Global J. Environ. Sci. Manage. 10(2): 743-758, Spring 2024, Serial #38

Global Journal of Environmental Science and Management
(GJESM)

Homepage: https://www.gjesm.net/

Podcasts

ORIGINAL RESEARCH ARTICLE

Balancing environmental impact: A sustainability index analysis of sorghum production for food and feed

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ARTICLE INFO

Article History:
Received 20 August 2023
Revised 07 October 2023
Accepted 06 December 2023

Keywords:
Feed
Food
Multidimensional scaling
Sorghum
Sustainability

DOI: 10.22035/gjesm.2024.02.20

ABSTRACT

BACKGROUND AND OBJECTIVES: Sorghum is a grain-producing commodity with the seeds being a food source, while the leaves, stems, and bran serve as animal feed. The productivity depends on the specific variety, environment, infrastructure, and technology used. Sorghum cultivation in Indonesia is carried out primarily using agroforestry or monoculture. Despite not being as popular compared to rice and corn due to the prevalence of these staples in Indonesian diets, sorghum has the potential to replace corn because its cultivation is easier and the results are more profitable. Therefore, this study aimed to determine sustainability index and potential of sorghum for food and feed by identifying dimensions and attributes that influence sustainability.

METHODS: This study was conducted at Raji, Demak, Central Java, Indonesia in 2023. Data were collected through focus group discussions and structural questionnaires consisting of 28 attributes associated with environmental, social, economic, and technological dimensions. Multidimensional scaling method and Rapfish software were used for data analysis. Monte Carlo analysis was used to ascertain sustainability level and attributes leverage, as well as check errors and variations in assessment.

FINDINGS: The results showed that sustainability index of sorghum for food and feed was 79.67, categorized as very sustainable. Analysis across four dimensions showed that the social dimension had the highest (83.80) sustainability index, followed by the technological (82.28), economical (77.46), and environmental (75.15) dimensions. A total of 12 attributes were found to greatly affect sustainability. These included land availability, the efficiency of water used, the prevention of natural resource exploitation, motivation level, minimal interference with primary agricultural activities, community acceptance, productivity, sales profit level, ease of sale and cultivation, tools availability, and technological sensitivity.

CONCLUSION: Sustainability index of sorghum for food and feed was categorized as very sustainable with a value of 79.67. This index consisted of the environmental (75.15), social (83.80), economical (77.46), and technological dimensions (82.28). The average productivity at the study site was 6-7 tons per hectare (tons/ha), with a production potency of 300-350 tons/year. Additionally, the potency of sorghum stover production was 471.8 ton per year of dry matter and could be used as feed for 163 animal units/year.

NUMBER OF REFERENCES
54

NUMBER OF FIGURES
5

NUMBER OF TABLES
2

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Note: Discussion period for this manuscript open until July 1, 2024 on GJESM website at the "Show Article".

