Degree of freedom	Mean Square	F-statistic	Significance
Between Groups	10.510	2	5.255	80.145	.000
Within Groups	5.705	87	0.066		
Total	16.215	89			

The results of the Tukey HSD post hoc test revealed statistically significant differences among the mean values of the three dimensions. Specifically, the social dimension had the highest contribution to the SI, with an average of 0.5145. The economic dimension followed, contributing a mean of 0.2555, while the environmental dimension had the lowest average value of -0.3043, indicating a lesser contribution to the overall sustainability of sugarcane production.

To further explore the contribution of each indicator to the composite index of each dimension, the results revealed that 'Rational use of inputs' (N7, 0.099), 'Compliance with regulations for the transportation, conservation, sale and appropriate disposal of pesticide waste and containers' (N9, 0.079), 'Water availability throughout the production cycle' (N5, 0.051), 'Existence of a suitable place to deposit waste' (N8, -0.008) and 'Use of sugar cane varieties adapted to local soil and climate conditions' (N6, -0.028) were the five indicators that most contributed to the environmental dimension composite index (see Figure 1).

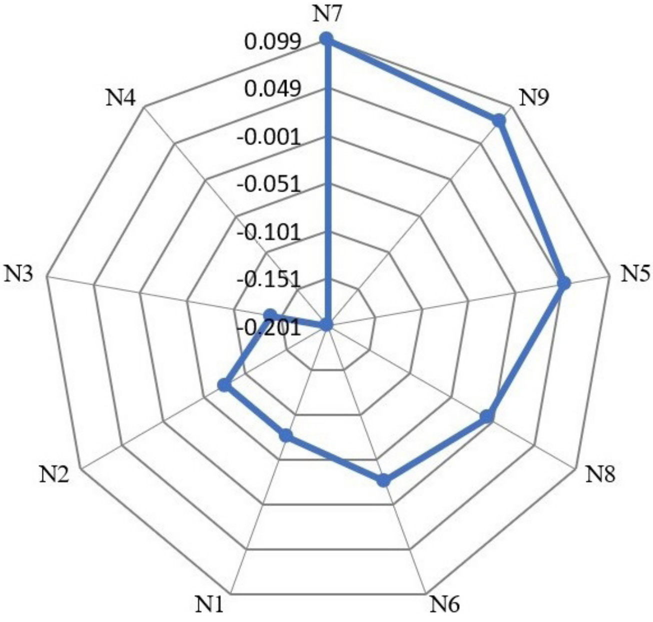

Figure 1. Environmental indicators contribution to the SI

Regarding social indicators, 'Presence of child labor' (S4, 0.222), 'Occurrence of accidents in the previous year' (S5, 0.142), 'Land conflict' (S13, 0.102), 'Alignment of working conditions with current law' (S1, 0.062) and 'Formalization of employment' (S3, 0.021) had highest contributions to the social dimension composite index, with 'Presence of child labor' (S4) in the lead among the mentioned indicators (see Figure 2).

In the economic dimension, the indicators: 'Existence of sugarcane transportation from the field to the factory' (E11, 0.090), 'Existence of planting planning' (E9, 0.085), 'Existence of harvest planning' (E10, 0.076), 'Existence of a production expansion plan' (E6, 0.041) and 'Sugarcane price' (E8, 0.036) had the largest contribution to the composite index of this dimension (see Figure 3).

3.4. The Sustainability Index of the Farmers

Among the calculated SI, 76.7% of production systems had an index above zero. The district of Nhamatanda had farmers with the five highest sustainability indexes, three of whom belonged to the Mudagrower association, while two were independent farmers not affiliated with any association. Conversely, all farmers with production systems exhibiting negative SI were located in the Búzi district and belonged to the Búzi Sugarcane Farmers Association. These results suggest a potential relationship between SI and the farmer's location (see Figure 4).

