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REVIEW

CONSTRUCTION OF AN INDEX SYSTEM FOR SUSTAINABILITY ASSESSMENT IN SMALLHOLDER FARMING SYSTEMS

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KEYWORDS

indicator aggregation, multi-indicator, smallholder agriculture, sustainability assessment, weighting method

HIGHLIGHTS

- A five-step process for quantifying smallholder farming system sustainability is proposed.
- Definition of system boundary, functional unit, and indicators depends on research issues.
- Weighting, conversion, and aggregation methods tightly relates to the validity of assessment results.

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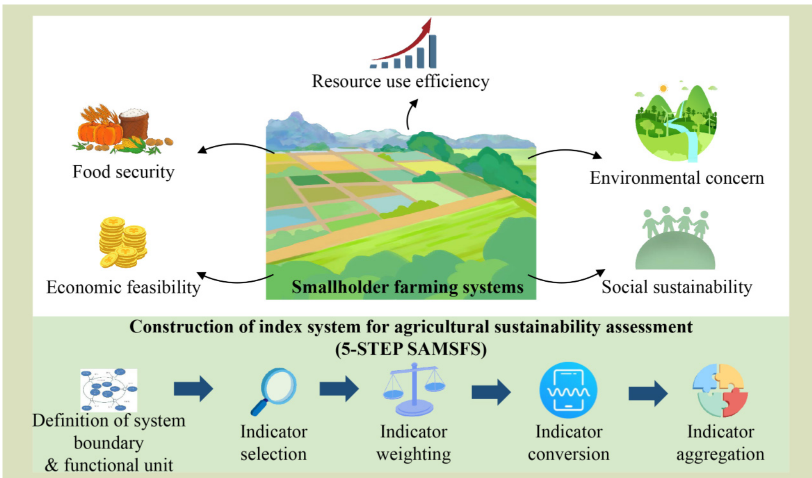
GRAPHICAL ABSTRACT



ABSTRACT

Smallholder farming systems are important for global food security, but these faces multiple environmental challenges hindering sustainable development. Although sustainable smallholder agriculture issues have been widely discussed and addressed by scientists globally, harmonized approaches in evaluating sustainability are still lacking. This paper proposes a five-step process for constructing a sustainability assessment method for smallholder farming systems, namely definition of system boundary & functional unit, indicator selection, indicator weighting, indicator conversion, and indicator aggregation. The paper summarizes the state-of-art progresses in agricultural sustainability assessment at different stages, and systematically discussed the benefits and limitations of weighting and aggregation methods. Overall, this evaluation process should be useful by providing rational and comprehensive results for quantifying the sustainability of smallholder farming systems, and will contribute to practice by providing decision-makers with directions for improving sustainable strategies.

1 INTRODUCTION

The agriculture sector relates to the nourishment essential for human existence[1]. However, the pursuit of high productivity has been accompanied by mounting resource inputs and pollutants, depleting natural resources and exacerbating climate change[2]. Specifically, agriculture accounts for about 21% to 37% of anthropogenic greenhouse gas emissions, over 70% of N_2O emissions, 80% to 90% of total atmospheric NH_3 emissions, and 90% of fresh water consumption globally[1,3]. In the long run, this will cause damage to ecosystems and human health[4]. The desire to increase food supply without further environmental harm calls for sustainable agriculture, which has attracted global attention and considerable research[5,6].

As the major agricultural participants, smallholders, who produce about 30% of total crop production using 24% of agricultural land, have a huge gap to achieve sustainable development[4]. Especially, China is a typical agricultural country where 200 million to 300 million smallholders work the cultivated land, accounting for over 98% of national agricultural operators[7]. Generally, Chinese smallholders cultivate small farms less than 1 ha using family labor to obtain the principal source of income[3,8]. Given the limited knowledge and the convenience of purchasing agrochemicals, smallholders tend to overuse fertilizer, pesticide and water to ensure high yield[9]. Going forward, such intensive management will damage soil productivity and trigger vicious cycles of environmental damage.

