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Pioneering Social Sustainability in Solar Drying Technologies: Evidence from the Social Life Cycle Assessment study in Tanzania

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ABSTRACT

Solar drying technologies (SDTs) provide fast and efficient method of drying of crops, improve the quality of the dried crops, extend the shelf life of crops and eventually reduce post-harvest loss. Despite all these benefits, previous studies have noted the potential risks of SDTs on humans and ecosystems. This study applied the social lifecycle assessment (SLCA) framework to evaluate the social impacts of SDTs in Morogoro and Arusha regions, Tanzania. Using a participatory approach 16 core social factors were identified and further expanded into 56 SLCA sub-indicators for studying the social life cycle of solar dryers. A structured questionnaire was administered to 244 respondents, including workers, consumers, local community and the society. Results show that SDTs contribute positively to enhance food security, reduction of post-harvest losses, creation of employment and reduction of child labour involvement in crop drying process. Further results indicate that most of the social factors assessed exhibited moderate level of performance indicating that progress has been made in some areas while remain opportunities for improvement to yield maximum results. Concern is for the factors that demonstrated very poor performance such as end-of-life responsibility, working hours, government policy and social benefits protection. Regionally, Morogoro outperformed Arusha across most indicators, with Arusha requiring more targeted interventions. This is the first comprehensive SLCA study on SDTs in Africa, introducing two new indicators "improved food quality" and "food security" into SLCA methodology. The study, provided critical insights for policymakers seeking to promote sustainable agricultural technologies. Finaly, the study supports the realization of the global sustainable development goals SDGs #1 on poverty alleviation, SDG ＃2: emphasizes on zero hunger and SDG # 7 affordable and clean energy.

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الريادة في الاستدامة الاجتماعية في تقنيات التجفيف الشمسي: أدلة من دراسة تقييم دورة الحياة الاجتماعية في تنزانيا

ملخص: توفر تقنيات التجفيف الشمسي (SDTs) وسيلة سريعة وفعّالة لتجفيف المحاصيل، كما تعمل على تحسين جودة المحاصيل المجففة، وإطالة فترة صلاحيتها، مما يساهم في الحد من الفاقد بعد الحصاد. وعلى الرغم من هذه الفوائد، أشارت الدراسات السابقة إلى وجود مخاطر محتملة لتقنيات التجفيف الشمسي على الإنسان والنظم البيئية. تهدف هذه الدراسة إلى تطبيق إطار تقييم دورة الحياة الاجتماعية (SLCA) لتقدير الآثار الاجتماعية لتقنيات التجفيف الشمسي في منطقتي موروغورو وأروشا في تنزانيا. ومن خلال نهج تشاركي، تم تحديد 16 عاملاً اجتماعياً رئيسياً، تم توسيعها لاحقاً لتشمل 56 مؤشراً فرعياً ضمن إطار SLCA لدراسة دورة الحياة الاجتماعية لمجففات الطاقة الشمسية. تم توزيع استبيان منظم على 244 مشاركاً شملوا العمال والمستهلكين وأفراد المجتمع المحلي والمجتمع ككل. وأظهرت النتائج أن تقنيات التجفيف الشمسي تُساهم بشكل كبير في تعزيز الأمن الغذائي، والحد من الفاقد بعد الحصاد، وخلق فرص عمل جديدة، وتقليل مشاركة الأطفال في عمليات تجفيف المحاصيل. كما أظهرت النتائج أن معظم العوامل الاجتماعية التي تم تقييمها أظهرت مستوى أداء متوسطا، مما يشير إلى إحراز تقدم في بعض الجوانب مع استمرار وجود فرص للتحسين لتحقيق أقصى النتائج. غير أن القلق يتركز على العوامل التي أظهرت أداءً ضعيفا للغاية مثل: المسؤولية في نهاية دورة الحياة، وساعات العمل، والسياسات الحكومية، وحماية المزايا الاجتماعية. وعلى المستوى الإقليمي، تفوقت منطقة موروغورو على أروشا في معظم المؤشرات، مما يشير إلى حاجة أروشا إلى تدخلات أكثر استهدافا. تُعد هذه الدراسة أول دراسة شاملة لتقييم دورة الحياة الاجتماعية لتقنيات التجفيف الشمسي في إفريقيا، حيث أُدخل مؤشرين جديدين إلى منهجية SLCA وهما :تحسين جودة الغذاء والأمن الغذائي. وتُقدم الدراسة رؤى مهمة لصانعي السياسات والمخططين الراغبين في تعزيز التقنيات الزراعية المستدامة. وأخيرا، تدعم الدراسة تحقيق أهداف التنمية المستدامة (SDGs)، ولا سيما الهدف الأول (القضاء على الفقر)، والهدف الثاني (القضاء على الجوع)، والهدف السابع (الطاقة النظيفة والميسورة التكلفة.

الكلمات المفتاحية: تقييم دورة الحياة الاجتماعية (SLCA) ، تقنيات التجفيف الشمسي (SDTs) ، فاقد ما بعد الحصاد(PHL) ، تنزانيا، أهداف التنمية المستدامة..(SDGs)

1. INTRODUCTION

1.1 Background and Motivation to the Research.

Post-harvest losses (PHL) possess a major threat to food security in developing countries where 30–40% of food produced is lost due to inadequate preservation techniques [1]. Drying is the oldest food preservation technique used to extend shelf life of varieties of crop products. In many rural areas, open-sun drying (OSD) is commonly applied due to its simplicity and availability at low cost. However, this method is inefficient, weather-dependent, prone to contamination, and leads to PHL. SDTs have emerged as a sustainable alternative solution providing more efficiency, preserve nutrients, food taste and colour. SDTs are relevant to regions with high solar radiation and limited access to grid electricity like Tanzania. Tanzania receives high intensity of solar radiations (intensity ranging 2,800-3,500 hours of sunshine per annum and a global radiation between 4-7kWh per m2/day) [2]. The use of SDTs could bring major impacts in crop drying but it has not been widely embraced due to many limiting factors including financial and technical challenges [3]. Based on this reality it is crucial that more efforts be directed to encourage more adoption and use of SDTs. Example of such efforts include research and development addressing the sustainability of solar dryers in order to generate more knowledge and provide clarity to guide society and other stakeholders to make informed decisions.

