A DATA-DRIVEN COMPOSITE SUSTAINABILITY INDEX (CSI) FOR INDEPENDENT SMALLHOLDER PALM OIL: EVIDENCE FROM PRINCIPAL COMPONENT ANALYSIS (PCA)

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Abstract:

Sustainability assessment in smallholder agricultural systems is essential for food security and long-term development. However, many composite indices rely on subjective weighting schemes and rigid sustainability pillars. This paper constructs a data-based Composite Sustainability Index (CSI) for smallholder agriculture using Principal Component Analysis (PCA) to empirically derive sustainability

dimensions and indicator weights. Principal Component Analysis (PCA) was employed to empirically identify latent sustainability dimensions and derive indicator weights based on variance contribution, thereby reducing subjectivity in composite index construction. The findings show three significant dimensions of sustainability that account for 53.9 percent of the total variance, which are: integrated sustainability issues, environmental-economic trade-offs and social-environmental tensions. Such results imply that smallholders view sustainability as systemic and not as independent aspects. The results of PCA-based weighting showed equal contribution in the economic, environmental, and social dimensions (34.2, 32.7, and 33.1), respectively, which highlights the necessity of composite sustainability interventions. The refined weights were then applied to build a CSI, which enabled the categorisation smallholders into the below-average, average, and above-average sustainability performance groups. Methodologically, this study advances sustainability assessment by proposing an empirically grounded composite index that avoids subjective weighting schemes and predefined sustainability structures. From a policy perspective, the resulting Composite Sustainability Index provides a practical decision-support tool for prioritising interventions, allocating resources, and monitoring sustainability performance in smallholder agricultural systems.

Keyword:

Composite Sustainability Index, Data-Driven Weighting, Principal Component Analysis, Palm Oil Smallholders, Smallholder Agriculture, Sustainability Assessment

Introduction

Sustainability evaluation of smallholder agriculture has become a significant research and policy issue especially with regards to food security and sustainability challenge in low-income and developing countries. The smallholder farmers represent a significant proportion of the world agricultural market and are at the heart of global food production considering the balance between environmental management, financial profit, and social welfare in the conditions of resource limitations and uncertainty (Talukder et al., 2018; Tsurayya et al., 2023). Notwithstanding this significance, the current methodologies of sustainability evaluation in smallholder agricultural systems are methodologically deficient, especially with the dependence on subjective weighting schemes of indicators and inflexible, a priori pillars of sustainability. To guarantee the long-term sustainability and resiliency of smallholder farming systems, however, it is important to have strong and robust methods of assessment that can guide effective policy-making, programme evaluation, and interventions (Goswami et al., 2017; Guo et al., 2022; Van-Heurck et al., 2020).

In this respect, composite indices of indicators have gained popularity in the academic literature and in policy-making systems as effective ways to measure sustainability performance. As the complex, multidimensional sustainability data is simplified into communicable metrics, these indices can be used to make comparisons, benchmark sustainability, and policy decisions (Bottero et al., 2015; Gao et al., 2023; Kocmanova et al., 2017; Munda et al., 2009; Ordouei et al., 2016; Phillips, 2024; B. R. Ssebunya et al., 2019; Talukder et al., 2018). Consequently, composite sustainability indices have emerged as key tools for tracking progress and informing sustainability-oriented interventions in smallholder agriculture.

Although they have been widely used, there still exist serious methodological constraints in their construction that compromise the robustness, transparency, and comparability of composite sustainability indices. The main issue is related to the allocation of the weights of indicators, which is often a matter of the expert opinion, the preferences of the stakeholders, or even arbitrary factors, introducing a subjective aspect and possible bias to sustainability measurements (Blanc et al., 2008; Gao et al., 2023; Mikulic et al., 2015; Ustaoglu et al., 2025; Usubiaga-Liaño & Ekins, 2024). Changes in weighting schemes may have a significant impact on composite scores and sustainability rankings and may provide inconsistent results and may generate misinformed policy conclusions (Gómez-Limón et al., 2020; Mikulic et al., 2015; Ustaoglu et al., 2025). The aggregation processes and linear utility functions also simplify the performance of composite indices to represent sustainability performances correctly and, in most cases, lead to comparative situations that mask the actual sustainability situations (Malinga et al., 2018; Talukder et al., 2018).