To improve the productivity and resource use efficiency of smallholder agricultural farming systems, various green planting technologies have been developed and applied (e.g., land preparation, nitrogen top dressing, sowing and harvest date, planting rate and cultivar)[10]. Quantifying and evaluating the environmental and economic performances can help provide a reference for understanding the strengths and weakness of these planting technologies, and for designing technology combinations in different farming regions (Fig. 1). Over the past 20 years, many evaluation indicators covering different dimensions have been proposed, such as greenhouse gas (GHG) emissions, resource use efficiencies, land use intensity, yield and economic output/input ratio[11–13]. Work on quantitative assessment of agricultural sustainability has also been conducted by global researchers[14–16]. Despite this, there are few studies summarizing these indicators[17], which might be due to the large amounts of indicators, and the research issues and scopes vary greatly. Meanwhile, the construction methods of index system for agricultural sustainability assessment from system perspective remain poorly known[18]. Hence, this review proposes a five-step process for constructing sustainability assessment method of

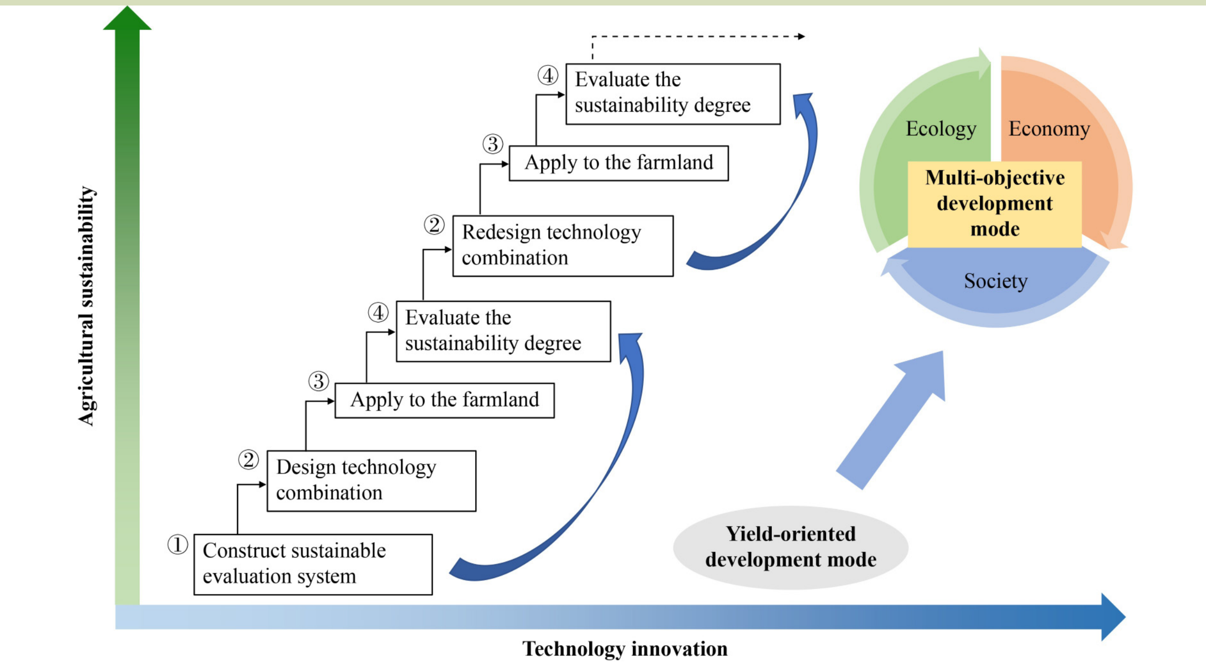


Fig. 1 Role of sustainability assessment in agricultural multi-objective development. Constructing a sustainable evaluation system would be helpful to evaluate the sustainable level when applying agricultural technology combinations to farmlands, and it can provide guidance for redesigning technology combination to achieve multi-objective development mode.

smallholder farming systems (5-STEP SAMSFS), and focuses on the latest progresses have been made in definition of system boundary & functional unit, indicator selection, indicator weighting, and indicator aggregation in agricultural areas (Fig. 2), to advance smallholder agricultural sustainability assessment.

2 DEFINITION OF SYSTEM BOUNDARY & FUNCTIONAL UNIT

Defining system boundary is the first step to conduct agricultural sustainability assessment. From life-cycle view, agriculture system should not only include farming systems, but also include upstream production of agri-inputs, for example, fertilizers, pesticides, electricity and diesel oil[19,20]. The system boundaries starts with the extraction of minerals and fossil fuels, and ends at crop harvest, which includes agricultural material production subsystem and farming subsystem[21,22], as shown in Fig. 3. The scope of farming subsystem depends on specific research objects, varying from 1 ha of farmland to village, county, province, country or global scale[23,24].