It is easy to assume that SDTs are environmentally friendly and economic viable because they use solar energy. However, looking at it from the life cycle point of view this assumption may be misleading. For example, extraction and processing of materials used to assemble a solar dryer may pose significant risk of materials depletion [4]. Furthermore, improper disposal of the components at the end of their useful life may lead to environmental pollution. More sophisticated solar dryers designed to enhance operational performance may limit their affordability to some users [5]. Many previous studies on the sustainability of solar dryers have focused mainly on their environmental and economic aspects, such as their potential to reduce GHG emissions [6] and lower energy costs [7]. However, the social dimension of sustainability of SDTs has received comparatively little attention in the literature. This gap is particularly significant in the context of African countries, which are predominantly located within equatorial and tropical zones and therefore possess high potential for harnessing solar energy for various applications, including solar crop drying.

Despite this abundant solar potential, the widespread adoption of SDTs for agricultural drying remains limited. Contributing factors include the initial cost of technology, limited technical expertise, and insufficient awareness of the broader socio-economic benefits of SDTs. Addressing these challenges requires greater research attention, particularly studies that explore and demonstrate the social and economic impacts of SDTs, which could in turn promote wider acceptance and utilization of solar thermal drying systems.

The main objective of this study was to assess how much stakeholders agree or differ in their views regarding the life cycle social impacts of adopting SDTs in the two selected regions of Tanzania. More specifically the study used the participatory approach to identify the key social indicators used to assess the social impacts of SDTs in Morogoro and Arusha regions. Finally, the study evaluates and compared the level of agreement or divergence regarding the social impacts of SDTs in Morogoro and Arusha regions.

1.2 Literature Survey

Several studies have covered the environmental, economic and social impacts of SDTs and related technologies in both developed and developing countries. Divyangkumar et al., (2024) [4], conducted a cradle-to-gate life cycle assessment (LCA) study using the ReCiPe 2016 method to compare the environmental impacts of a phase change material-based solar dryer (PCMBSD) and a cylindrical solar-assisted dryer (CSAD). The study found that PCMBSD had significant higher environmental impacts than CSAD in most end point categories, a 40% greater impact on human health and 37.04% more on ecosystems while CSAD had a 14.18% higher resource use. Overall, CSAD had a lower total environmental score (37.04%) compared to PCMBSD (40%) and thus recommended for long-term use in agricultural drying systems. Nayanita et al., (2022) [8] conducted a LCA study using the ReCiPe 2016 method to assess the environmental impact of two solar dryers; direct mode (MMTD) and mixed mode (DMTD) with a scope covering from fabrication to recycling. Results show that DMTD consistently obtain lower scores across human health, ecosystems, and resource use, making it more environmentally sustainable than MMTD. Switching to DMTD over MMTD was recommended for reducing environmental impact in solar drying applications.

Zine et al., (2025) [9], performed the sustainability assessment of greenhouse solar dryers at Al Qued University in Algeria. The study compared a novel greenhouse dryer (NGHD) equipped with an integrated drying chamber and a conventional greenhouse dryer (CGHD). The study analyzed various parameters including thermal efficiency, economic and environmental sustainability. In terms of drying efficiency findings show that NGHD achieved higher drying rates using only 390 minutes compared to 570 minutes and 920 minutes for CGHD and OSD respectively for the same product quantity. Furthermore, NGHD preserve more better product quality than CGHD and OSD because it effectively shields the mint from direct expose to sunlight. Economic analysis demonstrated that both dryers have favorable PBP of 0.925 years and 1.04 for NGHD and CGHD respectively. Environmental analysis shows that NGHD could mitigate 192.74 tons of CO2 emission in a lifespan of 15 years equivalent to $1927.40 of carbon credits earned while CGHD mitigate 194.51 tons of CO_2 emission and generated a carbon credit of $1945.15. Overall, it is evident that the NGHD demonstrate superior performance in all evaluated areas and provide thermal, economic and environmental sustainability for drying mint for small scale applications. Baddadi et al., (2023) [10] performed an experimental study analyzing the 4Es (i.e., energy, exergy, economic, and environmental) on a hybrid solar heating unit integrated with latent thermal storage materials ($CaCl_2 \cdot 6H_2O$ and paraffin) for drying food. Findings indicated that the innovative heating unit introduced resulted in a 30 °C increase in nighttime temperature relative to other types of collectors. Results further shows that the system exhibited an annual energy consumption of 640 kWh and achieved an energy payback period (EPBP) of 2.5 years. The environmental impacts assessment indicated a substantial reduction in CO_2 emissions, amounting to 39 tons. Overall, the proposed heating system improves the sustainability and economic efficiency of the drying process by lowering GHGs emissions and supporting energy-saving measures. Kingphadung et al., (2022) [7], conducted a study to compare the economic performance of a greenhouse solar dryers (GSD) versus hot air drying (HAD) used in crispy mango production. In this study both the internal rate of return (IRR), net present value (NPV), business cost ratio (BCR) and payback period (PBP) were evaluated. The findings revealed that both systems show favorable values of the evaluated financial metrics; low PBP (0.43 and 0.67), high values of NPV ($151K and $190K) greater IRR (233% and 150%) and high BCR (24.47 and 15.73) for HAD and GSD respectively. From these results both systems are efficient, however when the incremental method of rate of return (RoR) was applied the GSD was found to be the most economic viable for drying crispy mango for small to medium scale production. Dhanushkodi et al., (2015) [11] carried out life cycle economic analysis of solar, biomass and hybrid dryer systems for cashew nuts drying in India. The study tries to see the possibility of replacing conventional drying systems with either solar, biomass and hybrid dryers. The economic parameters used for this assessment were ARR, NPW, PBP and BCR. The BCR findings were 5.23, 4.5 and 3.32 for solar, biomass and hybrid dryers respectively suggesting that solar dryer offer the best option. Based on the NPW the findings reveal that solar dryer was also the best option with NPW of Rs. 323,725 followed by hybrid dryer Rs. 242,192 and the biomass dryer worth Rs.203,339. Biomass dryer provided the highest IRR (74.5%) whereas the solar dryer (65.5%) and the hybrid dryer had the lowest IRR of 49.1%. Lastly the PBP results were 1.99, 1.58 and 1.32 years for the hybrid solar and biomass dryer respectively. Based on the parameters assessed it was concluded that the hybrid dryer outperforms other type of dryers and provided economic sustainability for small scale cashew nuts processing industries.