INTRODUCTION

Sorghum is a versatile cereal grain plant used for multiple purposes including a source of food, feed, fuel, as well as industrial raw material. The various forms consist of grain, sweet sorghum, forage, and broom (Hao *et al.,* 2021). This plant holds a vital position as the most essential food crop in the world comparable to wheat, rice, maize, and barley (Rao *et al.*, 2014). The calorie content is approximately 332 calories per 100 grams (cal/g), with 11 percent (%) protein, 3.3% fat, 73% carbohydrates, and 28% calcium (Sihono *et al.,* 2019). Sorghum can be cultivated on suboptimal land with drought stress, high temperatures, less fertile soil, and minimal costs, and inputs (Dorcas *et al*., 2019). The planted area in Indonesia is estimated at 3,879 hectares (ha) with the largest occurring in East Nusa Tenggara (60%), while East Java, Central Java, West Java, Southeast Sulawesi, and West Nusa Tenggara account for 3-10%. Sorghum cultivation is carried out using agroforestry or monoculture but is not as popular compared to rice and corn, which are widely used as staples in Indonesian diets. However, sorghum has the potential to replace corn because the cultivation is easier and the results are more profitable. The productivity of several varieties in Gunung Kidul Indonesia with average 6.27 tons per hectare (tons/ha) is as follows: Bioguma (7.70), Plonco (8.41), Samurai (5.38), Kawali (8.21), Red Glutinous Sorghum (Ketan Merah**)** (3.91), and Black Sorghum Wareng (4.00) (Muazam *et al.,* 2023). The average productivity value is greater than the national average production of corn 5.71 tons/ha in Indonesia (BPS, 2021). The development in Indonesia has been very slow because farmers prefer to plant rice and corn. However, sorghum is more drought-resistant than corn, resulting in the development being directed at dry areas. The primary producers include the USA, Nigeria, Sudan, Mexico, and Ethiopia (USDA, 2022). Sorghum is a drought-tolerant plant and easier to cultivate depending on the variety, seed preparation, planting time, land preparation, planting, fertilizing, maintenance, and pest/disease control. The plant can grow optimally at 0-500 meters (m) above sea level using a monoculture or intercropping approach with secondary crops or vegetation on land. In this context, planting distance is calculated based on production purposes, either for food or feed. Sorghum needs water for optimal growth, specifically after seedling establishment, and is relatively more resistant to pests and diseases compared to other secondary crops. The common pests include sorghum fly (*Atherigona varia Soccata* (Rond.), *Prodenia litura* F., and *Spodoptera frugiperda* J.E. Smith (s). Furthermore, sorghum plays a significant role in global food security, offering an alternative feed option due to its ability to grow in arid and semi-arid areas. Environmental factors such as climate, soil, water, agricultural technology, and environmental changes can impact productivity for stable and sustainable food in the future. celsiusA temperature of more than 35 degrees Celsius (°C) can affect growth and crop yield (Chadalavada *et al*., 2021). Excessive humidity or prolonged rainy seasons also have the potential to reduce productivity (Hatfield *et al.,* 2011). Drought is a significant limiting factor in reducing crop yields, while other factors that affect productivity include soil type and fertility. Sandy, or clayey soils, and a potential of hydrogen (pH) close to neutral, support the growth of sorghum (Abreha *et al*., 2022). Moreover, fertilizer plays a key role in increasing productivity, providing major nutrients such as nitrogen (N), phosphorus (P), and potassium (K) (Samijan *et al.*, 2023; Samimi *et al.,* 2023). In this context, it is essential to adjust the nitrogen fertilizer dose based on soil conditions and local environmental factors. Land without N fertilizer resulted in a decrease in sorghum yield to 39.3% (Ganyo *et al.,* 2019). The optimum fertilizer dose per hectare is nitrogen (N) 160.4 kilograms (kg), diphosphorus penta oxide (P_2O_5) 43.7 kg, and dipotassium oxide (K_2O) 124.9 kg (Karimuna *et al.,* 2020). According to a previous study, understanding specific agricultural sites, including soil type and climatic conditions, is crucial for effective fertilization (Akinseye *et al.,* 2020). To significantly increase productivity, there is also a need to use appropriate irrigation technology (Ghalkhani *et al.,* 2023). Water availability during the growth phase plays a very important role in determining crop yields (Darmawan *et al.,* 2023). Meanwhile, sorghum is very sensitive to waterlogging at the stage of the fifth leaf and flowering. High humidity can increase the risk of pests and diseases, showing the need for pest control strategies (Huang *et al.,* 2013). Sorghum has economic value as food, feed, energy, and industry. This is attributed to its potential ability to substitute rice and corn or process into diversified products (Pontieri and Giudice, 2016). In a circular and zero-waste economy, sorghum is a sustainable source of biomass (Babicka *et al.,* 2022), and by-products including stover, stems, and bran can be used as feed. The nutrient of stover based on the dry matter comprises 7.82% crude protein (CP), 2.60% extract ether (EE), 28.94% crude fiber (CF), 11.43% ash, and 40.57% nitrogen-free extract (NFE) (Korima *et al.,* 2022). At the flowering stage, the nutrient content includes 10.8% water, 6.70% ash, 8.79% CP, 1.20% EE, 27.88% CF, and 49.83% total digestible nutrient (TDN) (Sriagtula *et al.*, 2017). Sorghum stalks contain roomi used as a source of energy for feed, and the stover nutrient from several genotypes ranges from 7.91-9.30% CP, 1.91-2.69% EE, 33.41-37.57% CF, and 8.25-9.11% ash (Harmini *et al.,* 2022). Singh *et al.*, (2018) estimated the energy of sorghum stover for ruminants at 2.0 kcal/g, while the potency for production is approximately 20-40 tons/ha depending on the level of soil fertility and variety. Meanwhile, sorghum bran contains a high protein level and is also a source of kafirin, xyloglucan, and glucan used as industrial raw materials (Sihono *et al.,* 2019). Agricultural sustainability is usually measured based on certain dimensions (Sulewski *et al.,* 2018), including social, economic, and environmental (Assan, 2023). Achieving sustainability, specifically in terms of food security, requires a comprehensive assessment of the interplay between different agro-economic and socio-environmental indicators (Karandish *et al.,* 2022). Therefore, this study aimed to assess sustainability index and potential of sorghum for food and feed. The results provide information on sustainability index from environmental, social, economic, and technological dimensions.

MATERIALS AND METHODS

Data retrieval

This study was carried out at Raji, Demak, Central Java, Indonesia in 2023, and data were collected through focus group discussions (FGD). A survey was conducted on eight experts in sorghum crop and business actors who have at least experience five years, using structural questionnaires. FGD assessed the current business environment supporting production as basic information for designing sustainability dimensions and attributes. Sustainability dimensions used were environmental, social, economic, and technological. The indicators included 28 attributes in a structural questionnaire with answer choices. Sustainability index (score) of each dimension was determined by entering the scores of each attribute into Multidimensional scaling (MDS) software. The scores were obtained from the respondents, namely 1 (too bad), 2 (bad), 3 (medium), 4 (fairly good), and 5 (good).