When system boundary is clear, the next step is to define functional unit. The value of indicators is closely associated with functional unit, especially in environmental dimensions[25]. Currently, there are three major functional units that are widely used in environmental sustainability assessment, namely per unit area, per unit product and per unit cash, emphasizing environmental burdens brought by land use, products and profits, respectively[25,26]. Some researchers combine two functional units to quantify environmental impacts, such as global warming, eutrophication, acidification and toxicity[27,28].

3 WIDELY USED INDICATORS FOR AGRICULTURAL SUSTAINABLE ASSESSMENT

Developing reliable index system is a prerequisite for agricultural sustainability assessment. Smallholder farming is a complex system that compiles multiple domains, such as climate change, ecosystem service, human health and resource depletion. Generally speaking, agriculture sustainability can be roughly divided to three matrices: environmental sustainability, economic sustainability and social sustainability[1,14]. Five relevant matrices were proposed by Smith et al.: productivity, economic sustainability, human wellbeing, environmental sustainability, and social sustainability[29]. Seven metrics proposed by Chaudhary et al. were used to assess the sustainability of food systems, including food nutrient adequacy, ecosystem stability, affordability and availability, sociocultural wellbeing, resilience, food safety, and waste and loss reduction[15]. Hence, this section covers above matrices, to introduce the most widely used indicators for assessing smallholder farming systems (Table 1).

To construct comprehensive index system, it should be developed in consultation with a varied group of stakeholders (e.g., farmers, agricultural companies, policymakers and scientists). Only in this case, the selected indicators can reflect the realities of smallholder farming systems. To choose detailed

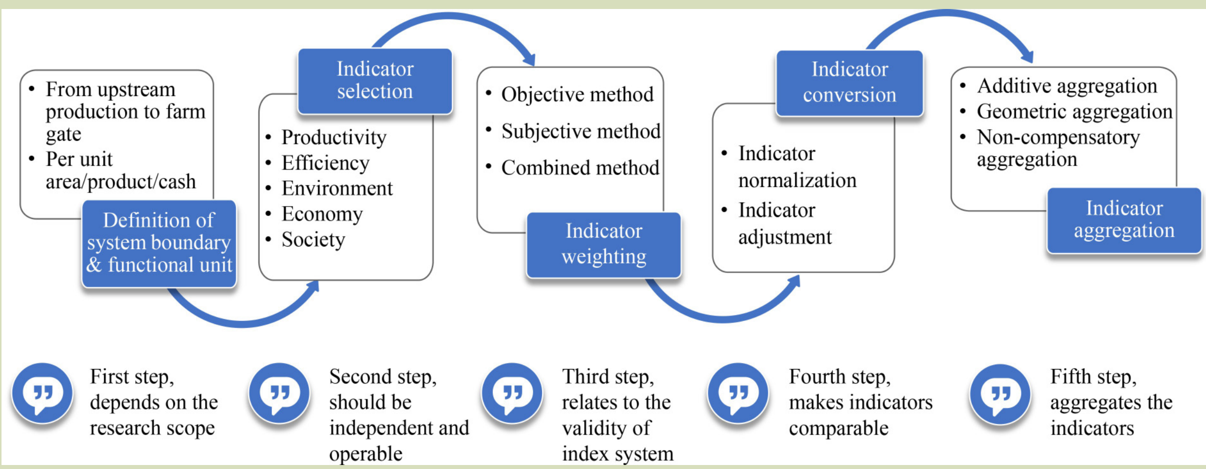


Fig. 2 A five-step process for constructing a sustainability assessment method for smallholder farming systems, which includes the definition of system boundary & functional unit, indicator selection, indicator weighting, indicator conversion, and indicator aggregation.