In addition, the majority of sustainability assessment frameworks still base themselves on a set of predetermined sustainability pillars, usually economic, environmental, and social, without an adequate empirical affirmation of their internal structure. These preset frameworks can ignore context-specific interdependencies, trade-offs and systemic challenges of smallholder farmers, where dimensions of sustainability can be perceived as integrated, rather than being independent (Gómez-Limón et al., 2020; Wulf et al., 2025). The same has been expressed in applied areas of decision-making, where the analytical rigour and applicability to reality are constrained by using unvalidated conceptual frameworks (Garcia et al., 2025; Wickremasinghe et al., 2016). As a result, the available sustainability measurement systems might not be able to reflect the empirical aspects of small hold agricultural systems.

Moreover, many studies can be found, which are analytically complicated and do not provide sufficient operational value to decision-makers, despite the fact that they offer detailed sustainability frameworks and sets of indicators. There is still a limited translation of the multidimensional sustainability outcomes into actionable performance categories that can be used to prioritise intervention and conduct monitoring (Ferrara et al., 2025; Hoben et al., 2017; Rabiee & Lan, 2025). Although other solutions based on data-driven applications have shown considerable usefulness in enhancing performance appraisal and decision-support in other fields including health information systems, urban sustainability, and risk management (Abdelhalim & Hassan, 2025; Kawakyu et al., 2024; Liu & Li, 2023), the usage of the technology in the assessment of the sustainability of smallholders remains underutilized. This highlights a clear research gap in the development of empirically grounded, data-driven, and operational sustainability assessment tools tailored to smallholder agricultural settings.

To address these limitations, this study applies Principal Component Analysis (PCA) to empirically identify sustainability dimensions and derive data-driven indicator weights. This study aims to: (i) identify sustainability dimensions in smallholder agriculture empirically; (ii) create an indicator weighting scheme to be data-driven reducing the subjectivity in sustainability evaluation; and (iii) build a Composite Sustainability Index (CSI) to transform multidimensional sustainability performance into performance action categories. By doing so, it contributes to sustainability assessment methodologies that are empirically based, context-specific and operationally significant on the one hand to provide evidence-based policy formulation and focused sustainability interventions in smallholder agricultural systems.

Literature Review

Sustainability Assessment in Smallholder Agricultural Systems

The smallholder agricultural systems sustainability assessment models usually incorporate a three-part model in the form of the tripartite model including environmental, social, and economic pillars. All these pillars are necessary dimensions of assessing agricultural sustainability, which gives a comprehensive picture of the performance of a farm. The environment assessment is concerned with the practices of the health of soils, biodiversity, and greenhouse gases in order to comprehend the ecological footprint of agricultural processes (Asiedu et al., 2025; Shi et al., 2023). The social pillar includes such points as labor conditions, community engagement, and food security, focusing on the fact that social equity should be ensured between the farmers and consumers (Huan et al., 2022; Westengen et al., 2017) . Economic analysis is used to determine the economic feasibility of farming methods, such as profitability and access to the market, which is essential to the sustainability of the farming entity (Bandanaa et al., 2024; Han et al., 2020).

Nonetheless, these pillars can be approached as autonomous structures, which can severely be restricted in practice. This isolated method overlooks the interconnections between the pillars, and this may lead to partial or biased assessments. An example is that environmental improvements can have counterproductive economic consequences, or social practice can have ecological consequences that are not represented by individual indicators (Bahta & Myeki, 2022; Gelaye, 2025). Moreover, these compartmentalized tests may not be congruent with the realities of the smallholder farmers who are usually constrained and cannot easily maximize the social, economic and environmental deliverables by themselves (Bruges & Smith, 2007). It may be possible to have more significant sustainability assessments through the incorporation of these pillars into a more coherent system that acknowledges their links with each other.

Composite Sustainability Indices and Weighting Approaches

Sustainability composite indices include the compilation of measures of the environmental, social, and economic pillars to obtain a measurable sustainability measure. Some methodologies used in the weighting of these indicators are equal weighting, expert judgment, and stakeholder based.

   (i).   Equal Weighting: It is the technique that gives equal weight to all indicators making it easy to calculate and interpret. Nevertheless, it does not consider changes in the relevance of indicators to context or particular sustainability objectives and,

therefore, creates the possibility of distorting reality (McKenzie et al., 2018; Ssebunya et al., 2016).

(ii).   Expert Judgment and Analytic Hierarchy Process (AHP): It is a method that applies expert opinion in assigning weights to indicators according to perceived importance. It may be a valuable means to gain a fine-grained insight, but it is prone to biases due to the subjective choices of specialists and the danger of imposing some normative values which do not necessarily represent the interests of the stakeholders in the wider context (Eidt et al., 2020). Additionally, the dependency on professionals will erode the lived experiences of smallholder farmers which will complicate the process of assessment further.