Data analysis

MDS through the Rap method (Rapid Appraisal for grain sorghum plants) was used for data analysis. This was developed and adopted from the Raffish (Rapid Appraisal for Fish) method to determine sorghum production sustainability using the following steps (Lloyd *et al.,* 2022):

1) Appraise dimensions and attributes of sustainability. This study used four dimensions with 28 attributes.

2) Assess attributes using scores. The scores of attributes formed a matrix X (n x p), where n is the regions and reference points number, and p is attributes used number. Each score was standardized using Eq. 1 (Borg *et al.,* 2018).

$$X_{ik}sd = \frac{X_{ik} - X_k}{s_k} \quad (1)$$

$X_{ik}sd$ = i-th regional standard score (including reference points) = 1, 2, …, n for each attribute = 1, 2, …, p

X_{ik} = i-th standard score (including reference points) = 1, 2, ..., n for each attribute = 1, 2, ..., p

X_k = average score on each attribute = 1, 2, …, p

S_k = scores standard deviation for each attribute = 1, 2, …, p

The shortest distance from the Euclidian distance was calculated with Eq. 2 (Borg *et al.*, 2018), and then using the regression Eq. 3 (Borg *et al.*, 2018), it was projected into two-dimensional Euclidian space (d12). The regression process used the ALSCAL algorithm by carrying out iterations leading to an intercept value of zero (a = 0). This change led to Eq. 4 (Borg *et al.,* 2018), and the repetition process was stopped after the stress (S) value was <0.25. The S value was obtained using Eq. 5 as follows (Borg *et al.,* 2018):

$$d = \sqrt{\left(|x_1 - x_2|^2 + |y_1 - y_2|^2 + |z_1 - x_2|^2 + \ldots\right)} \quad (2)$$

$$d_{ij} = \alpha + \beta\delta\beta_{ij} + \varepsilon \quad (3)$$

$$d_{12} = bD_{12} + e; \quad (4)$$

$$s = \sqrt{\frac{1}{m}\sum_{k=1}^{m}\left[\frac{\sum_i\sum_j\left(d_{ijk}^2 - o_{ijk}^2\right)^2}{\sum_i\sum_j o_{ijk}^4}\right]} \quad (5)$$

Sustainability indices and status were categorized as follows: not sustainable (0.00−25.00), less sustainable (25.01−50.00), moderately sustainable (50.01−75.00), and highly sustainable (75.01−100.00), according to (Rachman *et al.,* 2022).

Analysis of sensitivity (leverage) was conducted to determine attributes that greatly influence sustainability. This analysis was based on the sequence of changes in root mean square (RMS) ordination on the x-axis. When RMS had a significant value, it means that the role of attributes was prominent in sustainability status. Monte Carlo analysis to estimate the error rate in MDS model for all dimensions used a 95% confidence level. The smaller the difference between MDS and Monte Carlo analysis results, the better the resulting model. Furthermore, the goodness of fit was designated in the S value and coefficient of determination (R^2). The low S value means a good match and The high S value shows the opposite. The S value of less than 0.25 showed a good model, while an R^2 value close to 1 denoted that attributes used were quite accurate (Borg *et al.*, 2018; Samimi and Moghadam, 2024).

RESULTS AND DISCUSSION

Dimensions and attributes

FGD produced four dimensions including environmental, social, economic, and technological with several attributes (Table 1). Attributes in each dimension were used as material to obtain sustainability index. The results showed that sorghum as food and feed had sustainability index of 79.67, with a stress value of 0.1379 (Table 2). This shows the validity and accuracy of the four dimensions determined by Monte Carlo test.

Environmental dimension

Environmental dimension sustainability index was recorded at 75.15, showing the dimension had a significant impact on sorghum cultivation. The three crucial attributes from this dimension were land availability, water use efficiency, and the prevention of natural resource exploitation (Table 1). At the study site, sorghum was planted in rotation with shallot plants, commencing in March during the transition from the rainy to the dry season. The available land was relatively large, reaching 100 ha and sorghum plant was best suited to the characteristics and the season, resulting in optimal production. The

Table 1. Attributes of four dimensions for sustainability of sorghum as food and feed