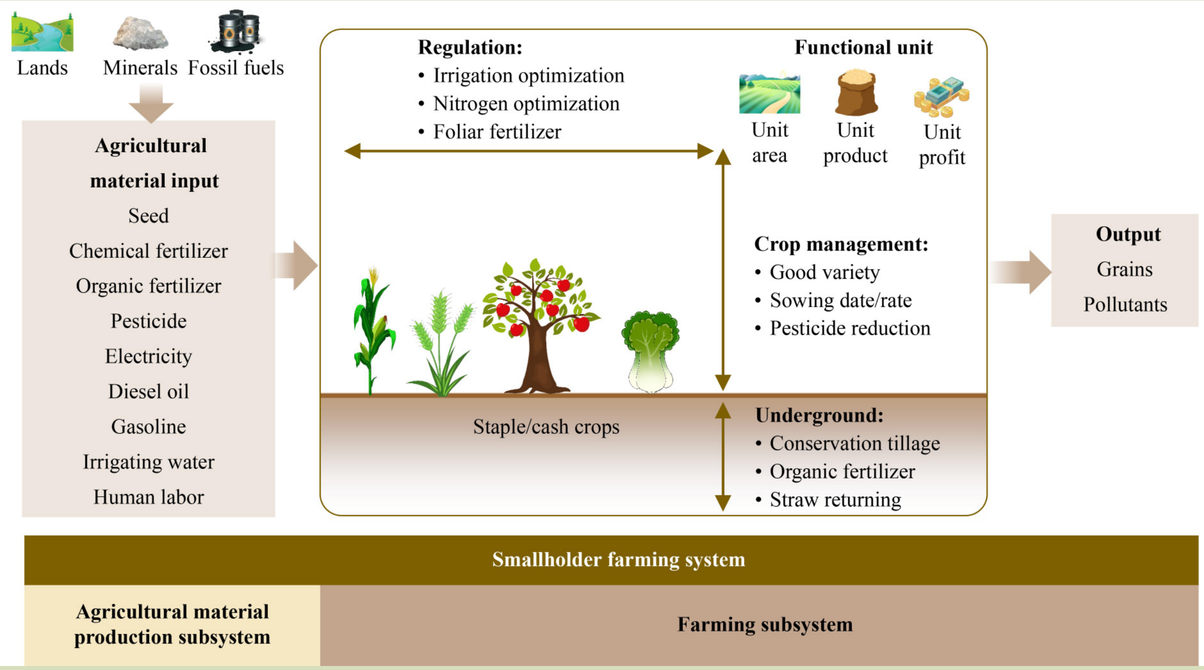


Fig. 3 System boundaries and functional unit of smallholder farming system. The system boundaries are set as extraction of minerals and fossil fuels through to crop harvest. Specifically, smallholder farming systems consist of agricultural material production subsystem and farming subsystem.

Table 1 Typical evaluation dimensions and indicators of agricultural sustainable assessment

Dimensions	Indicators
Agricultural productivity	Yield, attainable yield, yield gap
Resource use and resource use efficiency	Resource consumption, N use efficiency, water use efficiency, unit emergy value
Environmental sustainability	Global warming potential, acidification potential, eutrophication potential, human toxicity, ecotoxicity, land use, soil health, biodiversity
Economic sustainability	Gross margin, net profit, output/input ratio, labor productivity
Social sustainability	Nutrition availability, rural poverty ratio, gender equity

indicators, Hsu et al. proposed five principles for indicator selection[30], which are (1) describing issues of assessment, (2) diagnosing problems to be addressed, (3) discovering occurrence patterns of problems, (4) developing solutions for measurement, and (5) driving action through application of the indicators. Though these process, the appropriate indicators covering different metrics can be selected.

3.1 Agricultural productivity

Yield. Yield is the most widely used indicator to assess the productivity of farmland. It refers to the amount of produce harvested per unit area in a certain period of time[29], and it has been used as an indicator in many studies[2,21,29]. However, two extended indicators, attainable yield and yield gap, have been discussed in agricultural system areas in recent years. Attainable yield is the largest yield that can be achieved under the growth condition of a certain area, whereas yield gap refers the difference between actual smallholder yield and the potentially attainable yield[10]. These two indicators are used to evaluate the improvement potential of agricultural productivity, and both of them are moving targets. Attainable yield and yield gap have been used to evaluate the effectiveness of technology adopted by smallholders in China[10].

3.2 Resource use and resource use efficiency

Resource consumption. Agricultural production is a resource-consuming process, which requires large amounts of renewable resources (e.g., solar, water, air and biomass) and non-renewable resources (e.g., fossil fuels, minerals and soils). Therefore, indicators related with resource consumption should be used in agricultural sustainability assessment, such as energy depletion, water depletion and land occupation, to reflect the dependence on renewable and non-renewable resources[31]. Many studies have used resource consumption as an assessment indicator[15,21,32].

Nitrogen use efficiency. Nitrogen is a key plant nutrient applied in fertilizers, and nitrogen use efficiency reflects the amount of N input being utilized by crops. Hence, N use efficiency is an important indicator relating to nitrogen management and nitrogen cycle[33]. There are three principal N use efficiency quantification approaches, namely N difference approach, ^{15}N tracer approach, and N balance approach, which need to be appropriately chosen under different situations[34]. Also, partial factor productivity refers the ratio of crop yield to fertilizer application amount (i.e., N, P_2O_5 and K_2O), and it is the simplest indicator to roughly assess nutrient use efficiency without actual measurement[35]. In farmland research, N use efficiency had received considerable attention[3,12,26].

