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Social Life Cycle Assessment of Irrigation Technologies in Indian Cassava Farming

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HIGHLIGHTS

- Solar irrigation farmers achieved higher social sustainability scores than electricity irrigation farmers. Renewable irrigation technology promoted inclusive and sustainable cassava farming system.
- Community participation, labour welfare, and capacity building improved significantly under solar irrigation.
- Seven principal components explained 79.42% of total social sustainability variation.

ARTICLE INFO

Keywords: Social life cycle assessment, Solar irrigation, Cassava cultivation, Social sustainability, Renewable energy.

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ABSTRACT

Sustainable irrigation technologies play a vital role in improving rural livelihoods and strengthening social sustainability in agriculture. The present study assessed the social sustainability performance of cassava production systems under solar-powered and electric irrigation technologies in Kallakurichi district of Tamil Nadu, India, during 2025. A Social Life Cycle Assessment (SLCA) framework integrated with Principal Component Analysis (PCA) was employed to evaluate seven social dimensions, namely labour availability, labour welfare, women participation, capacity building, household welfare, community participation, and post-harvest participation. Primary data were collected from 640 cassava farmers using a structured interview schedule. The Kaiser–Meyer–Olkin value (0.853) and Bartlett's test of sphericity ($p < 0.001$) confirmed the suitability of the data for factor analysis. Seven principal components explained 79.42 per cent of the total variance. The findings revealed that farmers adopting solar irrigation achieved higher social sustainability scores than electric irrigation farmers across all dimensions. Greater improvements were observed in labour welfare, community participation, and capacity building. The composite SLCA index was higher for solar irrigation farmers (0.65) compared to electric irrigation farmers (0.50). The study concluded that renewable irrigation technologies promoted social sustainability, farmer welfare, and inclusive rural development in cassava production systems.

INTRODUCTION

Cassava (*Manihot esculenta* Crantz) was an important tropical tuber crop cultivated widely in Asia, Africa, and Latin America because of its adaptability to diverse agro-climatic conditions and its contribution to food security, agro-industrial development, and rural livelihoods (Pretty et al., 2018; Zhu et al., 2023). In India, cassava cultivation was concentrated mainly in southern states such as Tamil Nadu, Kerala, and Andhra Pradesh, where favourable climatic conditions supported commercial production.

Agricultural sustainability included economic, environmental, and social dimensions. Social sustainability focused on equity, labour welfare, participation, and community well-being, which influenced technology adoption, livelihood security, and long-term

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sustainable agricultural development (Eizenberg & Jabareen, 2017; Pal et al., 2017). Social factors such as education, extension contact, institutional credit, and market accessibility significantly influenced farmers' adoption of improved technologies and livelihood outcomes. Yadav et al. (2026) identified landholding size, education, extension contact, and credit access as important socio-economic determinants influencing sustainable agricultural development and farmer welfare in Punjab.

Social Life Cycle Assessment (S-LCA) emerged as a framework for evaluating the social and socio-economic implications of agricultural production systems. Unlike conventional Life Cycle Assessment (LCA), which primarily concentrated on environmental impacts, Social Life Cycle Assessment (S-LCA) was employed to evaluate the social and socio-economic impacts of production systems on various stakeholder groups, including workers, farm owners, local communities, and value chain actors. The assessment considered indicators related to labour conditions, occupational health and safety, employment opportunities, social benefits, community engagement, technology transfer, food security, and stakeholder welfare throughout the product life cycle (Mulyasari et al., 2023). Principal Component Analysis (PCA) was increasingly applied in sustainability studies to identify major dimensions influencing social sustainability outcomes.

Irrigation technologies played an important role in determining agricultural productivity. Conventional electric irrigation systems often faced challenges such as unreliable power supply, increasing operational costs, and groundwater depletion. Renewable energy-based irrigation technologies, particularly solar-powered irrigation systems, gained increasing attention as sustainable alternatives because they provide daytime irrigation and improved irrigation efficiency. Upreti et al. (2023) reported that solar-powered tubewells reduced irrigation costs and improved farm efficiency in Rajasthan. Similarly, Peer et al. (2026) observed that solar-powered irrigation systems improved crop yield, crop quality, crop diversification, and plant development among farming households in the Kashmir Valley. Kaur and Sharma (2022) also emphasized that improved irrigation scheduling methods enhanced water-use efficiency and promoted sustainable agricultural production systems in north-western India.