Environmental	Social	Economic	Technological
1. Land availability for sorghum cultivation	1. Farmer education level	1. Productivity of sorghum plant	1. Ease of sorghum cultivation
2. Water use efficiency for sorghum cultivation	2. Family workforce involvement	2. Management of sorghum plant	2. Tools availability for sorghum cultivation
3. Level of pest and disease control	3. Motivation level of sorghum cultivation	3. Increasing business scale	3. Potential to increase sorghum production
4. Efficient use of fertilizer for sorghum cultivation	4. Level of community acceptance of sorghum cultivation	4. Increasing worker welfare	4. Level of technological sensitivity
5. Level of water, land, and air pollution	5. Sorghum cultivation does not affect the main work	5. Efficient use of production facilities	5. Ease of pest and disease control
6. The prevention of natural resource exploitation in sorghum cultivation	6. Worker knowledge level	6. Ease of obtaining production facilities	6. Ease level of processing results
	7. Work safety level	7. Ease of selling sorghum	
	8. Suitability of business type	8. Profit level of sorghum sales	

Table 2. Sustainability index and status of sorghum as food and feed

Dimension	Index	Stress	R^2(SQR)	Status
Environmental	75.15	0.1434	0.9319	highly sustainable
Social	83.80	0.1335	0.9457	highly sustainable
Economical	77.46	0.1341	0.9430	highly sustainable
Technological	82.28	0.1407	0.9269	highly sustainable
Average	79.67	0.1379	0.9368	highly sustainable

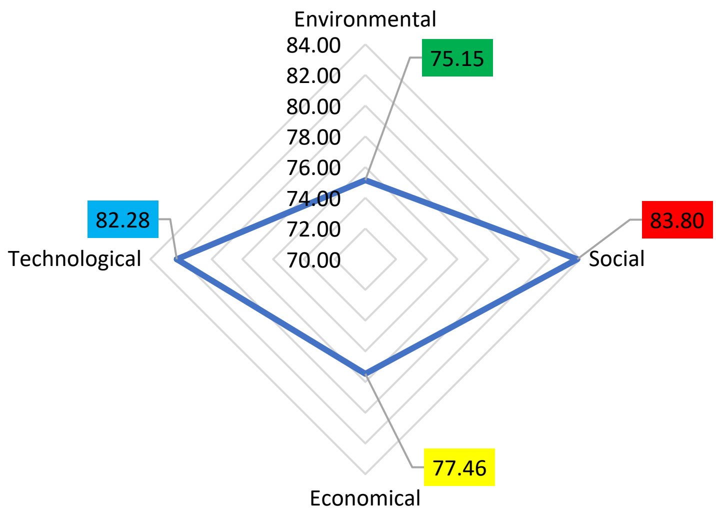

Fig. 1: Sustainability level sorghum as a source of food and feed

availability of land for cultivation significantly impacts food security and a sustainable environment, underscoring the importance of maximizing productivity (Fig. 2). Sustainable agricultural methods such as agroforestry and crop-livestock integration are effective in increasing land use efficiency by optimizing the use of available natural resources (Zomer *et al.*, 2014. Furthermore, soil quality and field characteristics can help maximize sorghum yields with minimal land exploitation (Foley *et al.*, 2011). Water use at the study site was very efficient, with the sources being irrigation and rainwater. Irrigation practice is one way to increase water use efficiency in sorghum cultivation, including the use of technology such as drip or sensor-based irrigation that accurately measures soil moisture to determine when plants need water. Using these methods, farmers can avoid wasting water and provide an accurate amount based on plant needs. Furthermore, sorghum is tolerant to drought (Abreha *et al.*, 2022), and has a greater ability to maintain water compared to maize as stated by Safian *et al.* (2022). The optimal water use requirement at an early stage was 78.71 mm, then 173.20 mm, and 174.46 mm in mid-season. This means that the total water requirement in all stages of growth and development was 401.25 mm (Shenkut *et al.*, 2013). Sorghum has a 20% greater water use efficiency in arid areas compared to maize, resulting in good prospects for wide-scale cultivation and climate variations (Hossain *et al.*, 2022). Based on the result, the natural resource prevention exploitation at the study site was relatively high. Cultivation was carried out using a rotation approach with shallot to avoid exploitation in line with the principles of sustainable agriculture. Rotating sorghum with other crops such as legumes or cover crops can also increase soil fertility and reduce the land degradation risk (Aristya and Samijan, 2022). Conservation efforts, including the judicious use of fertilizers, contribute to maintaining soil fertility and reducing natural resource exploitation (Jug *et al.*, 2021). Furthermore, environmental impact analysis and sustainability indices between sorghum production and other crops may vary depending