Water use efficiency. Agriculture water depletion is becoming increasingly severe with the growing populations and excessive irrigation[36]. Exploring effective water use is crucial for water-limited areas and groundwater recharge areas. Water use efficiency can also be called water productivity, and it is calculated as the ratio of grain yield to water input (rain plus irrigation) over a study period[36]. Also, irrigation water use efficiency is defined as the ratio of grain yield to total amount of irrigation water, and it only takes irrigation water consumption into consideration[37]. As the most important resource for crop production, the water use efficiency is of increasing concern[1,15,29,36].

Unit emergy value. Emergy analysis being proposed by Odum has been widely used in agricultural system to evaluate environmental burden, production efficiency and sustainability[38,39]. As one of the emergy indices, unit emergy value can measure how much emergy is taken to produce one unit of product, in other words, it can evaluate the emergy efficiency of production process[40]. Different from fertilizer or water use efficiency, unit emergy value converts all resources to emergy, including solar, rain, fertilizer, pesticide and labor. Hence, it is a comprehensive tool to describe the resource use efficiency, and has been widely adopted by global scientists[40–43].

3.3 Environmental sustainability

Global warming potential. Agricultural is a major source for greenhouse gases emissions, accounting for 70% and 50% of global anthropogenic N_2O and CH_4 emissions, respectively[44]. Thus, it is necessary to take global warming potential into account for agricultural sustainability assessment. Generally, it refers the global warming effects caused by greenhouse gas emissions (i.e., CO_2, CO, CH_4 and N_2O) from agricultural activities per unit of harvested area[1], and CO_2 equivalent factors are used to aggregate total global warming potential derived from different greenhouse gases[31]. Therefore, it is the most widely used indicator to evaluate the productivity of agricultural systems[1,15,29,32].

Acidification potential. Enhanced nitrogen fertilizer inputs would intensify soil acidification problems, changing soil structure and chemical properties, and threatening food security and human health[45]. In the process of acidification potential estimation, N_2O, NO_x, NH_3, and SO_x emissions are taken in account, and SO_2 equivalent factors are generally used in acidification potential estimation[22]. Acidification potential has become a common indicator for assessing the environmental quality of agricultural systems[13,19,21].

Eutrophication potential. Agricultural non-point source pollution has emerged as the primary source supplying nutrients to water bodies, which deserves attention in agricultural sustainable development[46]. Excessive nitrogen and phosphate fertilizer use would destroy the N and P balance within waterbodies, and lead to aquatic eutrophication[47]. In the process of quantifying aquatic eutrophication, total phosphorus, NO_3^-, NH_4, NH_3, and COD are taken into account, and PO_4 equivalent factors are generally used for aggregating aquatic eutrophication potential derived from different sources[22]. Currently, eutrophication potential is commonly used in environmental sustainability assessment of agricultural systems[13,19,21].

Human toxicity and ecotoxicity. Human toxicity, aquatic ecotoxicity, and soil ecotoxicity refers the toxic impacts brought by toxic organic pollutants and heavy metals to human and aquatic/soil organisms[48]. In the process of toxicity quantification, it needs to divide pesticide into three fractions, namely the fractions entering air, water and soil, because the toxicity of one organic pollutant varies greatly across different environmental media[19]. Currently, the most state-of-art toxicity assessment method is adopting SimaPro as LCA software and USEtox as toxicity characterization method[49]. Finally, the characterization factors of pesticides and heavy metals are converted to 1,4-dichlorobenzene equivalent factors[19], in order to obtain the overall toxicity value. Some works employed toxicity-relevant indicators as the environmental evaluation basis[13,26].

Land use. Land use refers the land cover change due to agricultural activities, also known as lost forested area due to agricultural activities, and generally expressed as ha deforested/ha cropland area/year. As an important basis of agricultural production, land use directly relates to sustainable development process of human beings[50]. Land use and its related changes can affect global ecosystems, biogeochemical cycles, climate change and soil degradation[51]. Hence, land use should be considered for sustainability assessment of agricultural activities, and is generally expressed as ha cropland area/year. Land use due to agricultural activities has been considered as an environmental indicator in many studies[1,15,52].