(iii). Stakeholder-Based Weighting: Involving the stakeholders in the process of weighting helps to democratize the decision-making and increase the relevance of the process by allowing the stakeholders to be heard. Nonetheless, bias may also come about in this approach especially when only selected groups are involved, thus sidelining the views of important stakeholders (Singh et al., 2022). The perceived significance of the different dimensions of sustainability may be aborted by power relations between the stakeholders, and this may affect the effectiveness and fairness of the assessment.

To sum up, though each of the three approaches to weighting sustainability indicators has its advantages, the danger of bias and normativity distortion brought by each of them is critical. This highlights the need to have more advanced, data-intensive approaches that help to reduce these risks and improve on the validity of composite sustainability indices in assessing smallholder agricultural systems. More detailed models combining qualitative information with quantitative data are to be aimed at to make sure that sustainability measurements can capture the multidimensional nature of smallholder agriculture (Antony et al., 2020; Hoffman et al., 2014).

Principal Component Analysis (PCA) in Sustainability Research

PCA is an effective dimension reduction algorithm that can be used to explore complicated datasets in sustainability studies. PCA allows the reduction of many correlated variables into a few uncorrelated elements, which makes it effective to discover the hidden structures behind sustainability data sets. This ability is especially useful in sustainability measurements in which a great number of indicators are used. Using the PCA, researchers can determine the indicators that have the largest contribution to variance, which underscores the important aspects in the sustainability models that might otherwise be obscure when indicators are assessed individually (Li et al., 2016).

Some research has successfully used PCA to measure sustainability across different settings. As an example, Li et al. (2016) employed the use of PCA in order to design composite indices that captured the elements of environmental, economic and social aspects in smallholder agriculture. Their output can be used to demonstrate the usefulness of PCA in transforming complex data on indicators into an understandable system that may be used to make a decision. Equally, Park et al. (2017), underlined the application of PCA in the tools of sustainability assessment, underlining the fact that it helps simplify information processing and increase its interpretability. Through the examination of these previous studies, it is clear that although the concept of PCA has been skillfully applied to compress rich datasets, there is still the need to

enhance sustainability measurements to a large extent by the use of fine weighting and index development.

This paper is a continuation of earlier studies in that; specific importance is given to the improvement of the weighting systems used with the PCA method. Our study aims to generate a smoother CSI by combining data-driven processes of establishing the weight of indicators through expert judgment or an egalitarian method, with the goal of establishing a more sophisticated CSI. The use of refined weights supported by empirical analysis will see us develop a more representative sustainability index and be able to systematically connect the latent dimensions identified by PCA to the final evaluation hence maximizing the rigor and relevance of sustainability assessments in smallholder agriculture.

Analytical Framework for Sustainability Index Construction

The method of this paper follows an analytical framework that presents a process of systematic association between sustainability indicators, empirically acquired latent dimensions, weighting of data and development of CSI so that various types of meaningful performance can be classified in smallholder agriculture. The framework is used to explain logical design of the study and to make sure that there is coherence between the sustainability theory, empirical analysis and practical application. The framework will start with the choice of sustainability indicators that will jointly indicate the environmental, social, and financial aspects of smallholder agricultural activities. These pointers are the empirical basis of the evaluation and are selected to reflect the multidimensional aspect of sustainability of the smallholder farming systems. Instead of giving these dimensions significance in a priori manner, the framework acknowledges that their relative significance and relationship with each other should come out as a result of empirical evidence.

Thereafter, the selected indicators are subjected to PCA to minimize the dimension and to determine the latent dimensions of sustainability that is hidden within the data. In this, we get a chance to see underlying patterns and relationship between the indicators, and this enables the derivation of sustainability dimensions based on empirical evidence as opposed to being imposed in a conceptual manner. The step also meets the restrictions linked to predetermined sustainability pillars and contributes to the situational relevance of the assessment. After the latent dimensions are identified, a weighting process based on the data is used to enhance the significance of the single indicators. A weight is calculated in terms of the indicator loading and explained variance of the retained principal components such that weaker contributors to overall sustainability variation are weighted to a lesser extent. This is the difference between the framework and the traditional weighting techniques, which are based on subjective expert opinion or arbitrary assumptions. The resulting refined weights are then aggregated together to form a Composite Sustainability Index (CSI), which is multidimensional sustainability data condensed into one, interpretative index. The CSI offers a holistic indicator of sustainability performance but maintains the empirical framework that has been revealed by PCA thereby making it possible to compare and benchmark sustainability across smallholder farming units.

