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REVIEW PAPER

Economic and environmental sustainability of agriculture production at the crop level

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ABSTRACT

Ensuring the long-term sustainability of food systems and the welfare of current and future generations depends critically on the economic and environmental sustainability of agricultural production. Implementing strategies that maximize resource use, reduce environmental effect, and guarantee profitability is necessary to achieve economic and environmental sustainability at the crop level. Farmers need to be able to support their costs of production and crop sales through agriculture. In order to sell their goods at competitive prices, farmers must handle problems including market monopolies, price instability, and fair trading practices. The use of land, water, fertilizer, and pesticides affects production costs and earnings. Farmers can employ a variety of techniques, including as crop rotation, cover crops, agro forestry, organic farming, carbon sequestration and decreased tillage, which enhance soil health and lessen erosion, to preserve environmental sustainability. Water management strategies, such rainwater collection, drip irrigation, and water recycling, are used to save water and ease the strain on freshwater resources. Moreover, using drones and global positioning system-guided tractors maximizes input application, lowers fuel consumption, and boosts overall agricultural productivity. Beneficial insects, birds, and other animals find a home when hedgerows, buffer strips, and wildlife corridors are kept up around and inside fields at crop level. Farmers may improve the resilience, profitability, and long-term viability of their farms while reducing their negative environmental effects and advancing wider sustainability goals by incorporating economic management, environmental and social sustainability concepts at the farm level. Economic management, which lowers market risk and stabilizes farm revenue, involves cost analysis, budgeting, and community supported agriculture. The goals of integrated pest management and organic farming are to preserve the sustainable environment, control diseases and pests at the farm level, and use less chemicals overall. In order to ensure social sustainability, farm workers must engage with their local communities and customers, support resilient local food systems, and have safe working conditions, access to healthcare, and an education that upholds human dignity and social equality. To address the problem of unsustainable production practices, accounting for them by bringing all aspects of sustainability under a single umbrella is paramount. In spite of widespread interest in sustainability in agriculture production at the crop level, very little work has been done towards measuring the economic and environmental sustainability of individual crops at the farm level, particularly in developing countries like India. In the present study, a framework was developed that determines the sustainability of a particular crop's output using farm level information. Micro level indicators of sustainability only for the relevant dimensions of sustainability, viz., economic and environmental sustainability, were compiled and evaluated for their relevance, usefulness, and measurability for agriculture at the crop level. The sustainability scores of farmers were found to be 50.99 and 67.65 under the composite sustainability score under rainfed conditions. The composite sustainability scores for the composite environmental conditions were found to be 45.58 and 40.03 under rainfed and irrigated conditions, respectively. The economic sustainability indicator weights were found to be 30, 30, 15, 15, and 10 for the economic sustainable indicators 1, 2, 3, 4, and 5 respectively. A further procedure for deriving composite indicators by aggregating individual indicators has been provided. The long-term viability of two sample respondents growing tomatoes was evaluated, demonstrating the applicability of the framework of agricultural production that balances environmental and economic sustainability at the crop level.