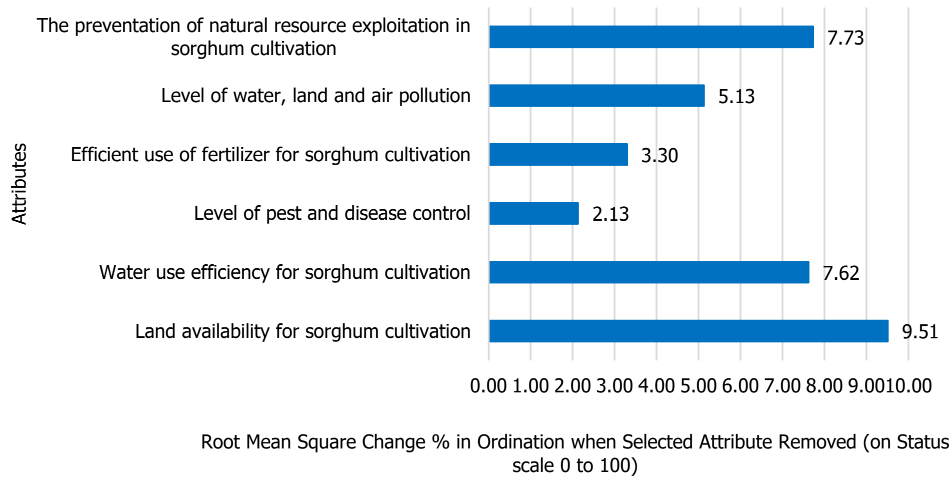

Fig. 2: Environmental attributes leverage

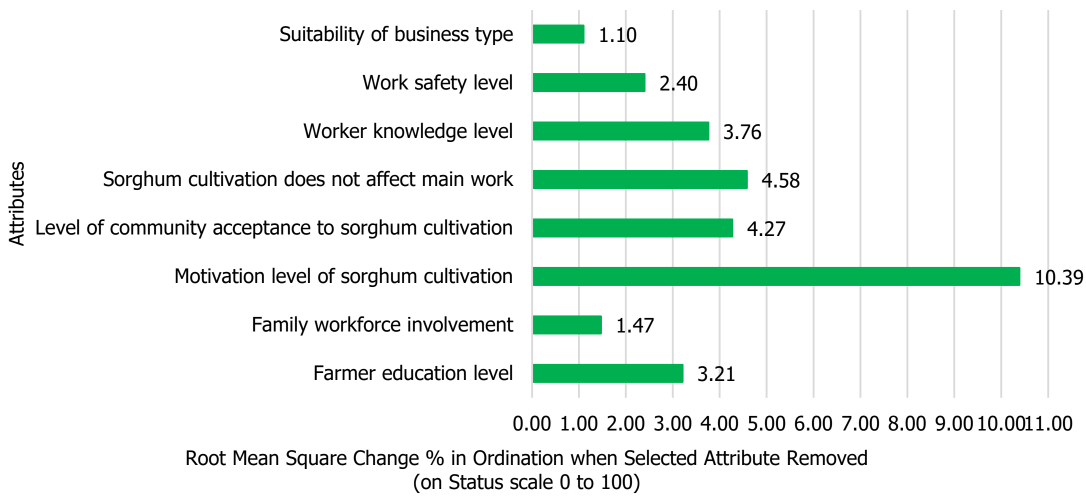

Fig. 3: Social attributes leverage

on various factors, including agricultural practices, local climate, and soil management. Some common considerations consist of water and pesticide use, greenhouse gas emissions, soil sustainability, as well as fertilizer requirements. In terms of water use, sorghum is often considered drought-resistant compared to several other food crops (Jamil *et.al.,* 2021; Behera, *et.al.*, 2022). This makes the plant suitable for areas experiencing drought or have limited water availability. Regarding fertilizer and pesticide use, sorghum may require less nitrogen fertilizer compared to crops such as corn (Pan and An, 2020). The plant can also efficiently remove heavy metals from contaminated soil (Zhuang *et.al.*, 2009). In terms of potential greenhouse gas emissions, several studies stated that sorghum had a lower carbon footprint compared to other food crops, such as corn. The use of biosolids as a nitrogen source in sweet sorghum production can reduce greenhouse gas emissions without losing yield (Glab and Sowinski, 2019). Concerning soil sustainability, cultivating this crop has previously been shown to improve soil chemical properties, such as increasing phosphorus content and available organic matter (Thawaro *et.al.,* 2017). Additionally, sorghum has the ability to emit allelochemicals with biological nitrification inhibition capacity, which can reduce nitrification and reduce nitrogen pollution (Ping et.al., 2009). This represents a positive factor in terms of soil sustainability. In the context of production for food and feed, differences may occur in terms of nutritional requirements and resource use. Production for animal feed may have higher sustainability in terms of resource efficiency because sorghum can grow well in areas that are less fertile or have low water availability (Sanni *et.al.*, 2022).