Despite the increasing adoption of renewable irrigation technologies, limited empirical evidence was available regarding their social sustainability implications in cassava production systems. Most previous studies mainly focused on productivity enhancement and environmental efficiency, while comparatively less attention was given to labour welfare, women participation, household welfare, and community engagement. Therefore, the present study evaluated the social sustainability performance of cassava production systems under solar-powered and electric irrigation technologies in Kallakurichi district of Tamil Nadu using a Social Life Cycle Assessment framework integrated with Principal Component Analysis.

METHODOLOGY

The study was conducted in Kallakurichi district of Tamil Nadu, India, one of the major cassava-producing regions in the state. The district was selected because cassava cultivation is closely associated with starch and sago processing industries, which provide employment opportunities and support rural livelihoods. Primary data were collected during the 2025 agricultural year using a multistage sampling design. Major cassava-growing blocks and villages were identified based on the extent of cassava cultivation, and farmers were randomly selected from the identified villages. A total of 640 cassava farmers were surveyed, including 320 farmers using solar-powered drip irrigation systems and 320 farmers using conventional electric drip irrigation systems.

Primary data were collected through structured face-to-face interviews using a pre-tested interview schedule. Information related to labour availability, labour welfare, women participation, capacity building, household welfare, community participation, and post-harvest participation was collected from the respondents. All indicators were measured using a five-point Likert scale ranging from 1 (strongly disagree) to 5 (strongly agree). The selection of indicators was guided by the UNEP/SETAC guidelines for Social Life Cycle Assessment and previous sustainability studies related to agricultural sustainability assessment. The social sustainability indicators were selected based on the UNEP/SETAC Guidelines for Social Life Cycle Assessment and relevant agricultural sustainability literature. The suitability of the selected indicators was further verified through expert consultation, while their reliability and construct validity were assessed using Cronbach's alpha reliability analysis and Principal Component Analysis (PCA), respectively.

Before conducting the analysis, the reliability of the selected indicators was examined using Cronbach's alpha reliability analysis. The overall Cronbach's alpha value of 0.89 indicated a high level of internal consistency among the indicators. The collected indicator values were then standardized using the Z-score transformation method to remove scale differences among variables. The standardized value was calculated as:

$$Z_i = \frac{X_i - \overline{X}}{SD}$$

where Z_i represents the standardized value of indicator *i*, X_i denotes the original indicator value, $\overline{X}$ represents the mean value of the indicator, and *SD* denotes the standard deviation. Principal Component Analysis (PCA) was subsequently applied to identify dominant social sustainability dimensions and derive indicator weights. Components with eigenvalues greater than one were retained according to the Kaiser criterion, and Varimax orthogonal rotation was applied to improve interpretability. Principal Component Analysis (PCA) was conducted on the individual social sustainability indicators rather than on aggregated dimensions to identify the underlying factor structure and derive objective indicator weights. The complete rotated component matrix obtained through Varimax rotation is presented in Table 3.

The indicator weights were derived using factor loadings and eigenvalues obtained from PCA according to the following equation:

$$w_i = \frac{L_i \times E_j}{\Sigma(L_i \times E_j)}$$

PCA-derived weights were used to ensure an objective and data-driven assessment of indicator importance. Unlike equal-weighting approaches, this method assigns greater importance to indicators that contribute more substantially to the explained variance of social sustainability dimensions, thereby reducing subjectivity and improving the robustness of the composite SLCA index.

where w_i represents the weight assigned to indicator i, Li denotes the factor loading, and E_j represents the eigenvalue of component j. The indicator values were normalized using the min–max normalization method:

$$N_i = \frac{X_i - X_{min}}{X_{max} - X_{min}}$$

Dimension indices were calculated using:

$$DI_d = \frac{1}{n_d}\sum_{i=1}^{n_d} N_i$$

Finally, the Social Life Cycle Assessment (SLCA) index was constructed using weighted aggregation:

$$SLCA = \sum_{i=1}^{n} w_i N_i$$

The resulting SLCA index was used to compare the social sustainability performance of cassava farmers adopting solar-powered and electric drip irrigation systems.