Corona et al., (2017) [12] conducted a social life cycle assessment (SLCA) to study the solar power plant in Spain, introducing a structured social performance indicator in the social life cycle impact assessment phase. The results showed that the social performance indicator scored 0.42 on a scale ranging from -2 to +2 implying that the plant contributed positively to socio-economic sustainability factors such as household income, poverty rate reduction, job creation, job security, local economic stimulation, skills development and knowledge transfer. Furthermore, findings revealed negative social issues in factors such as gender inequality, corruption as well as huge gaps between the rich and the poor. The study had provided better insights into how a solar powerplant impacted the social dimension of sustainability from the life cycle perspectives. Corona & Miguel, (2019) [13], conducted a life sustainability assessment (LCSA) of a concentrated solar power (CSP) plant based on HYSOL technology comparing two models in Spain. The HYSOL BIO which use biomethane as hybridization fuel and HYSOL NG which use natural gas. This study asses both the three dimensions of sustainability (i.e. environmental, economic and social). LCA results indicate that HYSOL technology contribute to the reduction in climate change impact for both operations modes. Life cycle cost (LCC) analysis indicates substantial economic benefits per MWh of electricity for a HYSOL NG power plant but a decrease for the HYSOL BIO power plant. SLCA results indicated an increase in goods and services produced for both Spain and the neighboring economies. Finally, both electricity generation options provided a better environmental profile and an increase in the social welfare development of Spain.

Ayhan et al., (2024) [14], evaluated the social sustainability of six novel tomato-based products using different protein sources i.e., pea and leaf proteins, and drying methods (e.g., hot-air drying, microwave vacuum drying and conventional drying). Using 21 social indicators and expert input through the analytic hierarchy process, the study assessed each product as well as the process social life cycle impacts. Findings revealed regional variability on unemployment, water access, sanitation and labour conditions while stronger impact on discrimination, migrant labour, children's education and access to healthcare facilities. The most sustainable option was a tomato bar enriched with pea protein, and dried using microwave vacuum technology. Yet, the study did not consider solar drying, given the potentials of solar dryers, the omission of solar drying in the study represents a significant gap. Kumar et al., (2023) [15] noted that majority of solar dryer optimization studies prioritize technical or economic metrics while neglecting social factors like labour rights and gender considerations.

There is a notable lack of research on the social dimension of sustainability of SDTs in the African context Tanzania in particular as evidenced from the above literature survey. Existing literature indicates a predominant focus on environmental, and economic life cycle assessments, with social dimensions frequently overlooked or treated as secondary considerations. Previous studies addressing the sustainability of SDTs focused on assessing environmental sustainability using exergy sustainability indices such as sustainability index (SI), environmental impact factor (EIF), improvement potential (IP) and waste energy ratio, (WER), others focused their assessment based on thermal performance indicators such as drying time, carbon credits earned, carbon mitigation and carbon dioxide reduction, while others have based on life cycle assessment variables such global warming potentials, GWP (kg-CO_2 – equivalent), acidification potentials (AP), human toxicity potential (HTP) and so on. From an economic perspectives studies have evaluated sustainability of solar dryers based on various economic metrics such simple PBP, NPV, BCR and IRR. The social sustainability of SDTs remain significantly underexplored. Few available studies in this area had assesses solar dryers in its general form example [16.17]. This study will be much more specific to the study of indirect solar dryers made of metallic structures and wooden structures (ISDM) and ISDW respectively using the SLCA framework.

2. MATERIALS AND METHODS

The SLCA framework developed by the United Nations Environment Program (UNEP) and the Society of Environmental Toxicology and Chemistry SETAC, proposed a guideline for the social life cycle assessment of products, process or technologies across their entire life cycle. These guidelines provided six main categories of social impact assessment indicators for SLCA. They include human rights, working conditions, health and safety, cultural heritage and socio-economic repercussions [18]. Under each of the social impact categories above several sub categories of indicators exist which can be directly used or customized to suit the unique nature and scope of the study.

SLCA framework borrowed a classical structure of the LCA model which is organized into four (4) key phases i.e., goal and scope definition, social inventory analysis, impact assessment and interpretation. This structured approach ensures methodological consistency while enabling a comprehensive evaluation of the social impacts associated with solar dryer systems. SLCA has been applied in related agricultural studies. For example [19], assessed the agricultural production value chain, including processing stages using SLCA. Similarly, [20] argued for the suitability of SLCA methods in evaluating social sustainability within agro-processing systems for more sustainable results.

2.1 Goal and Scope definition

In SLCA research, scholars typically define their study objectives using one of two primary approaches i.e., the process-based approach or the company-based approach [21]. Many of the S-LCA researchers have adopted the company-based approach because the social impacts including child labour always occur independently of the physical inputs or outputs associated with specific processes [22.23].