Soil health. Soil is key for the survival human beings given that more than 95% of human food is produced using soil[53]. Inappropriate farming activities increase the potential of soil acidification, salinization and shallow plow layer, threatening soil productivity and food security[54]. As a result, soil health, or soil quality, is key to sustainability through supporting vital societal and ecosystem services. Soil health evaluation methods, developed over a long period, have been refined in recent decades, including comprehensive assessment of soil health, soil indicators, and soil management assessment frameworks[53,55]. Increasingly, recent studies have been including soil health as one of the indicators of environmental sustainability[1,26,29].

Biodiversity. Biodiversity consists genetic, species, ecosystem and landscape diversity, and is important for promoting ecosystem services[56]. About 40% of global land is used for agricultural production, thus agricultural biodiversity directly affects agricultural production, global food security and ecological safety[57]. Agricultural biodiversity should be considered as an indicator for ecological environmental quality assessment in agricultural systems. To quantify biodiversity, the terms species richness and species abundance are generally used, but these two terms are sometimes used in confusing ways[58]. Spellerberg et al. suggested Shannon–Wiener Index should be commonly used to measure the heterogeneity of communities, as it is a more conciseness way to describe biodiversity[59]. Biodiversity is of increasing concern and should be adopted as an environmental indicator for evaluating agricultural sustainability[1,15,29,32].

3.4 Economic sustainability

Total revenue and net profit. Total revenue and net profit are the most frequently used indicators in economic sustainability assessment[52]. Total revenue refers the money earned from the main products and byproducts. For example, in maize cropping system, the main products are maize grain and byproducts are maize straws, therefore, both of them need to be included in gross revenue calculation[60]. Net profit refers total income minus total economic input, which indicates the financial return of a farmland system[52]. These two indicators are the widely used indicators to evaluate the economic benefits of agricultural systems[10,29].

Output/input ratio. This indicator refers the profitability of agricultural systems, with the greater value indicating improved profitability[38]. This indicator can be used to estimate whether a planting mode is economically feasible, and changes in profitability due to adoption of an agricultural practice[52]. Output/input ratio has been used by some researchers to evaluate the profitability of agricultural production[61,62].

Labor productivity. Labor productivity is crucial for increasing farmer income and agricultural green development[1]. It can be expressed by the total margin per unit time, with the larger value indicating the higher labor productivity[63]. It can also be expressed by the labor time spent on producing one unit product, with less labor time indicating the higher labor productivity[14]. Labor productivity is popularly selected to evaluate the economic sustainability[1,29,32].

3.5 Social sustainability

Nutrition availability. Food systems influence human health by food availability, prices, consumer preference and food culture[64]. However, providing a population with a healthy diet has become an immediate challenge and a barrier to achieve sustainable agriculture development. Low-quality diets can cause micronutrient deficiencies and contribute to diet-related obesity and non-communicable diseases[65]. Worldwide, over 2 billion people suffer from micronutrient deficiencies, and nearly 860 million people suffer from hunger[64]. To quantify nutrition availability, multiple indicators can be used, such as prevalence of malnutrition, chronic disease and foodborne illness[66]. Nutrition availability can be used as a social indicator to evaluate social sustainability[15,29].

Rural poverty ratio. Poverty reduction is the imperative subject of sustainable development goals, especially in rural areas[67]. Rural poverty ratio is defined as the percentage of rural population with an income that cannot provide a basic standard of living, which affects farmer wellbeing and the urban-rural gap[68]. According to Sustainable Development Report 2019, the headcount ratio poverty line is 1.90 USD·d^{-1}[69]. It is worth noting that this indicator is more suitable for the village or county scale because it requires a population base to calculate the percentage. Rural poverty ratio has been employed to analyze the social equity and the improvement potential of social sustainability[15,67].

Gender equity. Gender equity quantifies the gaps between women and men across health, education, economy and politics[1]. It demonstrates a social dimension of sustainability but is still an elusive goal in many parts of the world. There will be no sustainable agriculture and rural development while half of the rural population is unseen or unheard[70]. If women are empowered economically and socially, and have the same assess to resources as men, they would have the potential to become leaders and make contribution to yield increase, economic growth and social progress[71]. Hence, relieving women of their burdens and redistributing gender roles in the discharging of family responsibilities would be conducive to sustainable development[72]. Gender equity has drawn global concerns and is selected to evaluate social wellbeing[1,29].

4 WEIGHTING METHODS OF INDEX IN MULTI-FACTOR ASSESSMENT

Index system for agricultural sustainability assessment is inherently complex because it requires the integration of multiple indicators[73]. Weighting the selected indicators is the key step and tightly relates to the aggregation and validity of holistic index systems and decision-making. Weights reflect the relative importance of indicators contributing to sustainability, thus, it is necessary to obtain rational and valid weights[52]. Generally speaking, weighting methods can be roughly be divided into objective weighting method and subjective weighting method.