3.5. Factors influencing the Sustainability of Sugarcane production

To analyze the level of sustainability of the production systems, the results of the indexes were incorporated and the sugarcane production systems were classified into different sustainability levels. The results of sustainability

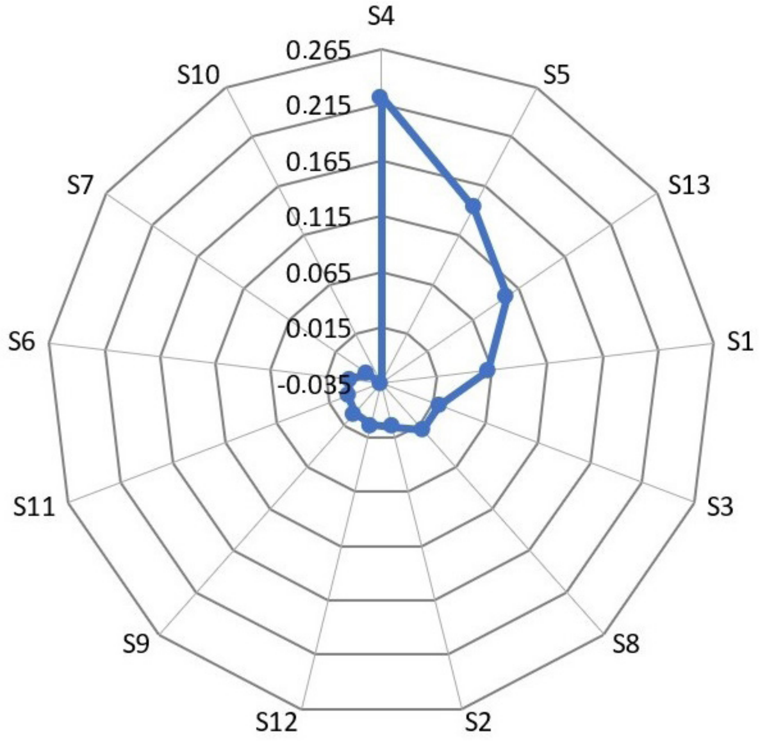

Figure 2. Social indicators contribution to the SI.

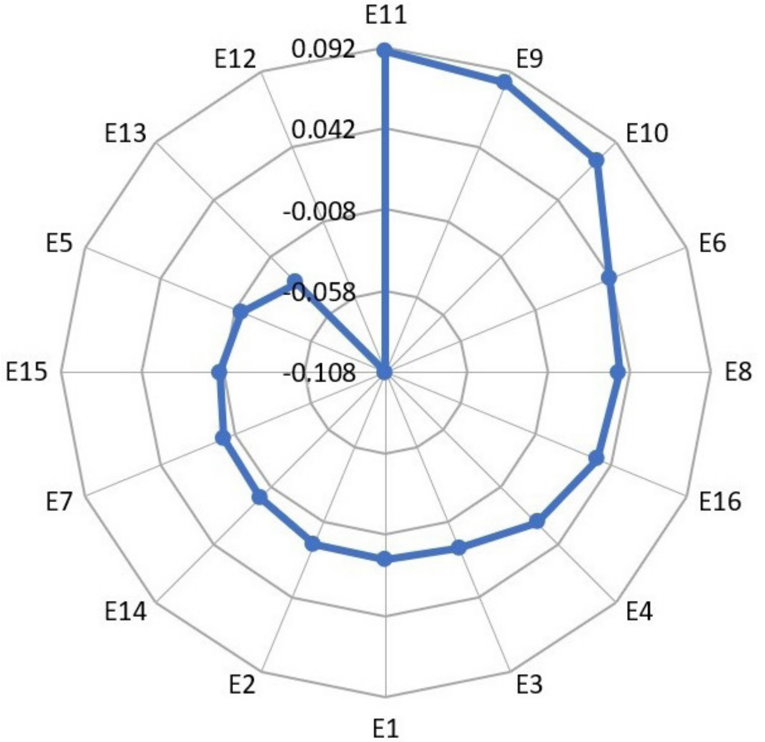

Figure 3. Economic indicators contribution to the SI.

semaphore show that the same percentage (20%) of farmers achieved high and low sustainability in their production. A higher percentage s, corresponding to 26.7% experienced no relevant changes in sustainability. Additionally, 13.3% of the farmers were classified as having systems with positive changes, though not reaching the high sustainability threshold, while 20% were identified as having negative changes (see Figure 5).