Lastly, the composite index enables the categorisation of performance of the smallholders into different sustainability performance categories. The given categorisation makes the assessment operational more valuable as it facilitates the targeted interventions, the allocation of resources prioritisation, and policy development to promote a better sustainability outcome. Under this analytical scheme, the quantitative evidence, as revealed by PCA, is effectively translated, as

actionable information to the stakeholders and decision-makers. The empirical operationalisation of this analytical framework is provided in the following methodology section via the use of the principal component analysis and the creation of a CSI.

Methodology

In the present study, the quantitative, data-based method is used to evaluate sustainability performance in smallholder agriculture by developing a CSI. The discussion proceeds using a list of 31 sustainability indicators, which include the environmental, social, and economic dimensions, which were selected to reflect the multidimensional concept of sustainability in the smallholder farming systems. All the indicators were based on primary data at the small-holder level and were transformed into zero mean and unit variance before analysis to provide the different scales into comparability (Jolliffe, 2002).

The application of PCA to the standardised sustainability indicators was used to identify latent dimensions. The eigenvalue-greater-than-one criterion was used together with scree plot and identification of the elbow point on the screen plot and the interpretability of the component structure to determine component retention as recommended by the usual methodological principles (Jolliffe, 2002). The loadings of the components were then analysed to understand how individual indicators promote the extract sustainability dimensions.

After the identification of the latent dimensions, a data-based weighting process was undertaken to obtain the relative weight of the sustainability indicators. The weights of indicators were estimated using their loading on the retained principal components and the eigenvalues they provide so the importance of indicators could be obtained empirically based on their contribution to the variance instead of being subjective estimates by a professional. This method is consistent with the accepted conventional ways of constructing composite indicators and increases objectivity and transparency of sustainability measurements (Nardo et al., 2005; Nicoletti et al., 2000; Organisation for Economic Co-operation and Development, 2008).

A weighted refined sum of the standardised scores on the indicators was then formed to obtain a CSI based on the refined weights obtained through PCA. The composite indices have been extensively adopted to package multidimensional sustainability data into a one interpretable measure that is easy to use in comparisons, benchmarking and policy analysis across units of observation (Nardo et al., 2005; Organisation for Economic Co-operation and Development, 2008). The CSI formulation maintains the empirical structure unveiled in PCA but allows the assessment of the sustainability performance to be effectively done at the level of smallholders. In order to make the assessment more application-friendly, the smallholders were subdivided into sustainability performance categories according to their CSI scores. Standard deviation cut-offs were used to set the performance thresholds in terms of the mean CSI, which is typically used in the analysis of composite indicators to ease classification of performance and interpretation of policy (Munda, 2005; OECD, 2008). Such a categorisation is useful in designing interventions, in prioritising resources, and helping through evidence-based decision-making in trying to enhance sustainability in smallholder agricultural systems.

Results

Identification of Sustainability Dimensions through PCA

PCA was used on the 31 sustainability indicators to reveal the latent dimensions of sustainability of the smallholder farmers. The initial analysis resulted in seven components whose eigenvalues were above 1.0 and which, together, explained 72.6% of the overall variance in the set of indicators. Looking at the scree plot (Figure 1), it is evident that there is an inflection point at the third component, with other components adding hardly any explanatory power. On the inspection of the scree plot and the consideration of the interpretability, three main components were selected to do further analysis work. The combination of these three items (Table 1) described 53.9% of the overall variation, which is just a parsimonious, but substantively significant, view of sustainability in the smallholder context. This finding reflects a systems-oriented perception of sustainability, in which environmental, social, and economic factors are experienced as interdependent components rather than separate pillars.

The first principal component (PC1) with a 30.7% variance had an identical loading of the environmental, social, and economic indicators. This tendency is an in-built dimension of sustainability challenges that imply that the dimensions of sustainability pressures on smallholders are felt as being integrated with each other and not in isolated settings. The second dominant component (PC2) that attributed 15.1% of the variance, had opposite loadings of environmental and economic indicators, which represented an environmental-economic trade-off dimension. The third major constituent (PC3), which explained 8.1% of the variance, had opposite relationships between environmental and social indicators, which showed tensions between social and environmental in smallholder farming systems.