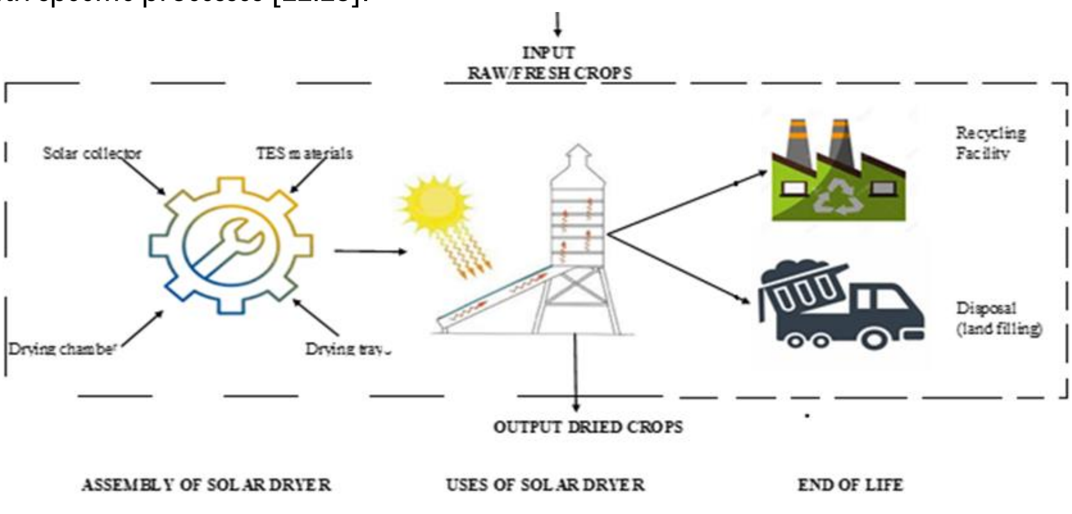

Figure 1: Life cycle boundary and scope of solar dryers (own's construction)

In alignment with this perspective, the present study adopted the company-based approach to assess social impacts of SDTs in Morogoro and Arusha regions, Tanzania. The goal of this study is to evaluate and compare the social impacts involved in the SDTs value chain activities in Tanzania, specifically the indirect mode solar dryers made of metallic and wooden frames (i.e. ISDM and ISDW) dryers. The scope of the assessment covers the entire life cycle of the dryers including the sourcing of materials and components, assembly and installation, operations and end-of-life stages such as recycling, disposal, or land-filling see Figure 1.

2.2 Sample size

SLCA studies required stakeholder input and thus a structured purposive sampling approach was employed in this study. A sample size (n=244 respondents) was selected i.e., solar dryer workers/fabricators, local community members, solar dryers users and users of dried products as well as the society. This approach ensured collection of socially relevant data like working conditions, access to training, and social economic contribution in alignment with the UNEP/SETAC guidelines. The selected study sample size was determined based on data saturation principles and based on prior similar studies that have employed the sample size ranging from 150- 450 [21.23.24.25.31]. Hence, the sample size (n=244) is considered sufficient for meaningful SLCA insights and interpretations. The data saturation principle provides methodological guide to ensure sufficient data were gathered while the selection of sample size based on previous studies provide a scientific justification.

The UNEP guidelines have outlined five major social impacts categories and their associated 31 social impact subcategories, organized under five main stakeholder groups i.e., workers, consumers, local communities, society and value chain actors. For the present study only four stakeholders' group was involved in the inventory data collection process, they are workers, local community, consumers and the society. These stakeholders were chosen due to their relevance in the product life cycle, as they are more likely to experience positive or negative social impacts from the implementation of SDTs. The four (4) group of stakeholders are listed and described in Table 1 below.

Table 1: Description of the four categories of respondents

Respondent group	Description
Workers(W)	Individual working at managerial and operational levels in solar drying facilities (SDFs). This group involves workers involved in the fabrication and installation of solar dryers and those involved in actual drying of agricultural produce.
Local community (LC)	People living nears the area where SDFs services are provided. Their perceptions provide valuable information in the evaluation of the social benefits of SDTs in the area they live.
Consumers (C)	Individuals using or receiving SDTs services such as the general public directly consuming solar dried products, SSFs and vendors who use SDFs to dry up their products
Society (S)	The group involve those who have knowledge and an understanding of SDTs including researchers, policy makers and non-governmental organization (NGO) involved in advocating the use of SDTs to reduce PHL.

In order to make a decision on what social impact subcategory and their inventory indicators to be used in the study, a focus group discussion was conducted by involving different stakeholders as listed in Table 2. For each focus group, the researcher organized participants into smaller sub-groups and assigned them the task of identifying the key social impacts they perceived as potential outcomes of adopting and using SDTs within their communities.

Table 2. Involving different stakeholders

Place	Focus group	# participants	UNEP/SETAC ategory
Morogoro	1	8	Workers and Local community
	2	7	Consumers and society
Arusha	1	6	Workers and local community
	2	6	Consumers and society
Total		27	

This was followed by a comprehensive literature review on previous research reports to identify the key social factors used in their assessment and finally a list of inventory impact categories was created. In this regard, a total of 16 impact subcategories were identified which were further expanded into 56 different inventory indicators. Table 3 provides a list inventory subcategory used per stakeholders which were included in the questionnaires.

Table 3. inventory subcategory used per stakeholders

Impact category	Source	TOT	W	C	LC	S
Health and Safety	UNEP*	13	10	NA	4	NA
Employment	UNEP	2	1	NA	2	2
Public awareness	UNEP	3	2	2	2	3
Fair income/Salary	UNEP	3	1	1	1	1
Education and Training	UNEP	2	2	NA	NA	1
Quality of dried products	OWN*	3	NA	3	NA	NA
Child labour	UNEP	2	1	NA	1	NA
Working hours	UNEP	2	2	NA	NA	NA
Equal opportunities/discriminations	UNEP	3	3	NA	NA	1
Technology transfer	UNEP	3	NA	NA	2	3
End of life responsibility	UNEP	3	3	NA	1	2
Social benefits/security	UNEP	3	3	NA	NA	NA
Community engagement	UNEP	3	1	NA	3	NA
Reduction of PHL	OWN	1	NA	NA	NA	1
Contributions to economic development	UNEP	2	1	1	NA	1
Public acceptance	OWN	1	NA	NA	NA	1
Increased food security	OWN	3	2	3	1	3
Government policy	UNEP	4	3	NA	NA	4
TOTAL		**56**				

UNEP*: Sub category obtained from the United Nations Environment Programme .