RESULTS

Social sustainability dimensions and principal component analysis

Table 1 The comparison of socio-economic characteristics revealed that farmers adopting solar-powered irrigation systems generally possessed stronger socio-economic profiles than those using electric irrigation systems. Solar irrigation farmers exhibited relatively better educational attainment, greater farming experience, higher involvement in cassava cultivation, larger landholding patterns, and improved income levels, indicating a stronger capacity to adopt and manage advanced agricultural technologies. Differences were also observed in occupational status, suggesting that solar irrigation adopters had comparatively better access to productive resources and livelihood opportunities. In contrast, family size, cropping pattern, and gender composition showed only minor variations between the two groups, indicating a broadly similar demographic structure. Overall, the findings suggest that favourable socio-economic conditions may have supported the adoption of renewable irrigation technologies among cassava farmers.

The assessment of social sustainability dimensions further demonstrated that solar irrigation farmers consistently outperformed electric irrigation farmers across all indicators. Higher levels of labour availability, labour welfare, women's participation, capacity building, household welfare, community participation, and post-harvest participation were observed among solar irrigation adopters. Stronger performance in community participation and capacity building reflected greater engagement with farmer organizations, training programmes, and institutional support systems, while improved labour welfare and women's participation indicated more inclusive and supportive farming environments. Although household welfare remained comparatively weaker than other dimensions, solar irrigation farmers still achieved better outcomes than their electric irrigation counterparts. These findings highlight that solar-powered irrigation systems contributed not only to improved farm operations but also to enhanced social sustainability, institutional engagement, and livelihood resilience within cassava production systems.

Table 1. Socio-economic characteristics of sample farmers and descriptive statistics of social sustainability dimensions

Characters	Solar Irrigation Farmers	Electric Irrigation Farmers	t-value	Confidence Interval	Effect Size
Age	1.83	2.05	-4.04	-0.22	-0.52
Educational Status	3.70	2.73	12.28	0.97	1.59
Experience in Farming	2.23	2.02	4.04	0.22	0.52
Farming Experience in Cassava	2.00	1.88	2.79	0.12	0.36
Gender	1.35	1.27	2.32	0.08	0.30
Family Size	1.87	1.93	-2.05	-0.07	-0.27
Occupation	1.77	1.63	3.01	0.13	0.39
Land Holding Patterns	2.20	2.00	3.84	0.20	0.50
Cropping Patterns	2.50	2.53	-0.53	-0.03	-0.07
Annual Income	2.07	1.83	4.24	0.23	0.55

Dimension-wise Descriptive Statistics of Social Sustainability Indicators

Dimension	Solar Irrigation (Mean)	Electric Irrigation (Mean)
Labour availability	3.58	2.98
Labour welfare	3.60	3.00
Women participation	3.57	2.97
Capacity building	3.60	3.04
Household welfare	3.55	2.93
Community participation	3.69	3.06
Post-harvest participation	3.59	2.98

Note: Higher mean values indicate relatively better socio-economic status and stronger social sustainability performance among cassava farmers. Effect size values represent the magnitude of differences between solar and electric irrigation farmer groups.

The Kaiser–Meyer–Olkin (KMO) statistic indicated a high level of sampling adequacy, confirming that the data were suitable for factor analysis. Furthermore, Bartlett's Test of Sphericity was significant, demonstrating the presence of sufficient correlations among the variables to justify the application of PCA. The significant Bartlett's test confirmed that the selected indicators were sufficiently correlated for dimensional reduction. These findings demonstrated that the dataset was appropriate for extracting principal components and constructing a reliable composite sustainability index.