4.1 Objective weighting method

Equal weighting. This is the simplest weighting method. All indicators are considered as equally important[73], as shown in Eq. (1). However, it has caused controversies over the validity and accuracy, because not all indicators have the same importance[74].

$$w_i = \frac{1}{n} \tag{1}$$

Variation coefficient method. The principle of this method is to determine the weights by calculating the variability within each indicator. The greater variation, the greater weight value. This method directly uses the information contained in each indicator, and is a totally subjective weighing method[75]. In Eq. (2), δ_i and x_i are the standard deviation and the average of indicator i, respectively.

$$w_i = \frac{\delta_i}{\bar{x}_i} \tag{2}$$

Entropy method. Entropy shows the degree of uncertainty in the data. Smaller entropy means that there is more useful information in an indicator, and greater weight should be given to that indicator [76]. Firstly, a vector of x_j refers the set X in terms of indicator i, as shown in Eq. (3) and Eq. (4). Secondly, the entropy value of criteria j can be obtained according to Eq. (5), where d_{ij} refers to the normalized value of x_j, and D_j refers to the total sum of d_{ij}. Lastly, the weights can be calculated according to Eq. (6)[52].

$$x_j = (x_{1j}, x_{2j}, \ldots, x_{mj}) \tag{3}$$

$$X_j = \sum_{i=1}^{m} x_{ij}, j = 1, 2, \ldots, n \tag{4}$$

$$e_j = -\frac{1}{\ln m} \sum_{i=1}^{m} \frac{d_{ij}}{D_j} \ln \frac{d_{ij}}{D_j} \tag{5}$$

$$w_j = \frac{1 - e_j}{\sum_{j=1}^{n} (1 - e_j)} \tag{6}$$

Principal components analysis or factor analysis. The principle of these two methods is dimension reduction, which means a group of relevant indicators are transformed to another group of irrelevant comprehensive indicators. The weight can be calculated according to Eq. (7), where r_j is the proportion of the explained variance of factor j, l_{ij} is the factor loading ratio of indicator i on factor j, and E_j is the variance explained by factor j[73]. These two methods are statistically based, which not only reduces the risk of double weighting, but also avoids classifying ungrouped indicators.

$$w_i = r_j ({l_{ij}}^2 / E_j) \tag{7}$$

Gray correlation method. The principle of this method is to determine the indicator weights by calculating the degree of relevance between and each status and ideal solution[52]. This method has the advantages of strong objectivity, simple calculation, reduced inaccuracies and no limitation on sample size[77]. Among gray correlation methods, the technical for order preference by similarity to an ideal solution proposed by Hwang and Yoon is the most widely used in indicator weighting[78].

4.2 Subjective weighting method

Deliphi method. This method relies on a panel of independent experts in relevant areas. Experts rank the importance of each indicator based on actual situation and their own experience[52]. The final weight can be directly obtained from the average of weight values given by experts after several rounds. This method makes full use of expert knowledge and experience to avoid results that are contrary to general cognition. However, the weights come entirely from subjective judgments[77].

Pairwise comparison. In this method, the relative importance of pairs of indicators can be first obtained by experts. After the priority sequence of indicators being formed, number the sequence according to their importance, as s_1, s_2, s_3, …, s_n. Next, the weight of indicator ranked i can be calculated based on binomial expression[77], as shown in Eq. (8).

$$w_i = \frac{C_{n-1}^{i-1}}{2^{n-1}} \tag{8}$$

Analytic hierarchy process. This method is a structural technique builds on the pairwise comparison method. Firstly, hierarchical structure consisting overall goal level, criteria level, and sub-criteria level need to be established[73]. Secondly, comparisons between criteria in the same level are required, and the matrix of pairwise comparisons at the same level using Eq. (9)[52]. Lastly, criteria weights can be calculated through eigenvector method, linear programming method, least square method and others[77]. This method combines both subjectivity and objectivity, and has been widely used in weight determination.

$$D = \begin{bmatrix} C1/C1 & \cdots & C1/Cn \\ \vdots & \ddots & \vdots \\ Cn/C1 & \cdots & Cn/Cn \end{bmatrix} \tag{9}$$

5 CALCULATION OF OVERALL SUSTAINABILITY INDEX

5.1 Indicator conversion

To compare the performance of different indicators in sustainable development, conversion process (i.e., normalization and direction adjustment) are needed[1]. Positive indicator means that the larger value of the indicator, the better performance, such as yield and nitrogen use efficiency. Negative indicator means the smaller the absolute value of the indicator, the better performance, such as GHG emissions and resource depletion. Hence, both positive and negative indicators need to be normalized, and the direction of negative indicators needs to be converted. The most widely used normalization methods are min-max normalization and Z-score standardization as shown in Table 2.