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INTRODUCTION

Climate variability (temperature and rainfall) and climate-driven extremes (heat stress, drought, floods, cold waves, and storms) have a number of detrimental effects on the agriculture sector in Asia, particularly on the cropping system, which is crucial to the region's food security (Rodelo-Torrente *et al.,* 2022). As a result, there are issues and challenges related to food security in Asia (Aryal *et al.,* 2019). Agriculture as a concept has steadily changed since the Brundtland definition of sustainable development (Brundtland, 1987). The concepts of sustainable development have changed over the years as well. Sustainable development was defined in the Brundtland report as 'development that meets the needs of the present without compromising the ability of future generations to meet their own needs'. Although this description (Sharachchandra, 1991) was ambiguous, it effectively covered two important issues: the need for economic expansion to reduce poverty and the issue of environmental damage that so frequently accompanies such progress. Agriculture sustainability is a complicated term, and academics have differing opinions on its components for different crops at farm levels (Hayati *et al.,* 2010). A lot of developing countries have prioritized agricultural productivity over sustainability, which has led to the depletion of vital and natural resources while production has increased. Poor and developing countries are more likely to experience soil degradation, water-related erosion, contaminated groundwater, and depletion of natural resources because they depend heavily on agriculture and natural resources (Maja *et al.,* 2021). By preserving resources while upholding other ecosystem services and long-term human development, agricultural techniques support society's demands for food, fiber, and other necessities both now and in the future. The secrets of sustainable agriculture are not technical solutions or specialized knowledge. Integrating ecological and sociological information requires adjustments to institutions, policies, and behaviour (Nightingale *et al.,* 2020). There are few quantitative evaluations of agricultural sustainability available, and definitions of sustainable agriculture differ greatly across nations. Some academics and professionals define sustainability as a collection of management techniques, while others refer to it as a philosophy or a set of objectives. Sustainable agriculture is coming to focus more and more on how it affects the environmental, economic, and social pillars of sustainability. For evaluating food system sustainability at the national and international levels as well as for figuring out sustainable agricultural intensification at the farm level, there are a number of frameworks and indicators available (Xin *et al.,* 2021). Sustainable agriculture and the multipurpose role that the primary sector is assigned are closely related. This sustainability strategy has three components: social, environmental, and economic. The impact on the global environment, consumer requirements, and local ecosystem services are taken into consideration while evaluating agricultural techniques. For ensuring the preservation of the environment, a multifunctional system promotes the health of rural communities, sustainable farming, and morality (Lanfranchi *et al.,* 2015). A number of metrics for assessing the sustainability of agriculture at farm levels have been proposed. The main issues facing agricultural aspects, practice, and policy is the implementation and assessment of sustainable agriculture. In spite of these challenges, numerous assessments methods have been developed during the past 30 years, nevertheless, more work needs to be done to create new interpretive techniques, particularly when it comes to incorporating them into the planning of social, economic, and environmental policies (Gómez-Limón *et al.,* 2010). It appears challenging to implement a single, integrated strategy. According to Rigby *et al.,* (2001), the primary concerns have to do with the incommensurability of various aspects or dimensions of sustainability. The three pillars are frequently included in each of which is treated differently and with varying relevance (Paul, 2020). People are studying the environmental pillar more because they are becoming more aware of ecological issues. Biopesticides are inexpensive, safe for the environment, have a targeted mode of action, are sustainable, don't leave behind residues, and don't contribute to the release of greenhouse gases. These pesticides are known as biopesticides and can be classified as either microbial, phyto, or nanobiopesticides (nanoparticles made from biological agents); Microbial pesticides function specifically, don't require costly chemicals to be sourced, and have no lasting effects on the environment, in contrast to synthetic pesticides (Ehzari *et al.,* 2022). In addition to exhibiting a multitude of phytochemical substances that enable them to function through diverse methods, phytopesticides pose a lower danger to human health than synthetic pesticides and do not contribute to the release of greenhouse gases (Pan *et al.,* 2023). On the contrary, there aren't many recognised, well-researched frameworks for evaluating economic and social sustainability (Dujon, 2010). The creation of an improved system for sustainable agriculture assessment at farm levels is essential to trace the consequences of human action and government intervention (Lancker and Nijkamp, 2000). The sustainability of agriculture system could be measured at the global, national, regional, local, or farm levels, yet many pieces of literature have strongly supported evaluation of sustainability at the farm level to ascertain accuracy for decision-makers (Reed and Doughill, 2003). Field level studies help in examining the extremities, which would otherwise smooth out the farm, regional, state, or national levels (Beeket *et al.,* 2003; Girardin *et al.,* 2000). Thus, the framework to evaluate the sustainability of vegetable production is paramount with farm-level data rather than just aggregated state-level information (Berrueta *et al.,* 2021; Sandhu *et al.,* 2021). As far as the time scale of sustainability is concerned, it is hard to evaluate sustainability over time, and indicators for sustainability are snapshot measures, however, the agro-ecosystem is highly dynamic (Cauwenbergh *et al*., 2007). Snapshot measurement is not accurate for all the indicators, and hence time-integrated indicators such as measuring frequencies need to be adopted. Since the measurements are at crop level, utilizing farm-level data, the social component of sustainability is less important than the economic and environmental dimensions (Robling *et al.,* 2023). The more importance is given to those aspects of the current study. The aim of the current study is to put forth a technique framework to evaluate the sustainability of farming systems at the individual crop level. Information and communication technologies (ICTs) are thought of as instruments that raise competitiveness and productivity in businesses and manufacturing facilities. The more ICTs are used, the greater these advantages become. The need for quality and safety has put pressure on agricultural businesses to implement information and communication technologies. Customers are embracing models like those seen in industrialized nations, which forces companies to compete in local and regional markets where traded goods are subject to set criteria (Bhakta *et al.,* 2019). In sustainable crop production, sustainable indicators and composite indicators are key frameworks to achieve environmentally sustainable crop production, and they are the important gaps identified in crop production. This study focuses mainly on the gap, such as sustainable indicators for sustainable crop production. The main objectives of this study are to create a framework that uses farm level data to assess the sustainability of a given crop's yield. Compiling micro-level economic and environmental sustainability indicators, these indicators were then combined to create composite indicators, which were then assessed for their applicability, usefulness, and measurability to crop-level agriculture (Taoumi *et al.,* 2023). The applicability of the agricultural production framework that strikes a balance between environmental and economic sustainability at the crop level was demonstrated by the evaluation of the long-term viability of two sample respondents who were producing tomatoes. This study was conducted at the University of Agricultural Science in Bangalore, India in 2023.