The Principal Component Analysis (PCA) results presented in Table 2 supported the retention of seven components based on the Kaiser criterion, whereby components with eigenvalues greater than one were considered significant. Prior to extraction, the suitability of the dataset for PCA was confirmed through KMO and Bartlett's tests, indicating adequate intercorrelations among variables. The retained components collectively explained a substantial proportion of the total variance, suggesting that the extracted factor structure adequately represented the underlying dimensions of social sustainability. The first two components accounted for the largest share of variance, while the remaining components contributed additional explanatory information and captured distinct aspects of the social sustainability framework. The retention of seven components was further supported by their conceptual relevance and strong factor loadings, which facilitated meaningful interpretation of the identified dimensions and ensured comprehensive representation of the social indicators included in the analysis.

The rotated component matrix presented in Table 3 revealed a clear clustering of indicators into seven distinct social sustainability dimensions. The strong association between indicators their respective components confirmed the conceptual validity of the selected dimensions. The extracted dimensions represented women participation, labour welfare, labour availability, capacity building, household welfare, community participation, and post-harvest participation.

Table 2. Total Variance Explained by Principal Components

Principal Component	Eigenvalue	Variance Explained (%)	Cumulative Variance (%)
1	4.286	14.29	14.29
2	4.112	13.71	27.99
3	3.798	12.66	40.66
4	3.339	11.13	51.78
5	3.189	10.63	62.41
6	2.705	9.02	71.43
7	2.396	7.99	79.42

Note: Seven components with eigenvalues above one explained 79.42% variance, indicating strong representation of social sustainability indicators.

Social sustainability performance of cassava farmers

The dimension-wise SLCA scores presented in Table 4 showed that solar irrigation farmers achieved higher sustainability values across all seven dimensions compared with electric irrigation farmers. Community participation emerged as the highest-performing dimension under solar irrigation systems, followed by labour welfare and capacity building. Women participation recorded higher values under solar irrigation systems compared with electric irrigation systems. Labour availability recorded higher values under solar irrigation systems than under electric irrigation systems. Household welfare recorded the lowest sustainability scores under both irrigation systems.

Farmers using solar irrigation systems achieved a higher average SLCA score, whereas electric irrigation farmers recorded a comparatively lower score. The variation observed between the two irrigation systems was statistically significant at the 1% level, as evidenced by the independent sample t-test results presented in Table 5. The results indicated that renewable irrigation technologies contributed positively toward improved labour organization, institutional participation, and overall social sustainability outcomes within cassava production systems.

Sustainability classification and distribution of farmers

The distribution of farmer-level SLCA scores was examined boxplot visualization in Figure 1. Solar irrigation farmers recorded

Table 4. Dimension-wise Social Life Cycle Assessment under Solar and Electric Irrigation

Social Sustainability Dimension	Solar Irrigation	Electric Irrigation	Difference
Labour availability	0.65	0.50	+0.15
Labour welfare	0.66	0.51	+0.15
Women participation	0.64	0.48	+0.16
Capacity building	0.66	0.51	+0.15
Household welfare	0.48	0.37	+0.11
Community participation	0.68	0.53	+0.15
Post-harvest participation	0.64	0.49	+0.15

Note: Index values range from 0 to 1, where higher values indicate stronger social sustainability performance under irrigation systems.

Table 3. Rotated Component Matrix of Social Sustainability Indicators (Varimax Rotation)

Principal Component	Indicators	Factor Loading Range	Identified Dimension
Component 1	W11–W15	0.879 – 0.902	Women participation and gender equity
Component 2	LW6–LW10	0.872 – 0.910	Labour welfare and working conditions
Component 3	L1–L5	0.882 – 0.891	Labour availability and employment
Component 4	CB16–CB19	0.892 – 0.907	Capacity building and knowledge access
Component 5	FH20–FH23	0.870 – 0.894	Farm household welfare
Component 6	CP24–CP27	0.860 – 0.885	Community participation and institutional support
Component 7	PH28–PH30	0.894 – 0.905	Post-harvest and market participation

Note: For better interpretation, only factor loadings above 0.70 are presented, and Varimax rotation was applied during analysis.