5.2 Indicator aggregation

Aggregation is the final step for index system construction and is needed to reflect the overall sustainable performance of agricultural systems. Generally speaking, there are three aggregating methods: additive, geometric and non-compensatory aggregation.

Additive aggregation. Additive aggregation is the most widely-used aggregating method. The sustainability index can be calculated according to Eq. (13), where w_i and I_i are the weight and score of indicator i, respectively. It is a linear aggregation method, thus indicators should be independent, with no synergy or trade-off among them [73].

$$\text{Sustainability index} = \sum_{i=1}^{n} w_i I_i \tag{13}$$

Geometric aggregation. This method is compensatory and limits indicators with low scores to be fully compensated by indicators with high scores. Sustainability index can be calculated according to Eq. (14), where w_i and I_i are the weight and score of indicator i, respectively.

Table 2 Common methods for indicator normalization

Method name	Formula	Explanation	Characteristic
Min-max normalization	$x'_i = \frac{x_i - \min(x_i)}{\max(x_i) - \min(x_i)}$ (10) $x'_i = \frac{\max(x_i) - x_i}{\max(x_i) - \min(x_i)}$ (11)	Equation (10) for positive indicators and Eq. (11) for negative indicators. Max(x_i) and min(x_i) represent the best performance and the worst performance of indicator values, respectively[79]	It is a unity-based normalization method, and it is used to bring all values into the range [0, 1]
Z-score standardization	$x'_i = \frac{x-\mu}{\delta}$ (12)	In Eq. (12), μ represents the mean value, and δ represents the standard deviation	Works well when populations are normally distributed

$$\text{Sustainability index} = \prod_{i=1}^{m} I_i^{w_i} \tag{14}$$

Non-compensatory aggregation. Unlike additive aggregation and geometric aggregation, the output of this method is a ranking instead of an overall score. It is a non-compensatory method, suitable for situations that substitution between indicators is unacceptable. Formula is shown in Eq. (15), where Rank (Unit_i) is the overall ranking of the researched units, φ_* is the corresponding score of the final ranking of these researched units, and e_{jk} is the generic element of the outranking matrix[73]. This method retains most of the information in the data, but does not have a final aggregation value, so is not efficacious for learning about the overall functioning of agricultural systems.

$$\begin{gathered}\text{Rank}(\text{Unit}_i)\\ i = 1, 2, \ldots, n\\ s.t. \varphi_* = \max \sum e_{jk}\end{gathered} \tag{15}$$

6 CONCLUSIONS

With the increasing need to shift toward more sustainable smallholder agriculture, measuring sustainability for the agricultural sector is a challenging task and is important for formulating localized strategies. This study provides a structured review of sustainability assessment works in smallholder farming systems. From systemic perspective, 5-STEP SAMSFS contains: definition of system boundary & functional unit, indicator selection, indicator weighting, indicator conversion, and indicator aggregation. Specifically, definition of system boundary & functional unit and indicator selection depend on research scales and focal targets, while indicator weighting and indicator aggregation are key steps, relating to the validity of assessment results and decision-making. Although strengths and weaknesses vary between different methods, it is still worth exploring the most suitable assessment framework through comparing and evaluating processes.

The limitation of this study is that it only provides a methodology to systematically evaluate the sustainability of smallholder farming systems, which lacks the case studies to verify the effectiveness. Also, this study provides multiple possible calculation methods for each step, without comparing the strengths and weaknesses of each calculation method.

In further studies, more case studies should be made based on 5-STEP SAMSFS, and the pollutant emission/leaching parameters used to calculate the environmental indicators require to be localized for each cropping system. In addition, a detailed and comprehensive indicator system for assessment agricultural systems should be built, and its applicable scope and calculation methods should also be provided. In this case, it would be convenient for relevant researchers to choose the indicators based on specific research systems and concerned issues.

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Compliance with ethics guidelines

Xiaoxia Guo, Chong Wang, and Fusuo Zhang declare that they have no conflicts of interest or financial conflicts to disclose. This article does not contain any studies with human or animal subjects performed by any of the authors.

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