METHODS AND MATERIALS

It is recognized that economic activity may be detrimental to sustainability. The conversation about market failures and sustainability best encapsulates this link between the economy and sustainability. Economic theory states that a market should not lead to inefficiencies like abuse of people or the environment. It is recognized that some of these detrimental effects stem from market imperfections that impede effective market distribution. Input and output market conditions, biological and geophysical elements, and other significant variables influence farmer decision-making and the adoption of land use practices or technologies. Water availability, soil fertility, flood, drought, frost, and insect or weed infestation hazards are examples of biological and geophysical elements that affect production; the significance of each of these factors' changes depends on the crops that are planted. A farmer's decision to produce can be influenced by input market conditions in several ways. For instance, it might not be viable to cultivate a crop with a relatively limited harvesting window during a month when there is a strong demand for agricultural labour in the area due to the dynamics of seasonal and local labour availability. Farmers may plant various crop mixes or more acreage in one crop than another due to input price volatility and economies of scale in terms of inputs or technologies. The cost of transportation, supply chain transactions, price volatility, and other output market factors all play a significant role in determining how lucrative it is for farmers to raise a crop. The position of these factors affects several of them.

Methodological framework for assessing sustainability

The conceptualization of framework forms a baseline for the assessment of sustainability of any kind (Armenia *et al.,* 2019). The present study proposes a framework that addresses sustainability from two main perspectives of farm managements, viz., environmental (agronomic practices that impact the environment in a broader sense and have an ecological impact on biodiversity) and economic (costs and benefits influencing continuation of a particular crop). Developing composite indicators to trace the trends in sustainability has shown to be more beneficial than identifying the trends of individual indicators separately (Saltelli, 2007). This analytical framework developed a composite indicator to measure sustainability, a multi-dimensional phenomenon for individual crops (Gómez-Limón *et al.,* 2020).