Table 1. Principal Components and Explained Variance

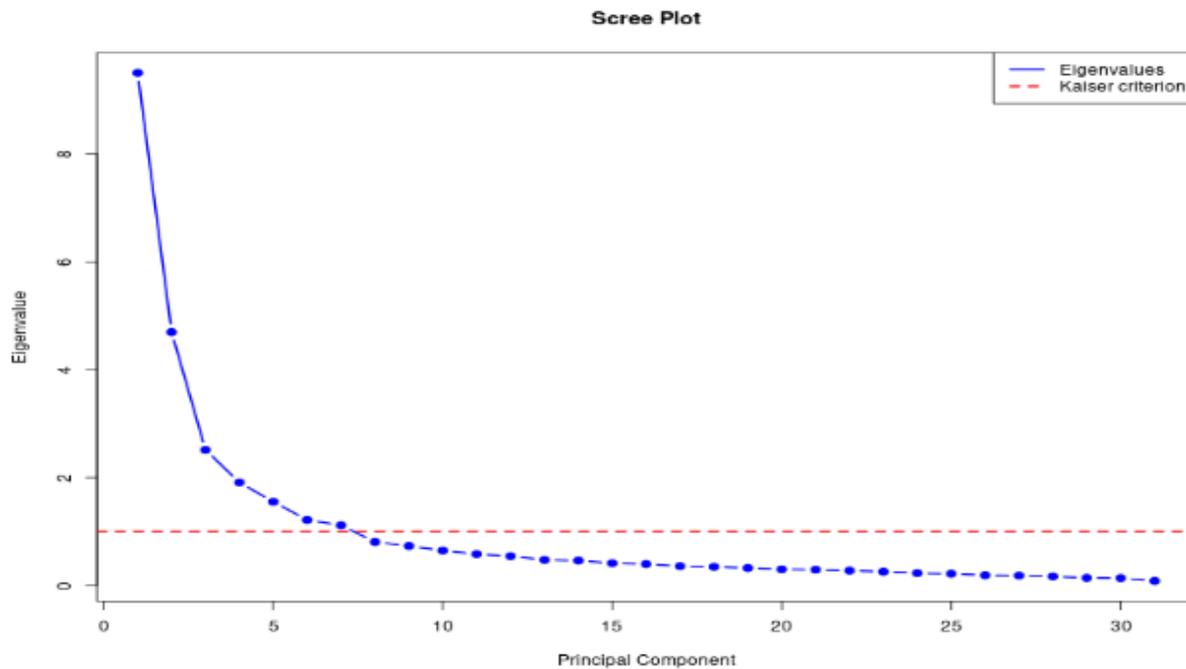| Component	Eigenvalue	Variance (%)	Cumulative (%)
PC1	9.52	30.7	30.7
PC2	4.68	15.1	45.8
PC3	2.51	8.1	53.9
PC4	1.92	6.2	60.1
PC5	1.55	5.0	65.1
PC6	1.32	4.3	69.4
PC7	1.14	3.7	73.1