Social dimension

Social dimension sustainability index was recorded at 83.80, showing that the dimension had a significant impact on sorghum cultivation sustainability at the study site. The three crucial attributes from this dimension were the motivation level, minimal interference with primary agricultural activities, and the level of community acceptance (Table 1). Motivation, defined as the inner drive compelling an individual to take action, plays an important role in achieving desired purposes. In the context of sorghum cultivation, farmers showed high motivation which stemmed from the desire to use the land during the waiting period for the next crop planting season. This was further supported by the characteristics of sorghum being easy to cultivate, having relatively high production, a promising selling price, and ease of selling. According to a previous study, commodities with economic value and technical feasibility contribute to increased motivation among farmers (Lakitan, 2014). It was also found that sorghum cultivation at the study site did not affect the main work of shallot farming. Every year, shallot cultivation was carried out in two planting seasons. Following the second planting season, farmers use land and time to cultivate sorghum. In other words, farmer activities at the study location each year entailed using seasons I-II for planting shallots, and III for sorghum. This rotational approach was carried out to break the cycle of pests and diseases. Planting season III was in the dry season, and suitable for drought-resistant plants. Furthermore, the community acceptance level of sorghum cultivation at the study site was very good (Fig. 3). This was marked by a longstanding practice spanning generations, over 30 years. Local communities have good reason to accept this commodity, resulting in high sustainability.

Economical dimension

A total of eight attributes significantly impacted the economic dimension sustainability of sorghum production. Based on leverage analysis (Fig. 4), three attributes with the most sensitive influence included plant productivity, profit level of sales, and ease of selling. The analysis results for economic dimension obtained sustainability index of 77.46 (Table 2). This value showed that sorghum production supported economic development at the study site due to ease of selling. The production was relatively high (6-7 tons/ha) compared to the varieties of Numbu (4.12 tons/ha), Kawali (3.92 tons/ha), Unpad 1 (3.86 tons/ha), Batari (3.26 tons/ha), Keller (3.04 tons/ha), and Taomitsu (3.44 tons/ha) (Karimuna *et al.,* 2020). The potency of production amounted to 300-350 tons/y with a land area of 50 ha, attracting brokers eager to purchase sorghum from farmers as harvest approached. This efficient process ensured that farmers did not encounter difficulties selling the harvest and incurred minimal costs for marketing. Consequently, net income was derived by substrating the selling price from cultivation and production costs, showcasing efficient management. This condition shows that farmers produce sorghum to meet market demand, as also stated by Sulewski *et al.* (2018). Based on the results, the profit level at the study site was relatively high. Profit is one of business purposes, contributing significantly to sustainability. Sorghum prices ranged from US$ 0.39-0.58/kg, resulting in farmers earning a gross income of US$ 2,516.67-3,755.00/ha. In comparison, the profits in Yogyakarta and Central Java were estimated at US$ 882,03 and 813.07, respectively (Widodo *et al.*, 2023). The nominal income of farmers depends on the amount of production and selling price, with a higher selling price per unit of production, leading to greater profits (Septiadi *et al.,* 2023). Furthermore, ease of selling sorghum was facilitated by the readiness of brokers, contributing to cultivation sustainability. It is crucial to develop sorghum in areas with a feed industry to ensure market stability and raw material availability. The plant could also be developed in areas consuming the product as local food. The level of market demand had a significant impact on ease of selling, underscoring the importance of expanding market coverage (Fig. 4). Selling sorghum