OWN*: Subcategory, developed by the researchers in consultation with stakeholders, which were not adopted from the UNEP guidelines

2.3 Inventory Analysis

The inventory data collection process was conducted via a structured questionnaires from the key stakeholders. This phase was the most challenging and time-consuming, particularly in ensuring data validity, reliability, and relevance. Informants were selected using convenience sampling. As shown in Table 4, the majority of respondents in the studied regions had attained secondary education. The largest proportion of respondents fell within the age range of 31–40 in Morogoro, and 18–30 in Arusha. Additionally, significant portions were in the 18–30 age group in Morogoro and 46–55 in Arusha. The majority respondents in Arusha and Morogoro, reported a monthly income ranging between USD 100 and 200, indicating a relatively modest earning level. A smaller proportion of respondents in each region reported earning less than USD 100 per month, suggesting the presence of low-income participants. Conversely, a notable number of participants earned more than USD 200 monthly indicating regional disparities in income levels, with Morogoro exhibiting a higher representation of relatively higher-income earners. In both Morogoro and Arusha, a higher percentage of respondents were employed in the private sector. Furthermore, both places showed a greater number of male respondents compared to females.

Table 4. the majority of respondents in the studied regions had attained secondary education.

Number of Respondent by Category		
Stakeholders Group	Morogoro	Arusha
Consumers	84(53.5%)	35 (40.6%)
Local community	31 (20%)	14 (16.3%)
Society	20 (12.7%)	5 (5.4%)
Workers	22 (13.8%)	33 (10.9%)
Gender		
Male	86 (69%)	57 (65%)
Female	71 (31%)	30 (35%)
Age		
18 - 30	48 (30.5%)	37 (43%)
31 - 40	57 (36%)	21 (23%)
46 - 55	50 (32%)	25 (29%)
56 - Above	12 (1.5%)	4 (5%)
Monthly income (US$)		
Less than 100	12 (7.5%)	18 (20%)
100 – 200	90 (57.5%)	44 (51%)
200 and above	55 (35%)	25 (29%)
Education level		
Primary certificate	39 (25%)	29 (33%)
Secondary certificate	57 (36%)	38 (44%)
Bachelors' degree	49 (31%)	16 (18%)
Masters' degree	10 (6%)	3 (4%)
Doctorate degree	2 (0.08%)	1(0.05%)
Occupational Sector		
Private	118 (75%)	61 (60%)
Public	69 (25%)	26 (30%)
Total respondents	157 (100%)	87 (100%)

The study employed a convenience sampling technique, selecting participants (n=244) based on the availability and accessibility which is cost-effective but may introduce bias. Hence, to minimize bias and improve reliability, the sample was diversified by selecting participants from various sources, locations, companies and demographic groups (e.g., gender, age, education) see Table 4 above. Additionally, a snowball sampling method was used to reach respondents who were not initially known, where participants referred others until a saturation point was achieved.

2.4 Social Life Cycle Impact Assessment (SLCIA)

The SLCIA uses a characterization method to convert survey results into inventory scores [26, 27]. There is currently no agreement on characterization method as evidenced by the wide variety of scoring methods employed in the literatures. Previous studies used various scales to assess the social impacts. Borgo et al., (2001) [28] applied a binary scale of 0 -1, to evaluate the social indicators such that if the score is so close to 1, means positive impacts, while if close to 0, indicate a negative impact, and 0 means no impacts. Hilty et al., (2013) [26] used a characterization method to classify data as positive (+) or negative (-) while Achillas et al., (2011); Rutta, (2022) [29.30] used a scale of 1, 0 and -1, where 1 refer to positive social impacts, -1 refer to negative impacts and 0 refer to neutral/no impacts. Foolmaun & Ramjeeawon, (2013) [21] and Franze & Ciroth, (2011) [32], suggested the use of a logical scoring system where indicator results are first converted to percentages and then placed into five score categories as follows 0–20% (1), 20–40% (2), 40–60% (3), 60–80% (4), and 80–100% (5). This study adopted the five-point Likert scale whereas 1 = very low, 2= low, 3 = medium, 4 = high and 5 = very high. The Likert Scale results were then converted into impact scores. For those impact category with a single indicator, Likert Scale results were multiplied by the number of participants and the results being aggregated. Finally, the total was divided by the total number of respondents to obtain the impact score for such category. For the impact category with more than one inventory indicator, the score for each indicator was obtained in a similar way as explained above, and the final score for this category was obtained by taking summation of the scores obtained from each indicator, and divided to the total number of indicators. Characterization of the social impact of each subcategory was done based on a color-coding system based on a scale of 1 – 5, with lower values indicating negative social impacts, and higher values indicating positive impacts see Table 5.

Table 5: Social Impacts subcategory characterization values

Category	Colour code	Scores
Very high impact		4.5 - 5.0
High impact		3.5 - 4.5
Moderate impact		2.5 - 3.5
Low impact		1.5 - 2.5
Very low impact		1.0 - 1.5

The characterization values (Table 5) were used as follows. The initial step involves calculating the overall score for each indicator: This was done by determining the mean (and standard deviation) of the individual scores provided by respondents. Each score was weighted by multiplying the number of respondents selecting a specific value (ranging 1 to 5) by that value, and then dividing the sum by the total number of respondents. An illustrative example of the data processing procedure is presented for the "Public acceptance" sub-category in Morogoro as follows:

In response to the indicator question, "public acceptance"; Level of acceptance of SDTs for crop drying in Morogoro. Likert Scale results were: 1 = Very low = 23; 2 = Low =43; 3 = Medium = 12; 4 = High = 31 and 5 = Very high = 48. The first steps involved the computation of the overall indicator scores whereby the individual respondent ratings for each indicator were aggregated into mean values (accompanied by standard deviations) using a weighted averaging method. This involved multiplying the frequency of each score (ranging from 1 to 5) by its corresponding value, summing the results, and dividing by the total number of respondents. The Likert score for each response category was computed by multiplying the number of respondents selecting a specific Likert scale value by the corresponding score value (ranging from 1 to 5) using Eq 1.

$$\text{Likert Score} = (\text{Number of Respondents for Score i}) \times (\text{Score Value i}) \quad (1)$$

Where, the Likert scale score results were multiplied by their corresponding values as described by Eq 1 above. Where 1 = very low = 23 x 1 = 23; 2 = low = 43 x 2 = 86; 3 = medium = 12 x 3 = 36;4 = high = 31 x 4 = 124 and 5 = very high = 48 x 5 = 240.