Figure 1: Scree Plot of Eigenvalues for The Sustainability Indicators

Component Loadings and Interpretation

The interactions between sustainability indicators and their contribution to the dimensions extracted are represented in the biplot of the first two principal components (Figure 2). Environmental indicators do not widely disperse meaning that the correlations of indicators are high and there is a shared variance. On the contrary, economic indicators are placed in opposite directions at the second major component, which is a graphical confirmation of the environmental-economic trade-off observed in PC2. The distribution of social indicators in both domains is indicative of the cross-cutting nature of social indicators in the formation of integrated sustainability concerns and mediating between the relationship of environmental, social, and economic aspects in trade-offs. All in all, the loading structure proves that sustainability performance of smallholders is structured around a small number of dominant dimensions manifested by integration as well as tension between sustainability domains.
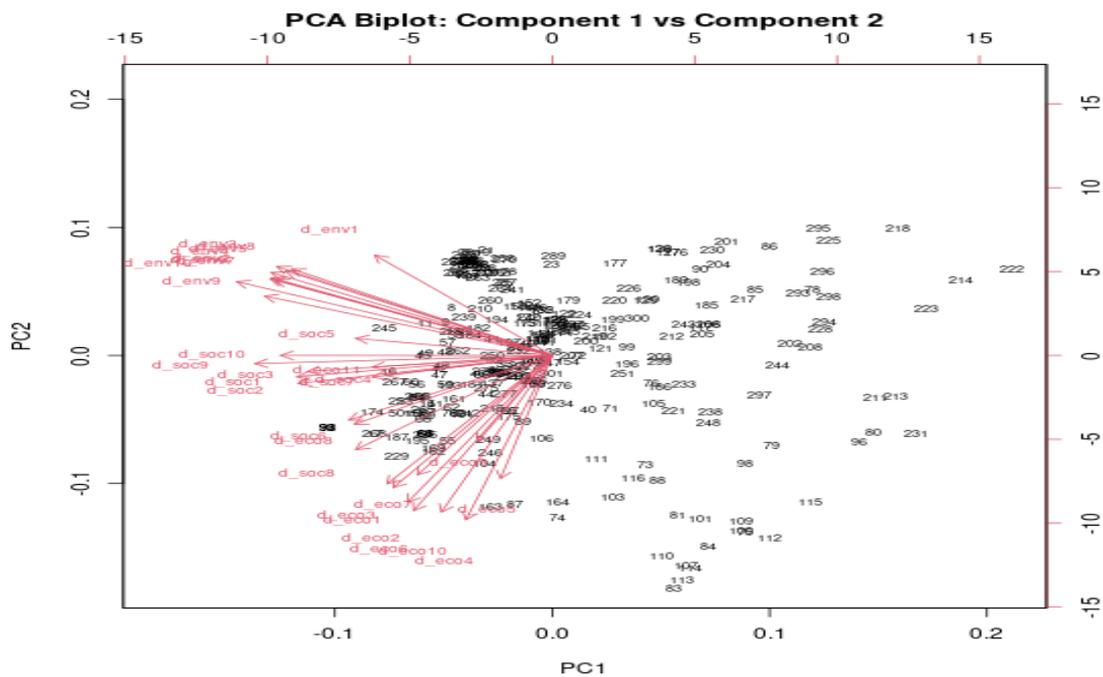
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Figure 2: Biplot of First Two Principal Components

Data-Driven Weight Refinement for Sustainability Indicators

Building on the PCA results, we developed a data-driven approach to refine indicator importance weights. The refined weight for each indicator ii was calculated as:

$$w_i = \frac{\sum_{k=1}^{3}(l_{ik}^2 \times \lambda_k)}{\sum_{i=1}^{31}\sum_{k=1}^{3}(l_{ik}^2 \times \lambda_k)} \times 100\%$$

where lik represents the loading of indicator ii on component k, and λk is the eigenvalue of component k. This formulation weights indicators according to their contribution to the key sustainability dimensions identified through PCA. The top ten indicators ranked by refined importance weights are presented in Table 2.

Table 2. Top Ten Sustainability Indicators by Refined Importance Weights

Rank	Indicator	Dimension	Weight (%)	PC1	PC2	PC3
1	d_soc9	Social	3.84	-0.244	-0.016	-0.026
2	d_soc2	Social	3.71	-0.209	-0.055	-0.166
3	d_soc10	Social	3.70	-0.223	0.000	-0.073
4	d_env10	Environmental	3.67	-0.259	0.146	0.138
5	d_soc1	Social	3.60	-0.210	-0.042	-0.190

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6	d_soc5	Social	3.55	-0.161	0.034	-0.449
7	d_env7	Environmental	3.52	-0.227	0.150	0.202
8	d_soc7	Social	3.48	-0.148	-0.043	-0.085
9	d_eco4	Economic	3.45	-0.071	-0.326	0.230
10	d_env6	Environmental	3.40	-0.231	0.152	0.195

Note: PC1-PC3 loadings shown for interpretation context

Development of Composite Sustainability Index (CSI)