Indicators

In general, an indicator is an either qualitative or quantitative measure produced from a set of observable facts that might show relative positions (for example, of a nation or farm) in a certain location. The indication is as a partial but a representative mapping of a compound attribute of a phenomenon under study into a one-dimensional metric that is pertinent to the formulation of policy-making (Nijkamp and Ouwersloot, 1998). Sustainability indices take social, ecological, and economic aspects into account (Nijkamp and Ouwersloot, 1998; FAO, 2011). The ideal number of indicators to assess sustainability strikes a balance between an excessive number of indicators, which endanger the complex phenomena linked to them, and too many indicators, which endanger the efficiency of the assessment framework (Nijkamp and Ouwersloot, 1998). A total of 20 indicators were selected, with 9 and 11 indicators under the economic and environmental pillars. The major challenge associated with indicator selection, as reported by Olde *et al.,* (2016) a "startling lack of consensus" among a large group of sustainability specialists who were asked to rank the relative significance of selection criteria for individual indicators and balancing criteria for a group of indicators. The representative experts from the relevant sustainability in agriculture fields were consulted to choose the sustainability metrics for the present study.

Composite indicator

Composite indicators are employed when the phenomenon is complex and cannot be measured directly. Nevertheless, this may communicate misleading policies, if constructed poorly. The significance of considering indicators as a set to evaluate sustainability of any system rather than as a single indicator for a specific theme (Lyytimäki and Rosenstrom, 2008; Niemeijer and Groot, 2008). To provide a more thorough and all-encompassing estimation of a systems or societies environmental performance, composite indicator for environmental sustainability is a metric that combines numerous distinct environmental indicators into a single value (Bithas, 2020). These indicators can include a wide range of environmental factors, including resource utilization, greenhouse gas emissions, biodiversity, and air and water quality etc., (Erickson, 2017). The primary steps in using composite indicator for environmental sustainability are i) making sure, it is scientifically proven, identifiable, and indicates the main elements of concern, ii) making certain that it has a scale value of 0 to 1 so that it can be compared to a standard, iii) creating the composite indicator using the feedback of experts and consultations with stakeholders, and (iv) determining the composite indicator's reliability and accuracy by comparing it to real-world data (Gómez-Limón *et al.,* 2020; Yi *et al.,* 2019). To create a composite indicator for environmental sustainability, it is crucial to examine the methodology with great care, indicator choice, and data quality. The Environmental Performance Index (EPI) and the Sustainable Development Goals (SDG) Index are two of the composite environmental sustainability indicators were in use (Beck *et al.,* 2019). These indexes combine a variety of environmental indicators to evaluate and rank each country's environmental achievements and advances towards sustainable development objectives. Referring to environmental sustainability, they have stressed indicators should be chosen based on how best they jointly answer the environmental questions.

Steps in construction of composite indicator

There is a process involved in creating composite indicators, beginning with the creation of a conceptual framework and moving forward to the dissemination of composite indicators (Fig. 1). Every step has significant effects on the step that comes after, the choices made at each step are equally vital (Nardo *et al.,* 2008).

Step 1: Theoretical framework

The underlying conceptual framework that directs the creation and building of a composite indicator is referred to as a theoretical framework in the design of composite indicators (Albo *et al.,* 2017). Composite indicators are statistical tools that combine many distinct indicators into a single aggregated measure (Areal and Riesgo, 2015). They are frequently used to describe sophisticated concepts or situations that are challenging for just one indicator to fully portray. A theoretical framework gives the justification for choosing particular indicators, setting their relative importance, and outlining their relationships in the context of construction (Basile *et al.,* 2021). The composite indicator's ability to effectively reflect the underlying notion it seeks to measure is improved thanks to this methodology. Building composite indicators is transparent, repeatable, and accurate given to a well-developed theoretical framework (Lü and Lü, 2021). Results are more significant and trustworthy when the construction method is consistent with the theoretical foundations of the notion being measured. Existing sustainability research approaches might be distinguished into