The following step involves the aggregation and calculation of average scores: The scores were totaled to derive a cumulative score for each indicator. To determine the average score, the total was divided by the number of respondents within each stakeholder group, see Eq 2.

$$Score = \frac{total\ Likert\ score}{otal\ number\ of\ respondents} \quad (2)$$

$$Score = \frac{23 + 86 + 36 + 124 + 240}{157} = \frac{509}{157} = 3.24$$

The third step involve the conversion to social impact scores: when a sub-category contained only one indicator as in the case of 'public acceptance' the individual indicator score was used directly. For sub-categories with multiple indicators, the respective scores were aggregated and averaged to produce a single composite score. This approach enabled consistent comparison across different social impact sub-categories in Eq 3.

$$Impact\ score\ for\ public\ acceptance = \frac{\sum total\ indicator\ score}{total\ number\ of\ indicators} \quad (3)$$

$$= \frac{3.24}{1}$$

Such that this score reflects a moderate social impact for the "public acceptance" sub-category (interpretation base on table 5).

3. RESULTS AND DISCUSSIONS

The S-LCIA was conducted to evaluate the social sustainability performance of SDTs across multiple impact categories. The results and discussions are presented based on the two specific objectives of the study. Identification of the key social factors for the SLCIA of SDTs and the SLCIA of SDTs.

3.1 Identification of Key Social Factors for the SLCIA of (SDTs)

The identification of key social factors for SLCIA of SDTs was carried out through a multi-step process combining desk research and stakeholders' engagement. Initially, a comprehensive review of literatures was conducted to examine previous studies on the sustainability of SDTs and related studies that employed SLCA methodology. The review identified commonly key social indicators applied. In addition to this the UNEP guidelines for SLCA was also used where a number of impact category was obtained from it and being customized for this particular study. Lastly the impact categories were compiled, scrutinized and validated by expert through participatory approach to ensure contextual relevance and methodological rigor. The final list of inventory subcategory is presented in Table 3. This approach is consistent with those used in previous SLCA studies. For example, Nubi, (2022) [25], employed a participatory methodology to identify key social impacts and subcategories in the SLCA of proposed waste-to-energy systems in Lagos and Abuja, Nigeria. Similarly, Azimi et al., (2020) [24], utilized a similar method to compile a list of impact categories for the SLCA of household waste management systems in Kabul, Afghanistan. While specific SLCA studies focusing SDTs are currently lacking, this study is the first of its kind to apply the SLCA methodology to the assessment of SDTs. In addition to utilizing indicators derived from the UNEP/SETAC guidelines, the study also introduced two additional indicators, complementing those adopted from the UNEP/SETAC guidelines, to address the specific context of SDTs. These subcategories are "reduction of post-harvest loss" and "increased food security", along with their associated indicators, provide valuable insights that may also be relevant in similar SLCA studies.

3.2. Social Life Cycle Impact Assessment Results

The results revealed a diverse distribution of scores across the evaluated subcategories. Several impact categories demonstrated high positive performance, with scores above 4.0. A second group of categories received moderate scores between 3.2 and 4.0, reflecting average social performance. The last category of indicators scores below 3.0 which indicate negative social impact. These results highlight the need for strategic interventions to enhance the long-term sustainability and social inclusiveness in the implementation of SDTs. Overall, the findings offer a solid foundation for identifying both strengths and areas for improvement in future policy and technology deployment efforts. Table 6 presents the consolidated indicator scores alongside the color-coding scheme used for each social impact sub-category. The results show some differences in scores between Morogoro and Arusha across all sub-categories.

Table 6 presents the consolidated indicator scores

Social Impacts subcategory	Morogoro	Arusha	Combined
	(n=157)	(n= 87)	
Health and Safety	3.94	3.12	3.65

Social Impacts subcategory	Morogoro	Arusha	Combined
Employment	4.02	4.1	4.05
Public awareness	3.5	3.42	3.47
Fair Income/Salary	3.61	2.88	3.35
Education and Training	3.8	2.94	3.49
Quality of dried Products	3.64	3.98	3.76
Child Labour	4.18	3.98	4.11
Working Hours	2.5	2.21	2.30
Equal Opportunities/Discriminations	4.21	3.98	4.13
Technology Transfer	3.51	2.96	3.31
End of life Responsibility	2.01	1.61	1.87
Social/benefits/Security	3.01	2.12	2.59
Community Engagement	3.4	3.08	3.29
Reduction of PHL	4.11	3.97	4.06
Contributions to Economic Development	3.62	3.04	3.41
Public Acceptance	4.18	3.92	4.09
Increased Food Security	3.82	4.21	3.96
Government Policy	2.12	1.96	2.06
Average score	3.60	3.35	3.51

1.0 - 1.5	1.5 - 2.5	2.5 - 3.5	3.5 - 4.5	4.5 - 5.0

← Poor performance Better performance →

3.2.1 High-Performing Impact Categories

Top performing impact categories with overall score above 4.0 were employment, public acceptance and awareness, reduction of PHL, equal opportunities and child labour see table 6 above. The high score in the employment category is a recognition that implementation of SDTs contribute positive to the creation of both formal and informal employment. Another category with outstanding high performance is the public awareness and acceptance. Awareness and acceptance are fundamental drivers of adoption and use of technology. Such high score in awareness is a clear indication that stakeholders recognize the benefits of using SDTs for sustainable food processing for long-term sustainability within the community. Child labour is another indicator with positive scores. This suggests that the adoption of SDTs has a positive impact in reducing or eliminating children's involvement in crop drying processes. This outcome is attributed to the fact that SDTs use less drying time, and minimal labour involvement, thereby reducing the demand for child participation in post-harvest activities. Equal opportunity is another indicator with high score which strongly suggests that the introduction of SDTs is widely perceived to enhance fairness and inclusivity in terms of access and participation. Furthermore, SDTs are accessible to individuals regardless of gender, age, socioeconomic status, or other demographic characteristics, thereby contributing to more equitable technological diffusion in the communities