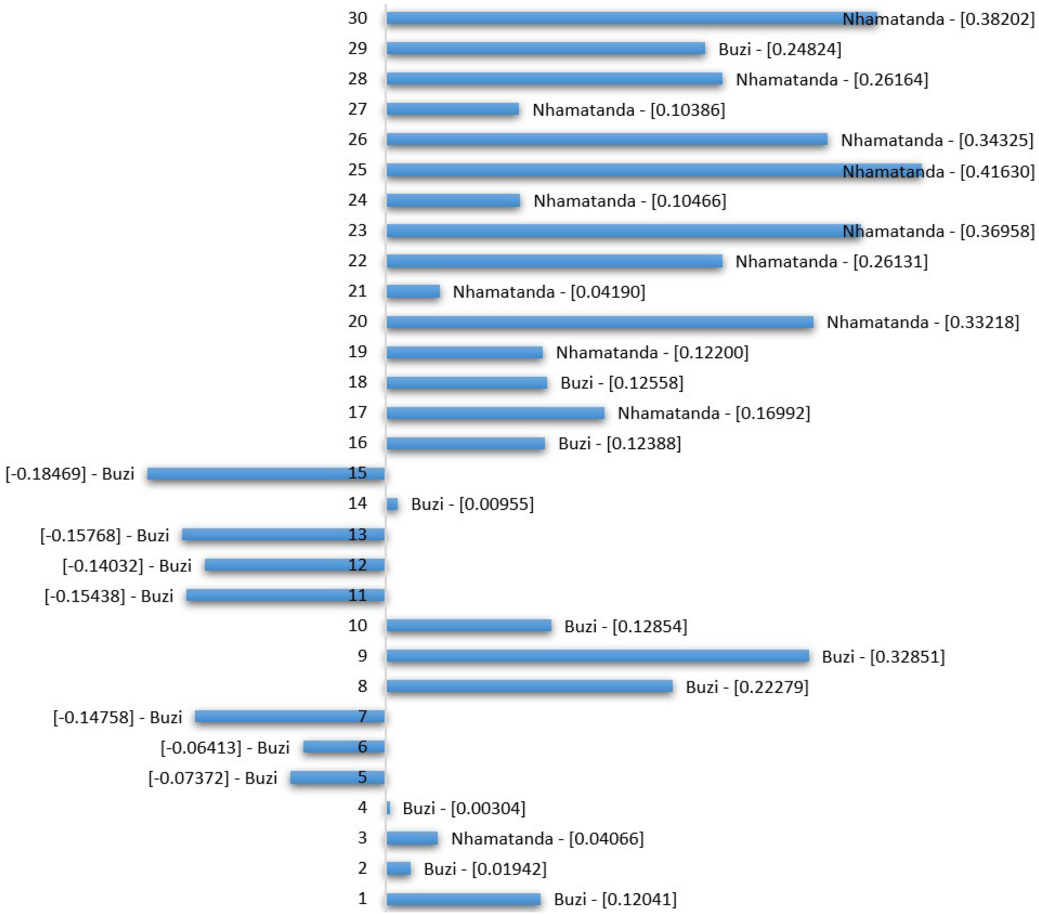

Figure 4. SI of the 30 farmers included in the sample study.

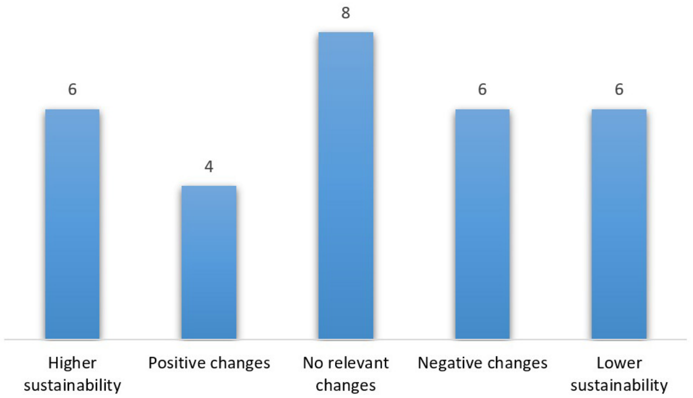

Figure 5. Sustainability level of sugarcane farmers.

Regarding the sustainability levels of the two districts within the study area, the results indicated that the Búzi district had a SI of -31 (the average of the farmers' indexes in this district), reflecting systems with negative changes and a tendency toward low sustainability. In contrast, the Nhamatanda district presented a SI of 37, indicating that its sustainability level falls within the category of positive changes, leaning towards high sustainability. Overall, the results suggest that sugarcane production systems in the study area do not exhibit relevant changes in the sustainability (see Table 5).

Table 5. Sustainability index and level in the study area.

Local	Sustainability index	Sustainability level
Buzi district	0.02397	-31
Nhamatanda disctrict	0.22687	37
Sofala province	0.11189	-1.3

A regression analysis at a 0.05 significance level was performed to analyze the influence of farmers' socioeconomic characteristics on the SI. The SI was modeled as a function of several household factors, including the farmers' location, gender, age, farm size, household size, farming experience, and education level. The regression results (see Table 6), revealed that only the farmer's location significantly influenced the SI, with p-value < 0.01. This finding suggests that the proximity of farms to the processing facility has a notable impact on the SI and consequently, on the sustainability of sugarcane production.