With the optimised indicator weights, an index of CSI was calculated to each of the 301 smallholders as a weighted aggregate of standardised scores of indicators. The CSI scores distribution is shown in Figure 3 and is close to normal distribution, with 68.4 percent of small holders within within the mean variance of a standard deviation. This distribution demonstrates the adequate variability that can be used to make meaningful differentiation of sustainability performance.
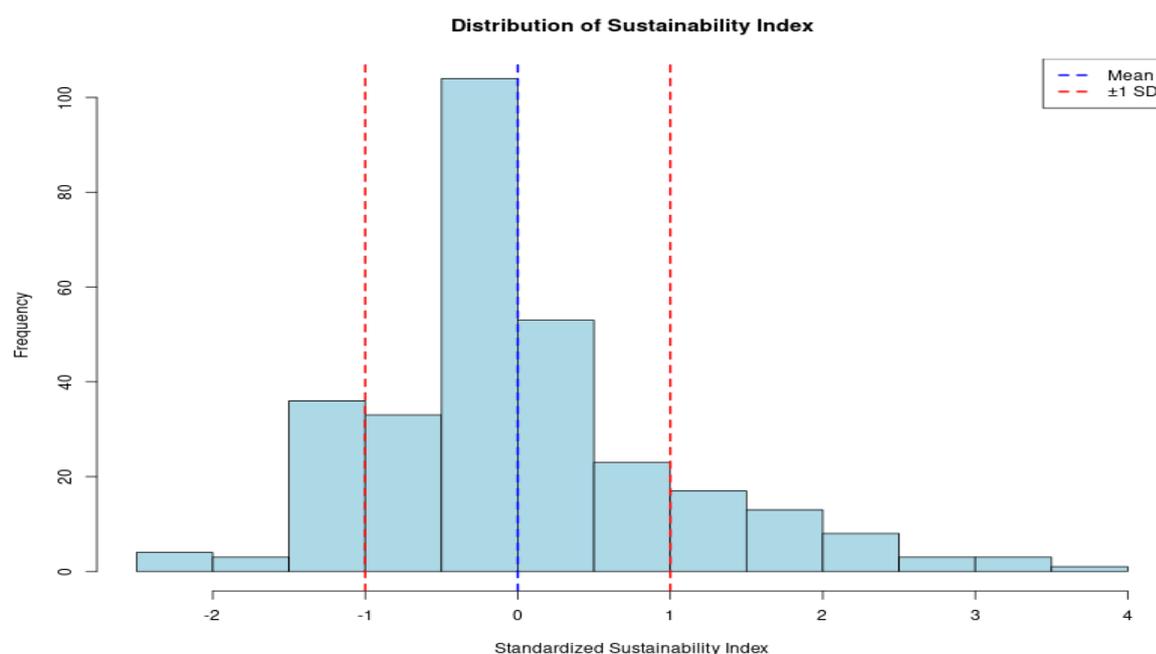

Figure. 3: Distribution of CSI Scores

According to the standard deviation thresholds, there were three categories of sustainability performance with smallholders (Table 3). There were about 16.3% of below-average performers who were identified as smallholders who are a high-priority group of indicated sustainability interventions. Most of the smallholders (68.4) were in the average performance category, with 15.3% performing above average sustainability and can be used as reference or model farmers in a benchmarking and knowledge-sharing program. All in all, the CSI is a brief and practical measure of comparing the sustainability performance and evidence of making evidence-based decisions on smallholder agricultural systems.

Table 3. Smallholder Performance Categorisation Based On CSI

Performance Category	Score Range	Frequency	Percentage (%)	Priority for Intervention
Below average	CSI < -1 SD	49	16.3	High
Average	-1 SD ≤ CSI ≤ +1 SD	206	68.4	Medium
Above average	CSI > +1 SD	46	15.3	Low (model farmers)

Discussion and Implications

The PCA of sustainability indicators of the palm oil smallholders disclosed three empirically significant sustainability dimensions which provide valuable information of the plan of sustainability as how sustainability is perceived and operationalised in the palm oil farm level. The coded principal component, which accounts 30.7 per cent of the total variance, found in Section 4.1, is integrated sustainability issues, meaning that the smallholders do not view environmental, social, and economical dimensions as three separate constructs. Rather, these dimensions are encountered as a related system where the other aspects are bound to be influenced by the alteration of one. This observation is consistent with the rest of the sustainability literature, which is becoming more and more open to the interdependence of the dimensions of sustainability and warns of siloed policy or assessment frameworks. As an example, Kroll et al. (2019) state that the results of sustainable development are determined by the multidimensional interzones of interactions between social, economic, and environmental variables, and that focusing on one of them can have unforeseen outcomes. Conceptualized in the case of palm oil smallholders, there is an interdependent perception that the interventions directed to enhance the performance on the environmental front, should also take into account the social welfare and economic feasibility to be effective.

The second major part, which accounts 15.1 percent of the variance, represents an environmental-economic trade-off dimension, covering the perceived tension between practices oriented towards conservation and economic livelihoods. This aspect sheds light on a well-documented dilemma in small holder agriculture whereby farmers are usually faced with a tough choice to either go green or continue generating economic benefits in the short term. This result is in line with the literature that has recorded the existence of trade-offs as result of sustainable agro-transitions especially in the resource-limiting systems of farming. As an example, Zhang et al. (2024) show that the agricultural activities often result in trade-offs as smallholders do their best to strike a balance between the environment and income. These trade-offs are particularly relevant in the palm oil planting where environmental laws and sustainability principles are likely to add to the cost or decrease the short-term productivity. The identification of this aspect is thus essential in formulating sustainability interventions that reduce the risks in the economy and advance environmental performance.