Table 5. Independent Sample t-test for Comparison of SLCA Scores

Variable	Mean SLCA Score	t-value	p-value
Solar irrigation farmers	0.65	12.4	< 0.01
Electric irrigation farmers	0.50		

Note: Independent sample t-test results confirmed a significant difference ($p < 0.01$), indicating superior social sustainability among solar irrigation farmers.

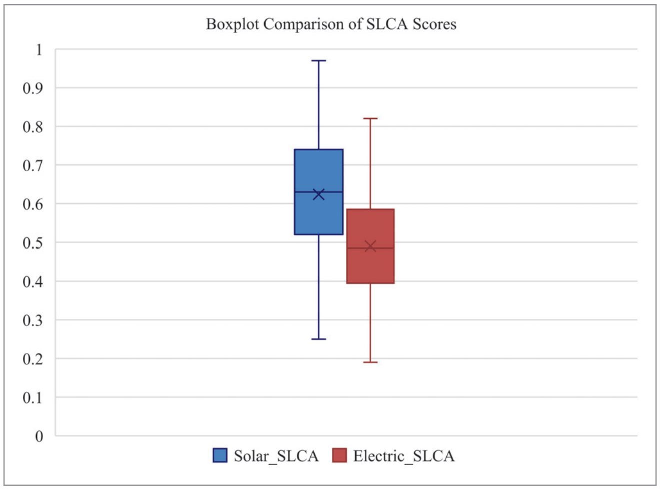

Figure 1. Boxplot Comparison of SLCA Scores by irrigation type

a broad range of SLCA scores, with most observations concentrated at relatively higher sustainability levels. In contrast, electric irrigation farmers recorded comparatively lower sustainability values, with the majority of observations concentrated within the moderate sustainability category. The higher median and upper quartile values observed under solar irrigation systems indicated broader improvements in labour welfare, institutional participation, and livelihood resilience among solar irrigation adopters.

Farmers were categorized into low sustainability (SLCA < 0.40), moderate sustainability (0.40–0.60), and high sustainability (SLCA > 0.60) groups. Approximately 65 per cent of solar irrigation farmers belonged to the high sustainability category, while only 29 per cent of electric irrigation farmers achieved similar sustainability levels. In contrast, 22 per cent of electric irrigation farmers fell within the low sustainability category compared with only 6 per cent among solar irrigation farmers. These results demonstrated broader and more inclusive sustainability improvements under solar irrigation systems.

DISCUSSION

The study demonstrated that solar-powered irrigation systems enhanced the social sustainability of cassava production systems compared with conventional electric irrigation systems. The observed improvements extended beyond irrigation performance and reflected broader benefits for labour welfare, institutional participation, capacity building, and livelihood resilience. These findings suggested that renewable energy technologies can contribute to socially inclusive agricultural development by reducing operational constraints and improving farmers' access to resources and opportunities.

The superior social sustainability performance of solar irrigation farmers could largely be attributed to the reliability and flexibility of solar-powered irrigation systems. Consistent access to irrigation enabled farmers to undertake agricultural operations according to crop requirements rather than being constrained by irregular electricity supply. Improved scheduling of farm activities likely strengthened labour management, reduced production uncertainties, and enhanced overall farm efficiency. Similar findings were reported by Siririka et al. (2025), who found that renewable irrigation technologies strengthened socio-economic sustainability and supported rural agricultural development.

Community participation emerged as a key contributor to social sustainability among solar irrigation farmers. Greater involvement in farmer organizations, extension programmes, and collective activities indicated stronger social networks and institutional linkages. Such interactions facilitate knowledge exchange, improve access to information, and encourage collective problem-solving among farming communities. Okolie et al. (2024) similarly reported that farmer networks and institutional participation enhanced resilience and promoted the adoption of sustainable agricultural innovations. The findings therefore highlighted the importance of strengthening community-based institutions alongside technological interventions.