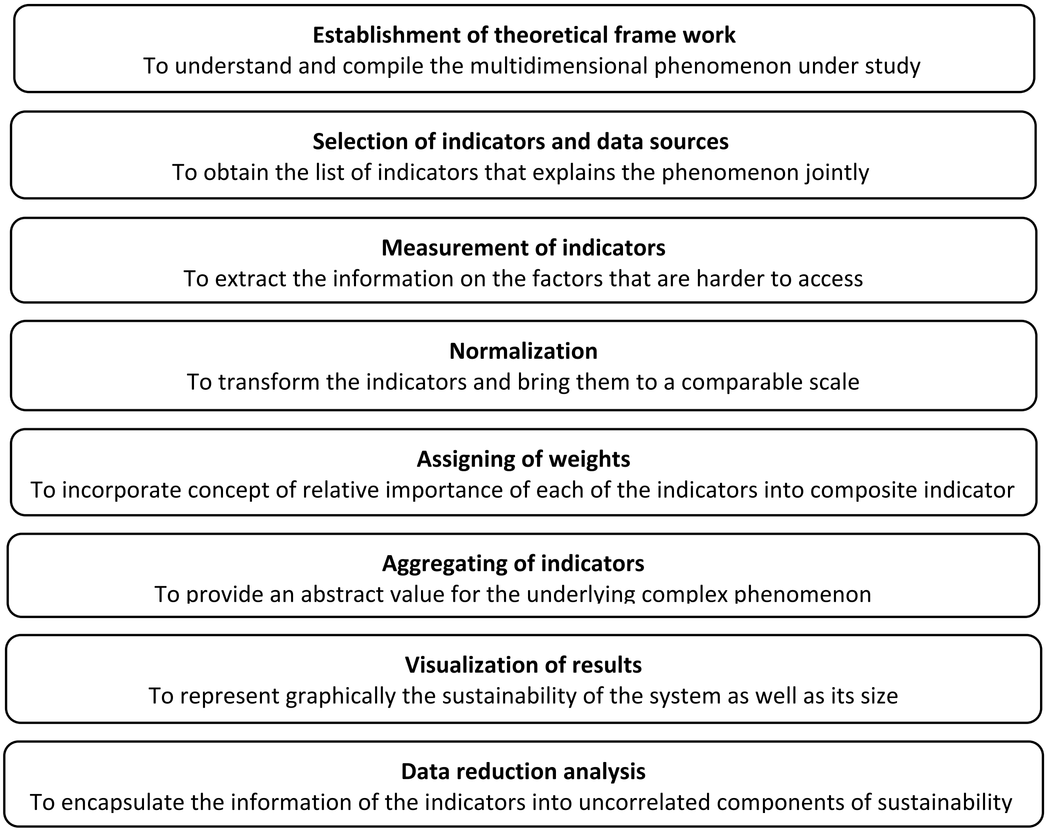


Fig. 1: Steps followed and their objective in creating a composite sustainability indicator

two interpretative schemes: goal prescribing, and system describing models (Hansen, 1996). The goal prescribing models are intended to determine methods for enhancing an agricultural system's sustainability. The system prescribing models evaluate a group of characteristics of agriculture for their sustainability, therefore aiding in decision-making as opposed to offering practical answers (González, 2018). The present study falls under the latter category, where the evaluation of vegetable production's sustainability took place using an indicator-based approach to identify the strengths and weaknesses of the production system.

Step 2: Selection of indicators and data sources

As suggested by Katie *et al.,* (2014), sustainability indexes or indicators fall into one or another stage of the casual chain of activities such as public policy, farmer practice, and biophysical performance. Environmental sustainability is easily and effectively studied at the practice stage only. On the other hand, the performance stage provides a greater understanding of economic sustainability than the other two stages. Thus, the indicators of particular pillars are resulting from the appropriate stage of the casual chain to create a composite indicator. Olde *et al.,* (2016) studied the criteria that the experts found crucial for selecting sustainability assessment indicators. Based on this, the sustainability indicators were chosen using the following criteria:

a) Relevance to sustainability issue:

The indicator should be as relevant as possible for sustainability aspect. It ought to gauge important characteristics of the environment, economy, and society that impact farming's level of sustainability (Marchand *et al.,* 2014). When evaluating sustainability factors in agriculture, the indicators' applicability is crucial (Bathaei and Štreimikienė, 2023). Key elements of the environment, economics, and society that affect how sustainable agricultural methods are should be adequately captured by indicators (Lipper *et al.,* 2022). Indicators can measure significant aspects of the economy, society, and environment that affect farming's sustainability by following the principles of multidimensionality, flexibility and adaptability, contextual relevance, measurability, and data availability (Essono *et al.,* 2023). This makes it easier to create policies, implement management techniques, and make well-informed decisions that support more sustainable agricultural systems.

b) Measurability:

The availability or easy acquisition of data and a well-documented calculation method. The usage should be justified in terms of cost and time consumption (Tarjan *et al.,* 2020). The use of composite indicators for evaluating agricultural sustainability must be supported by data availability and a well-established calculation technique, especially in light of the time and money required for their creation and use (Nziguheba *et al.,* 2021; Dong *et al.,* 2023). The usefulness of composite indicators as instruments for decision-making assistance in the advancement of sustainable agriculture may be enhanced by guaranteeing openness, specificity, and involvement of stakeholders throughout the development and implementation phases (Ndamani and Watanabe, 2017).

c) Policy relevance/ Usefulness for the end-users

Indicators should be able to convey a precise message and offer sufficient information to support management and policy decision-making. To assist management and policy decision-making in agriculture through clear communication, contextual information, benchmark, trend analysis, and scenario analysis, indicators must be precise and useful (Valencia *et al.,* 2022). Indicators should provide enough information to direct successful interventions while also sending a clear and actionable message. These characteristics enable indicators to provide enough data to assist management and policy decisions in agriculture while also successfully communicating precise signals (Alaoui *et al.,* 2022). This increases the sustainability of agricultural systems, encourages collaboration among stakeholders, and encourages informed action (Siankwilimba *et al.,* 2023).

Since, the assessment of agricultural sustainability is a multidisciplinary subject, experts for selection and assigning weight were chosen from pertinent departments, such as Agriculture and natural resource economics, Agriculture Extension, Forestry and Environmental Sciences, Agronomy and Soil Science, to form a total of 11 members as an expert group. Scores were obtained from experts ranking for individual ranking based on its relevance to sustainability, measurability and policy relevance. Questionnaire used for obtaining scores is provided in Supplement 1 and the scores calculated from the ratings are given in Supplement 2.

Step 3: Measurement of indicators

To give a more complete picture of a complex concept, a composite indicator is a single value that combines several different individual indications (Cerofolini *et al.,* 2019). It is essential to take into account the composite indicator's goal, the kind of data being used, the accessibility of accurate data, and the preferences of the stakeholders while measuring indicators for a composite indicator. The choice of technique for assessing indicators has its own benefits and drawbacks, the method should be in line with the particular context and measurement objectives (Scaccabarozzi *et al.,* 2022). For the results to be accurate and reliable, it should also be founded on strong statistical and methodological principles. The threshold value of the indicators to obtain their scores. It is complicated to derive a single threshold value for the variables to be called sustainable, specifically for pressure categories (practices) of indicators, which is true for the environment pillar. For the economic pillar, as suggested by Goswami *et al.,* (2017), the threshold values have no significance since they are more of a subjective concept. Before normalizing the variables, it is important to assign a "direction" to the indicators, as a higher value of any variable does not always imply that the indicator is operating well (Floridi *et al.,* 2011).

Step 4: Normalization of indicators

Since the indicators of agricultural sustainability are hardly measured in similar units, aggregating them into one composite indicator is particularly important. Number of normalization methods exist, however only ranking, distance to target, Z-score, rescaling, and range are the five strategies for composite indicators, which have been used in the literature the most frequently (min-max or max-min) and proportionate normalization (Nardo *et al.,* 2008; Saisana *et al.,* 2011).

Among the various normalization techniques available, this study employ rescaling or ranging normalization. Using the minimum and highest values as a guide, this approach rescales data into various intervals using Eqs. 1 and 2 (Nardo *et al.,* 2008).