Table 6. Regression analysis results for SI determinants.

Model	Regression Coefficients (B)	Standard. Error	Beta	t-statistic	Significance
(Constant)	.793	.300		2.646	.015
Location	-.211	.064	-.594	-3.299	.003
Gender	-.179	.111	-.346	-1.614	.121
Age	-.006	.004	-.399	-1.573	.131
Farm size	.001	.001	.261	1.243	.228
Household size	-.017	.017	-.214	-.986	.335
Farm experience	.003	.003	.258	1.307	.205
Higher Education	-.117	.098	-.305	-1.197	.245
Secondary Education	.000	.086	.001	.003	.998
R Square	0.514				
Adjusted R Square	0.329				

4. Discussion

The study assesses the sustainability of sugarcane production in Sofala province, Mozambique, by integrating the SustenAgro Index approach with the EWM. The findings reveal that most of the sugarcane farmers in study area are male. According to Eleazar et al. (2024) and Sumbele et al. (2018), this predominance is attributed to the labor-intensive nature of sugarcane production, which demands significant physical strength, as well as men's greater access to land ownership and control over agricultural resources. These findings align with Cheruiyot (2021), who reported that 69% of sugarcane producers were male.

Moreover, the majority of farmers fall within the middle-age range, characterized by vigor, enthusiasm, and moderate experience in cultivating sugarcane. Farmers in this age group are often considered more efficient than their younger or older counterparts. Similar observations have been reported by Cheruiyot (2021) and Pawar & Devendrappa (2022).

The environmental dimension contributed the least to overall sustainability, with water management indicators exerting a particularly negative influence. As a water-intensive crop, sugarcane production is heavily impacted by irrigation practices, making water availability a critical factor in sustainable management (Surendran et al., 2016). Proper irrigation is essential for maintaining soil moisture, which supports healthy crop development and high yields. Effective management of sugarcane production, therefore, requires accurately assessing water needs throughout the growth period (Li, 2023; Sela, 2023; Yadeta et al., 2021).

The absence of systems to monitor water quality, control irrigation water quantities, manage primary water sources, and track overall use impedes effective water management. This lack of oversight complicates efforts to sustainable manage this vital resource. Dingre (2023) states that drought and inadequate irrigation practices are major factors contributors to reduced sugarcane productivity. Similarly, Gupta & Singh (2015) highlight the importance of accurately determining water application based on water quality, resource availability, and supply reliability.

The poor performance of water-related indicators may be attributed to farmers' limited financial resources, which restricts their ability to invest in advanced infrastructure and effective water collection and management tools. Consequently, many farmers depend on basic systems, such as motor pumps and other local equipment, to transport water directly from rivers to their fields. Despite deficiencies in water management, the sugarcane varieties cultivated are well-suited to the region's edaphoclimatic conditions. These varieties are selected by sugar companies based on soil quality assessments and local environmental conditions, aiming to optimize production and productivity.

Although water management indicators were given greater weight within environmental dimension, only 'Water availability throughout the production cycle' (N5) made a strong contribution to the top three indicators. This finding aligns with results from Jesus et al. (2014) and Kautzar et al. (2020), who pointed out that water use has a significant impact on the performance of the environmental dimension.

Unlike the environmental dimension indicators, in the social dimension, the indicators 'Presence of child labor' (S4), 'Occurrence of accidents in previous years' (S5) and 'Land conflict' (S13) contributed the most to the social composite index and received higher weight. Prasara-A et al. (2019), Aguilar-Rivera (2022) also indicated 'Employment and Labor Conditions', 'Health and Safety', 'Community Engagement', 'Education and Training', and 'Gender Equality' as key indicators for assessing and enhancing social sustainability in sugarcane production. Therefore, the findings of this study show a partial convergence with the indicators highlighted by these authors, emphasizing common areas of social impact within the sustainability of sugarcane production.