The results also suggested that solar irrigation technologies indirectly promoted capacity building through increased interaction with extension services and training programmes. Access to technical information and advisory support enhanced farmers' understanding of irrigation management and sustainable production practices. Naveen et al. (2024) reported that extension support improved farmers' adaptive capacity and facilitated the adoption of improved technologies. This indicated that the benefits of renewable irrigation technologies extended beyond physical infrastructure to include improvements in human capital and knowledge systems.

Labour-related dimensions also showed notable improvements under solar irrigation systems. Reliable irrigation reduced interruptions in farm operations and enabled more efficient allocation of labour resources throughout the production cycle. Improved working conditions and operational efficiency may have contributed to greater labour stability and welfare. Verma et al. (2020) similarly observed that renewable energy-based irrigation systems improved labour productivity and farm management efficiency. These findings emphasized the potential of solar irrigation technologies to support employment-related aspects of agricultural sustainability.

Women participation was another dimension positively influenced by solar irrigation adoption. Reduced irrigation constraints and improved operational flexibility may have created greater opportunities for women to engage in agricultural activities and farm-level decision-making. Quisumbing et al. (2014) reported that gender-inclusive agricultural systems strengthened household welfare and supported equitable rural development. The findings therefore underscored the importance of considering gender outcomes when evaluating the sustainability impacts of agricultural technologies.

The PCA results confirmed the suitability of the selected indicators for measuring social sustainability in cassava production systems. The strong factor structure demonstrated that the identified dimensions collectively captured the multidimensional nature of social sustainability. Similar PCA-based approaches were used by Sala et al. (2015) and Moldan et al. (2012) to evaluate sustainability performance across multiple dimensions. The integration of PCA with the SLCA framework therefore provided a robust methodological approach for sustainability assessment.

Despite the positive influence of solar irrigation technologies, household welfare remained a relatively weaker dimension. This finding suggested that technological improvements alone may not be sufficient to address broader socio-economic challenges affecting farming households. Factors such as market access, value-chain development, income stability, and financial support continue to play a critical role in shaping household welfare outcomes. Therefore, policy interventions should combine technological adoption with market and institutional support mechanisms to achieve more comprehensive sustainability improvements.

Overall, the findings highlighted that renewable irrigation technologies can contribute substantially to socially sustainable and resilient cassava production systems. By strengthening institutional engagement, labour welfare, capacity building, and gender participation, solar-powered irrigation systems supported broader rural development objectives and promoted inclusive agricultural sustainability.

Despite providing valuable insights into the social sustainability performance of cassava production systems, the study has certain limitations. The analysis was confined to selected cassava-growing areas of Kallakurichi district and may therefore be subject to selection bias, limiting the generalizability of the findings. In addition, the study relied on self-reported responses collected through farmer interviews, which may be influenced by recall errors or respondent perceptions. Furthermore, the cross-sectional nature of the study captured social sustainability conditions at a single point in time and did not account for temporal changes. Future studies employing longitudinal data and broader geographical coverage may provide a more comprehensive assessment of the long-term social sustainability implications of irrigation technologies.

CONCLUSION

The results indicated that farmers adopting solar-powered irrigation systems recorded higher social sustainability performance across key dimensions, including labour availability, labour welfare, women's participation, capacity building, community participation, household welfare, and post-harvest participation. The PCA results confirmed the suitability of the selected indicators and identified seven major dimensions that collectively represented the social sustainability structure of cassava farming systems. The findings suggest a positive association between solar irrigation adoption and improved social sustainability outcomes. From a policy perspective, promoting renewable energy-based irrigation technologies through targeted subsidies, affordable credit, extension support, and farmer training programmes may strengthen social well-being and livelihood resilience. Integrating social sustainability indicators into agricultural development programmes can further support evidence-based policymaking and contribute to inclusive and sustainable rural development.

DECLARATIONS

Ethics approval and informed consent: Throughout the study, the respondents were asked for their informed consent.

Conflict of interest: The research was carried out without any financial or commercial ties that might be seen as a potential conflict of interest, according to the authors. The authors affirm that they carefully examined, amended and edited the content as necessary when preparing this work. The final content of this publication is entirely the authors' responsibility.

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