The last indicator which scored high is the reduction of PHL. This results clearly demonstrate that the adoption of SDTs significantly contributes in minimizing FWL, particularly perishable crops such as fruits vegetables and spices. Using SDTs help to improve hygiene standards compared to traditional methods, extend the shelf life of agriculture produce thereby enhancing food safety as well as enabling access to more distant and high-value markets. Another indicator related to this which also scored high is the increased food security. SDTs play a major role to increase food security by ensuring that a greater proportion of harvested crops is properly processed to remains in good condition for consumption and distribution. Preservation of food through SDTs means that more food reaches consumers in usable form, reducing seasonal shortages and enhancing food availability at both household and market levels.

Overall, the consistently high scores obtained across all indicators in this category suggest that the implementation of SDTs is widely perceived as having potential to generate positive outcomes, including the reduction of post-harvest losses, increase food security, mitigation of child labour in crop drying processes, expansion of both formal and informal employment opportunities and the promotion of equitable benefits to diverse age groups.

3.2.2 Moderately Performing Impact Categories

Majority of the impact subcategories fall within this category which is an average and above average score ranging between 3.0 and 3.9. For the majority of the impact subcategory to fall under this category indicate that the implementation of SDTs have an average impact to the society. Impact subcategories with moderate social performance include health and safety, fair income and salary, public awareness, education and training, quality of the dried products, technology transfer, community engagement and contributions to economic development.

For the social impact subcategories of health and safety; it can be discussed based on two major views one the ability of SDTs to ensure food safety and hygiene and two safe operations environments to the stakeholders. Findings in this sub category indicate moderate performance indicating that stakeholders have an average confidence in the ability of SDTs to prevent food from contaminants such as dusts insects and other micro-organisms. The ability of SDTs to be able to maintain consistency temperature during drying process have a high chance of reducing spoilage and mycotoxins and hence extend the shelf-life of dried products. Second the assembly operations, use and end of life disposal of SDT's components does not pose major health hazards to the stakeholders involved. For the impact subcategory of quality of the dried product stakeholders also had an average perception that SDTs can retain essential nutrients such as vitamins and preserve the natural colour and texture of crops being dried especially fruits, vegetables and herbs. Based on findings provided above they provide clear evidence that SDTs outperformed traditional OSD methods in both health and safety standards and the quality of the crop being dried.

The impact subcategories of fair income/salary and contributions to economic development also scored moderate performance. Although SDTs is recognized as having positive economic potential, particularly in reducing post-harvest losses, increasing the shelf life of crops hence improving marketability of agricultural products, promote the generation of employment but the current scores indicate that their impact on income generation and economic development is only partially realized. The findings for these subcategories highlight the need for a stronger strategic mechanism, including improve access to markets of dried products, fair pricing strategies, and the formalization of employment structures for solar drying facilities. Addressing these issues will be essential to ensure that SDTs contribute to a sustainable livelihood for the stakeholders involved.

The impact subcategories of public awareness and community engagement obtained an overall average score indicating that community awareness and engagement in the implementation and operational use of solar dryers is only at an average level. Furthermore, this demonstrate that the community has not yet fully embrace the opportunities available in SDTs. This call for more efforts in awareness creation and engagement for the maximum realization of the potentials impacts of SDTs application in agri-food processing. The last two impact categories with average performance were technology transfer and education and training. These findings reflect that training and capacity-building activities have somewhat been implemented, but the results point to limited depth and coverage of these efforts. Many stakeholders may have received only basic instructions in SDTs operation and maintenance, which may not be sufficient to support widespread or sustained use of the technology. The findings highlight the need for a targeted efforts to strengthen the transfer of SDTs knowledge and skills, by introducing a comprehensive, ongoing, and inclusive training program, particularly in unreached areas, expanding access to SDTs education especially in rural and marginalized areas.

The predominance of moderate scores across most impact subcategories suggests that the two regions of Tanzania have not fully committed to leverage the available opportunities for effective implementation of SDTs. This indicates a partial rather than a fully adoption of SDTs, reflecting limited institutional or systemic effort toward maximizing the potential benefits of SDTs. Finally, a joint effort is required by multiple stakeholders the local community, the government, the NGOs and research institutions so as to maximize the impacts of SDTs to achieve higher positive results for a more socially sustainable and responsible food drying systems.

3.2.3 Low Performing Impact Categories

The low-performing social impact categories include subcategory which perform very low below 3.0. Only few indicators fall under this category which include working hours, social security, government policy and end of life responsibility which perform extremely poor. For the subcategory working hours to have poor performance it implies a non-compliance with both local and international labor standards in SDTs facilities regarding working hours. This point to a possibility of workers required to work for excessive working hours, a lack of rest and annual leave, and the absence of policies to regulate working time. Another sub category which had low performance was the social security and protection. This indicates a lack or absence of proper policy guiding employee welfare in the solar drying systems, as evidenced by the lack of social insurance coverage and inadequate provisions for maternity and paternity leave. The findings above suggest that the social sustainability performance of SDTs is critically low in areas directly affecting worker rights and well-being. The findings under the subcategories working hours and social security protection underscore the urgent need of the managers of the SDTs facilities and government regulatory organs to provide close oversight and strategic guidance to businesses utilizing SDTs facilities to promote greater investment in employee welfares.