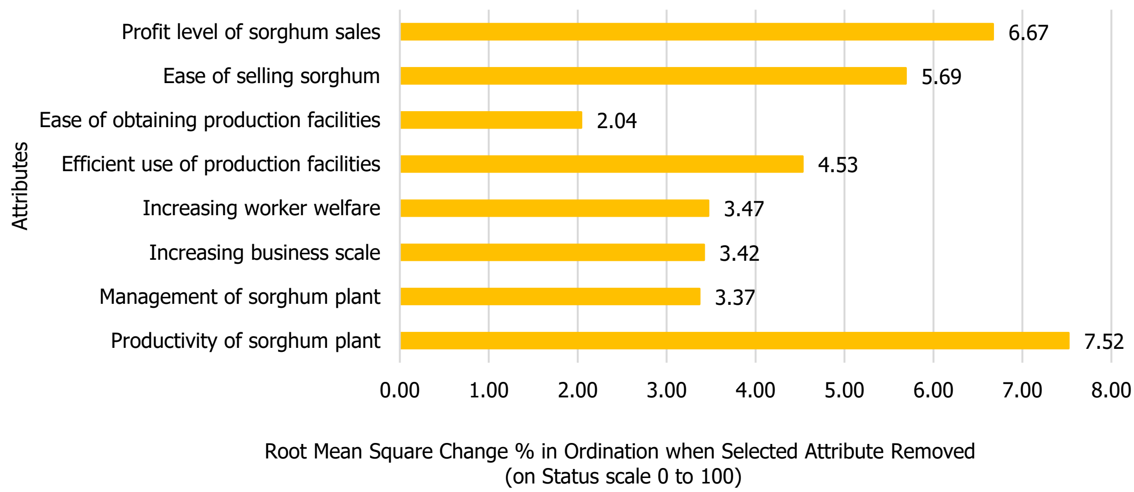

Fig. 4: Economical attributes leverage

in various markets serves multiple purposes, acting as a means of promoting new healthy food products, a potential marketing tool, and a trigger to promote upper-market segmentation, thereby increasing business capacity and marketing scope. According to a previous study, indicators of economic feasibility include ease of selling, reasonable price, low cost of input and production, as well as decent profits (Tugga *et al.,* 2023). The economic potential that could still be developed at the study site was using sorghum stover as feed. Despite the economic value, farmers have not yet explored this avenue due to a lack of knowledge and equipment for processing stover. The production of sorghum stover reached 9.44 tons/ha or 471.8 tons/y dry matter and could be used as feed for 163 animal units (AU)/year. This was lower compared to Cardoso *et al.* (2013) and Prakasham *et al.* (2015), which reported 15.62 tons/ha (harvested twice a year) and 24-32.5 tons/ha, respectively. To maximize the value of sorghum by-product, complete feed should be made from the main raw materials of stover and bran. The feed ration of steer with 66 and/or 100% sorghum silage supplementation increased body weight with economic benefits (Jabbari *et al.,* 2011).

Technological dimension

Technological dimension sustainability index was recorded at 82.28, greatly impacting sustainability of sorghum cultivation at the study site. The three crucial attributes from this dimension were ease level of cultivation, tools availability, and technological sensitivity (Table 1). Based on the results, ease level of sorghum cultivation adoption was very high, due to the knowledge and skills obtained directly from experienced farmers and passed down through generations. The technology of cultivation consists of various aspects including land processing, planting distance, planting methods, fertilization, pest and disease control, as well as the use of organic materials (Fig. 5). In essence, technology was adjusted to local requirements, aiming to increase production and maximize the benefits of sorghum as both food and feed. Indicators of the technical feasibility including ease of planting, maintenance, harvesting, post-harvest processes, and inputs (seeds, fertilizers, and pesticides) were easy and did not require high levels of equipment or skills. The availability of tools for cultivation and harvest is very important for sustainability of sorghum. Farmers used tools such as hoes, planter hole punchers, sickles, sprayers, and seed threshers. Despite being simple, these tools played crucial roles in land processing, planting, maintenance, pest and disease control, and harvesting. Furthermore, the sensitivity level of technology to the quality and quantity of sorghum production was relatively high. The potential for increased production was indicated through the adoption of superior varieties and balanced fertilization. In this context, farmers currently use local varieties and fertilizers were not applied in line with the recommended dose. Samurai

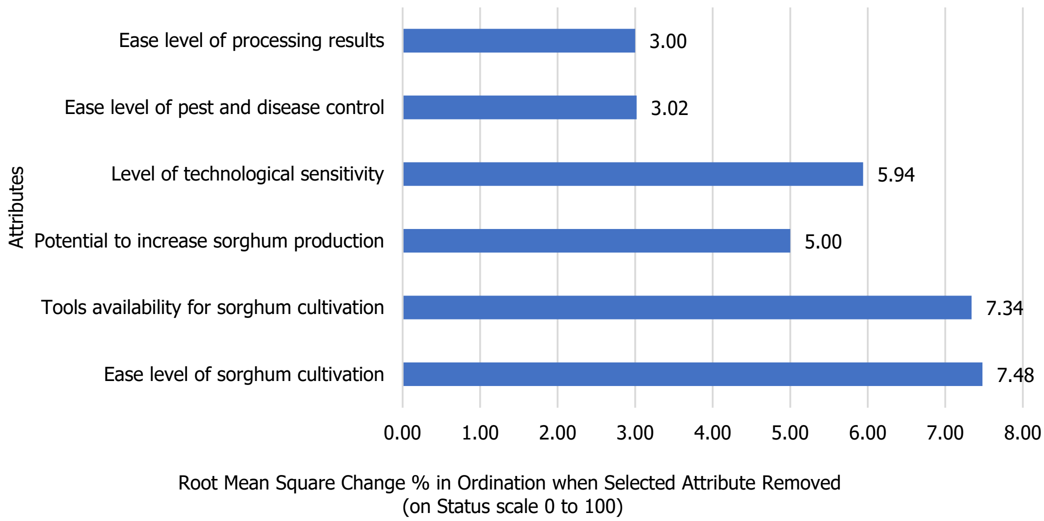

Fig. 5: Technological attributes leverage

variety showed more potency to be developed into forage, specifically in coastal areas, while the Numbu variety had more potency as a seed production. Farmers preferred local varieties due to the low height (2.1-2.5 m) and ease of harvest, short harvest time (90 days), and substantial production (6-7 tons/ha). According to a previous study, ecological type, variety, and planting distance suitability have a significant influence on sorghum yield (Yan *et al.,* 2023). The suitability of varieties with land conditions was identified as a crucial aspect of cultivation technology. Optimum yield in the dry land could be achieved with a recommended planting distance of 10 cm x 70 cm, 200 kg urea fertilizer, 100 kg SP-36, 50 kg/ha KCl, and 10 tons/ha organic fertilizer. The use of organic fertilizer for Numbu and Kawali varieties was found to increase the weight of stover and grain. In essence, both lowland and dryland could be developed into integrated agriculture through a community farming system approach, with the integration of ruminants supporting sustainable agriculture (Sekaran *et al.,* 2021).