One of the most important methodological contributions that the research makes is the use of data-based weight refinement via results of PCA, which represents an evidence-based alternative to the conventional arbitrary or expert-based schemes of weighting that are frequently employed in sustainability assessments. The obtained dimension-level weights, such as Economic (34.2%), Environmental (32.7%), and Social (33.1%), show a very impressive

balance of importance between all three pillars of sustainability. This balance also supports the claim that there should be no dominance of any dimension on sustainability assessment or policy intervention strategies of the smallholder setting. This has been urged to be the same case in the literature whereby the data-informed weighting models have been proven to contribute to more objective and comprehensive sustainability assessment. Indicatively, Dong et al. (2015) used a PCA-DEA model to generate equal sustainability measurements by obtaining the weights empirically so that various sustainability practices could be properly incorporated in performance measurement. Although the precise values of the weights can be different based on contexts, the indicators used, and agricultural systems, the even distribution found in this paper screams the importance of combined intervention designs that cater to economic, environmental, and social aspects.

Besides, the results are similar to earlier research that has employed the PCA to develop composite sustainability indices, as well as the need to measure multidimensional sustainability in a holistic way. Such as Ruiz et al. (2019) used PCA-based techniques to create sustainability indices factoring in on several dimensions, which supports the idea that assessment systems should not overweight one pillar in a scheme. According to these studies, the CSI created in this study gives a pragmatic and understandable instrument that converts complicated multidimensional data into practical information to the policymakers and practitioners. The index will facilitate the targeted interventions, benchmarking and monitoring of sustainability gains over time by facilitating the inclusion of smallholders by their sustainability performance. On the whole, the analysis of PCA findings supports the significance of understanding that sustainability issues are concepts that are inextricably linked and that there is inherent trade-off within the smallholder palm oil systems. Meanwhile, it also points out the usefulness of data-intensive approaches towards making sustainability evaluations more robust, transparent, and policy-relevant. This empirically derived dimension of sustainability and indicators weight make the study a part of the growing literature that suggests that more fine-tuned and evidence-based methodologies of sustainability evaluation may be employed to support more effective resource allocation and intervention approaches to smallholder farming.

Conclusion

The research enabled the formulation of a data-based CSI as a measure of sustainability performance in smallholder agriculture based on principal component analysis. The study empirically determined three significant dimensions of sustainability which are integrated sustainability challenges, environmental-economic trade-offs, and social environmental tensions according to the analysis of 31 sustainability indicators and the interconnectedness and multi dimensions of sustainability of smallholder palm oil systems. The weighting using PCA demonstrated the existence of balanced contribution of the economic, environmental, and social dimensions, and supports the idea of integrated sustainability actions instead of the actions focusing on one dimension. The resultant CSI gives a viable benchmarking tool to help in the performance evaluation of sustainability and grouping smallholders into manageable performance categories.

Theoretically, the current study also has a value in the literature of sustainability assessment by empirically confirming the dimensions of sustainability as opposed to using predetermined or a priori structures of pillars. The results show that the dimensions of sustainability come about due to the observed data and reflect the context-related interdependencies and trade-offs confronting smallholder farmers. The paper also proposes a solution through the PCA-based

dimensionality reduction with data-driven weighting of the contribution to the subjects under assessment in terms of subjectivity and arbitrariness, responding to decades of criticism about these issues in the sustainability measurement systems.

This study has great practical and policy implications. CSI and the related performance categorisation offer policy makers, certification agencies and extension agencies with a working decision support tool to enable them to identify priority areas of intervention, better allocation of resources, and tracking of sustainability changes as it changes with time. The identification of integrated sustainability issues and environmental-economic trade-offs allows the development of interventions to balance livelihood security and environmental goals and thus increase the viability and acceptability of sustainability promotion efforts by smallholder farmers.

In spite of these contributions, there are a number of limitations that are to be recognized. It is an analysis based on cross-sectional data, which restricts the possibility of observing dynamic changes in sustainability performance over time. Besides, the findings are context-specific to the smallholder palm oil system that has been studied and might not be directly generalisable to other crops and regions without adaptation. In future studies, this strategy can be expanded by longitudinal research, cross-regional studies, and the introduction of more data-driven methods, e.g., machine learning, to make the tools of sustainability assessment in smallholder agriculture even more resilient and applicable.

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