The impact subcategory government policy had a low performance which is a clear indication of poor enforcement of labour related laws and an absence of stakeholder's engagement or consultations in policy development. Additionally, the low score obtained under this category was also contributed by a lack of support on research and development activities especially by research institutions like universities and vocational training institutions. Most researchers in these institutions acknowledge their dependance on external donor funding for their research activities. The last subcategory with extremely poor performance is the end of life (EoL) responsibility. EoL responsibility is a very important undertaking to ensure sustainable product management, as it ensure that once products reach the end of their useful life, are handled in ways that minimize environmental harm and maximize social and economic values. The low performance in this subcategory was evidenced by a lack of proper policies promoting circular economy practices reuse and material's recovery. There was also low awareness to workers and the local community regarding EoL handling of components and inexistence of recycling programs, including poor waste collection for recycled materials. Collectively the findings above suggest the need for a creation of stronger policy framework and awareness creation to foster accountability and promote responsible and sustainable production and consumption in SDTs and crop processing sector in general.

It is evident from the findings above that SDTs perform poor in the impact subcategories of working hours, government policy social security protection and EoL responsibility. These findings highlight the need for a comprehensive reform to ensure compliance to labour laws, strengthen workers protection policy and promote sustainable and responsible operations.

3.3 Discussions

Due to the limited availability of SLCA studies specifically focused on SDTs, the discussion and comparison of findings in this study is based on existing SLCA research conducted in other sectors such as municipal household waste management, waste-to-energy bioenergy systems, and agricultural practices in general. Public acceptance was identified as having a positive social impact in this study. The findings are consistent with the results of [29] who reported that favorable public attitudes significantly contributed to the successful implementation of thermal waste treatment project in Thessaloniki, Greece highlighting the crucial role of community support in achieving positive social outcomes for the implementation of a new technology. This was also confirmed by the study by [3] and [30] who identified the lack of awareness as among the barriers of adoption and use of solar dryers for food drying in Mozambique and Tanzania respectively.

In this study, inventory indicators such as employment, occupational health and safety, public awareness and acceptance, increased food security, and reduction of PHL were found to have positive social impacts. The findings align with those of [25] who evaluated the social life cycle impacts of electricity generation from municipal solid waste, also reporting positive outcomes in similar social categories. In contrast, the findings of this study, which highlight the positive social impacts of SDTs in Tanzania particularly in areas such as employment creation, reduction of child labour, increased food security, and reduction in PHL; a study on the social impacts of waste management strategies in Kabul, Afghanistan by [23] reported negative social impacts in areas such as local employment, child labour and excessive working hours as the major social concerns within the waste management sector. These differences might be contributed by the nature of the technology under considerations (i.e. SDTs vs waste management technologies) and the socio-economic context which play a critical role in shaping social performance outcomes in SLCA studies.

Other SLCA studies with findings consistent with those of the present study include [12] and [13] who performed a SLCA of a solar power plant in Spain. These studies reported positive social impacts, particularly in areas such as job creation, economic improvement, and knowledge transfer. Furthermore [33], found that the use of SDTs in mitigating aflatoxin contamination in food crops contributes significantly to food safety and security. This study found out that the absence of EoL responsibility contributes to its low performance in SDTs which is consistence to the findings of [23] who also find out the lack of extended producer responsibility largely undermine the sustainability of the Kabul city waste management system. From this view it can be emphasized that regulatory policies be formulated to make product manufacturers directly responsible for the EoL management of their products, in order to enhance environmental sustainability.

This study on SDTs has contributed to a deeper understanding of how social challenges related to sustainable food drying can be addressed, while also demonstrating the relevance of SDTs in supporting the achievement of several United Nations Sustainable Development Goals (SDGs). For example, transitioning from conventional fossil fuels to renewable energy sources, such as those used in SDTs, is expected to reduce carbon dioxide emissions and help mitigate climate change. Key policymakers and stakeholders consulted in this study emphasized that the implementation of SDTs represents a more environmentally friendly alternative, and advocated for their integration into national policies, including the national renewable energy policy and other environmental regulatory frameworks. Such integration is a means to accelerate an environmentally and socially sustainable transition within the food drying sector.

4. CONCLUSIONS

This study assessed the social impacts of SDTs applied in Morogoro and Arusha regions of Tanzania. Overall, SDTs demonstrate significant socio-economic benefits including its contribution to the reduction of PHL, creation of employment opportunities, and fostering fairness and inclusivity in access to these technologies regardless of gender, age, or other demographic factors. Average scores were recorded in categories such as health and safety, public awareness and acceptance, fair income and salary, education and training, quality of the dried product, technology transfer, community development, and contributions to economic development, suggesting that they have not been fully embraced for maximum results. In this regards more effort should be directed to raise the impacts of these factors to yield maximum results. Low scores observed in in the subcategories of end-of-life responsibility, government policy, social protection and working hours, highlight critical areas where SDTs are associated with notable negative social impacts. This call for targeted policy and institutional support to enhance their overall sustainability. These efforts altogether directly support the achievement of the global SDGs #1 on poverty alleviation, SDG # 2: emphasizes on Zero Hunger and SDG # 7 Affordable and Clean Energy.

This study makes two key contributions. First, it addresses a critical knowledge gap by being the first/among the early study to do a comprehensive assessment of the social sustainability of SDTs, an area which have little coverage in the literatures. Second, the study advances methodological development by applying the SLCA framework to evaluate SDTs marking a significant departure from previous studies that focused on life cycle assessment (LCA) methods focused on environmental and economic dimensions. By integrating SLCA, the study offers a people-centered understanding of sustainability in solar drying systems.

Future studies should focus on developing robust characterization methods for SLCIA to improve the reliability, comparability, and generalizability of social sustainability research outcomes. Given the current lack of methodological maturity in SLCA, advancing a standardized impact characterization framework is essential for broader application and cross-study consistency. Additionally, future research studies should investigate the end-of-life management strategies of SDTs infrastructures within a circular economy framework, focusing on reuse, recycling, and responsible disposal for the long-term sustainability achievement.

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Ashiraf Abeid led the research process, including conceptualization, literature review, methodology development, data collection and analysis. He also drafted and finalized the manuscript.
Felichesmi Lyakurwa contributed to the research design and methodology, and provided critical feedback to ensure academic rigor and alignment with the study's objectives.
Eliaza Mkuna offered expertise in the framework design, reviewed the manuscript, suggested improvements, and ensured compliance with ethical standards.

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