CONCLUSION

In conclusion, farmers used local varieties and simple tools for cultivating and harvesting sorghum. Sustainability index obtained was 79.67, underscoring the highly sustainable character of the production across environmental, social, economic, and technological aspects. In terms of environmental sustainability (75.15), this study identified the crucial role of efficient land use, water management, and the prevention of resource exploitation. Social sustainability (83.80) was enhanced by factors such as farmer motivation, minimal interference with primary agricultural activities, and community acceptance. Economic sustainability (77.46) was evident through economic viability, high productivity, profitable sales, and easy market access. Furthermore, technological sustainability (82.28) was shown by the adaptability of sorghum to easy cultivation practices, the availability of necessary tools, and openness to technological advancements. In general, 12 attributes that greatly impacted sustainability included land availability, water use efficiency, the prevention of natural resources, motivation level of farmers, minimal interference with primary agricultural activities, community acceptance, productivity, sales profit level, ease of selling and cultivation, tools availability, as well as technological sensitivity. Based on the results, the average sorghum productivity ranged from 6-7 tons/ha, in addition to a production potency of 300-350 tons/y and a stover potency of 471.8 tons/y dry matter capable of feeding 163 animal units (AU) per year. This underscored the multifunctional and high-potential nature of sorghum in the region. This study not only affirmed the multifaceted role of the plant but also provided actionable insights for sustainable cultivation. Sustainability of sorghum as food and feed at the study site could be used as a reference for massive development. The results provided inspiration for other areas, specifically dry zones to develop sorghum with a good economic impact on the population. Optimal production at the study site remained uncertain, as farmers have not yet adhered to recommended fertilization practices. Furthermore, the application of simple tools and technology resulted in a high sustainability score. This study suggested that taking advantage of agricultural tools and technologies such as transplanters, drip irrigation, and harvesting machines might greatly improve sustainability index.

AUTHOR CONTRIBUTIONS

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ACKNOWLEDGEMENT

The authors are grateful to the respondents in Demak, colleagues in Demak Agriculture Service, as well as the National Research and Innovation Agency.

CONFLICT OF INTEREST

The authors declare no conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication or falsification, double publication or submission, and redundancy have been completely observed.

PUBLISHER'S NOTE

GJESM Publisher remains neutral about jurisdictional claims in published maps and institutional afflictions.

ABBREVIATIONS

%	Percent
°C	Degree Celsius
ALSCAL	Alternating least-squares algorithm
AU	Animal Unit
cal	calorie
CF	Crude fiber
cm	centimeter
CP	Crude Protein
d	Euclidian distance
d_{ij}	Euclidian distance from point i to point j
d_{ijk}	Squared distance
DM	Dry matter
EE	Extract eter
FGD	Focus Group Discussion
g	gram
ha	hectare
IDR	Indonesians Rupiah
K	Potassium
K_2O	Dipotassium oxide
Kcal	kilocalorie
KCl	Potassium chloride
kg	kilogram
m	meter
MDS	Multidimensional scaling
N	Nitrogen
NFE	Nitrogen-free extract
P	Phosphor
P_2O_5	Diphosphorus pentaoxide
pH	Potential of hydrogen
R^2	Coefficient of determination
Raffish	Rapid appraisal for fisheries, an analytical method to assess sustainability of fisheries based on a multidisciplinary method
SP-36	Single fertilizer with a P2O5 content of 36%
SQR	Structured query reporter, a programming language designed for generating reports from database management systems
Urea	Single fertilizer that has a high nitrogen (N) content of around 45 – 46%
TDN	Total digestible nutrient
USD	United States Dollar
USDA	United States Department of Agriculture

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HOW TO CITE THIS ARTICLE

Prabowo, A.; Hayati, R.N.; Ludfiani, D.D.; Minarsih, S.; Haryanto, B.; Supriyo, A.; Subiharta, S.; Nurwahyuni, E.; Hindarwati, Y.; Setiapermas, M.N.; Sudarto, S.; Samijan, S.; Utomo, B.; Winarni, E.; Suretno, N.D.; Wibawa, W.; Agustini, S.; Prasetyo, A.; Hantoro, F.R.P.; Hariyanto, W.; Aristya, V.E., (2024). Balancing environmental impact: A sustainability index analysis of sorghum production for food and feed. Global J. Environ. Sci. Manage., 10(2): 743-758.

DOI: 10.22035/gjesm.2024.02.20

URL: https://www.gjesm.net/article_709225.html