According to (Aguilar-Rivera, 2022; Bhatt, 2020; Bordonal et al., 2018), indicators such as 'Yield', 'Market prices', 'Profit margins' and 'Investment in technology' typically play a significant role in enhancing the economic sustainability of sugarcane production, ensuring it remains profitable and positively impacts the local and national economy. However, the findings from this study contradict these results, as the transportation of sugarcane from the field to the factory, plantation planning, and harvest planning contributed the most to the positive performance of the economic dimension. In contrast to the environmental dimension, the social dimension exhibited positive performance, with over 50% of responses rated as satisfactory. These findings diverge from those of García-Bustamante et al. (2018), who reported that in their evaluation of four sugar production systems in Mexico, economic performance outperformed both environmental and social dimensions. The discrepancy between the two studies can be attributed to different research focus. The present research examines individual farmers, while García-Bustamante et al. (2018) focused on production areas associated with the factory, which are more linked to economic gains. Also, the method used to construct a composite index and the type of indicators used in the two studies may have influenced the aforementioned discrepancy in the results.

Sugarcane production systems in Sofala Province do not exhibit relevant impacts on their sustainability, suggesting that farmer prioritize mitigating adverse effects rather than advancing overall sustainability. These findings contradict those of García-Bustamante et al. (2018), who reported that 50% of the assessed sites were potentially sustainable.

Only the farmers' location showed a statistically significant negative influence on the SI, suggesting that farmers from Nhamatanda district (58 km from the factory), have higher sustainability levels than those in the Buzi district (111 km from the factory). This finding contradicts the results of Jamal et al. (2017), who found that education and farm size were related to adoption of the Sustainable Sugarcane Initiative. However, it aligns with Prasara-A & Gheewala (2016), who identified distance to the sugar mill as a significant factor influencing the environmental and socio-economic impacts of sugarcane cultivation and, consequently, its sustainability. Farms located farther from the factory face challenges such as high transportation costs (imputed to the farmer), poor road quality, and cane loss during transport, all of which negatively affect farmer's income.

5. Conclusion

The present study assessed the sustainability of sugarcane production among 30 farmers in Sofala Province, Mozambique, using an integrated approach that combines the SustenAgro Index with the EWM. This method is particularly relevant and reliable for sustainability assessment, as it encompasses the three primary dimensions of sustainability: environmental, economic, and social. This comprehensive approach allows for a thorough evaluation at the level of individual production units. The entropy method employed to determine the weights of the indicators is transparent and effectively captures experts' opinions on the appropriate weights for the selected indicators, free from external interference, thus ensuring an objective and accurate assessment of sustainability.

Environmental aspects, particularly those related to water management, remain a significant challenge for the sustainability of sugarcane production. Although the sugarcane production systems in the Sofala Province have not present substantial improvements in sustainability, there are expectations for progress due to more frequent interactions between farmers and extension services, as well as experts from the sugarcane factory. These interactions are likely to promote the adoption of increasingly sustainable practices.

The indicators related to 'Measurement of the amount of water used in the production process', 'Measurement of the amount of water in the irrigation system', 'Existence of a water management and collection system', 'Respect for gender equality at work', 'Existence of actions to promote well-being of the local community', 'Existence of worker training programs', 'Consideration of the relationship between investment in machines, production and return on investment', 'Type of cultivation practices' and 'Investment in technologies', had the lowest contributions to the sustainability of sugar cane in Sofala. Therefore, these indicators require greater attention to develop strategies aimed at improving their performance.

The distance between production fields and the sugar factory significantly impacts the sustainability of sugarcane production systems in Sofala.

The model used to determine sustainability is effective, user-friendly, and adaptable to different regions, providing specific and relevant results. It can also be applied to other industrial crops with similar production characteristics, such as tobacco, sesame and cotton. However, despite its efficient and practicality, the indicators used in this study are not universal and may not be applicable in all contexts. Therefore, it is important to carefully identify indicators that are specific to the area under study and tailored to each unique context.

This work represents a significant contribution to the development of methodologies for assessing agricultural sustainability, specifically in sugarcane production. It is the first of its kind in Mozambique to incorporate the three main dimensions of sustainability within the same framework while employing the entropy method to determine the weights of the respective indicators. In the context of the sugar industry and farmers, this study provides an efficient and effective tool for measuring the performance of various production systems (small, medium, and large), making it simple and easy to apply. Politically, the framework presented serves as a guiding point for policymakers and decision-makers, emphasizing the importance of fostering deeper discussions on sustainable agricultural practices in sugarcane production.

Further studies in other provinces of Mozambique and across Southern African countries are recommended. Subsequent evaluations of sugarcane production sustainability will generate valuable comparative data and inform the development of targeted actions at both national and regional levels. This approach will enhance the understanding of sugarcane sustainability across diverse contexts, enabling the creation of tailored strategies that address the unique conditions of each area. Furthermore, incorporating a longitudinal approach into the method used in this study is essential, as it would provide more detailed quantitative data over time.

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