For greater the crude value, $$I_{rs} = \frac{(C_{rs} - C_{r\,min})}{(C_{r\,max} - C_{r\,min})} \tag{1}$$

For lower the crude value, $$I_{rs} = \frac{(C_{r\,max} - C_{rs})}{(C_{r\,max} - C_{r\,min})} \tag{2}$$

Where, I_{rs} and C_{rs} are, respectively, the normalized and crude values of indicator r for farm k, while $C_{r\,min}$ and $C_{r\,max}$ are, respectively, the minimum and maximum crude values of indicator k found in the sample of farms considered. Eq. 1 is used in cases where indicators mean "the greater the crude value is, the more sustainable the farm". On the contrary, Eq. 2 is used when indicators mean "the lower the crude value is, the more sustainable the farm". The following this procedure, the normalized indicators' values (I_{rs}) vary within a limitless spectrum [0, 1], whereby 0 corresponds to the worst possible value of indicator (the least sustainable) and 1 to the greatest (the most sustainable).

Step 5: Assigning of weights

An important step in aggregating individual indicators into a single composite indicator is assigning weights to them. There are many different weighting methods; some of them, like factor analysis (FA), data envelopment analysis (DEA), and unobserved component models (UCM), are derived from statistical models. According to expert opinion, non-statistical strategies may reward (or penalise) elements that are thought to be more (or less) influential to more accurately reflect policy priorities or theoretical considerations (Krishnakumar and Nagar, 2007). In the present study non-statistical expert scoring technique was used to acquire the weights needed for at principle level as well as indicator level.

Step 6: Aggregating of indicators

Applying the rule of the key given by Hansen (1996) and further followed by several other authors, the lowest score of the three dimensions of sustainability (economic, environmental, and social) was applied to each farmer's final sustainability score. Applying a single total score to each of the three pillars would lead to compensation between the pillars, and making it less reliable. Scores of better practice from one pillar will offset scores from another pillar's bad score, and vice versa. In various aggregation techniques to develop a single composite indicator have been documented (Nardo *et al.,* 2008), which are mainly of two types: compensatory and non-compensatory. Compensatory techniques use the linear function, the compensating any indicator dimension with the surplus from others (Tarabusi and Guarini, 2013). Multi-criteria analysis (MCA) is used for aggregating non-compensatory data. In general, MCA gives an overall ranking based on the values and weights of indicators. Ranking of the farmers based on their sustainability score was not the goal of this inquiry; it was to obtain the mean scores. The simple compensatory linear aggregation was deployed, where weights were used for compensation between the individual indicators.

Step 7: Visualization of results

Webs and radar charts are especially helpful for providing a visual depiction of findings when a study compares farms or is conducted on the same farm over several years of analysis (Bockstaller *et al.,* 1997). A radar chart is a graphic representation of data that is multivariate that shows three or more quantitative variables depicted on axes that all start at the same point. The present investigation's goal was not to rate the farms. Representing individual scores of sustainability dimensions is considered as more compatible with strong sustainability approach as compared to relying wholly on aggregate indicator (Gómez and Sanchez, 2010; Martinez and Neill, 1998).

Step 8: Data reduction analysis

According to Paracchini *et al.,* (2015), indicators used in sustainability assessments may be correlated or redundant. According to this perspective, farmers can benefit from a data reduction approach that summarizes the data found in the original database. As the framework's aggregative definition of sustainability components is arbitrary, the dimensions produced by the indicators can be verified by data reduction using Principal Component Analysis. Principal Components Analysis (PCA)'s main goal is to minimise the dimensionality of a data set made up of numerous connected variables while preserving as much of the data set's variance as possible. This is done by changing to a new set of unrelated variables called PCs and ordering them so that the majority of the variation found in all of the original variables (Stefanucci *et al.,* 2018). The sustainability scores of farmers were found to be 50.99 and 67.65 under the composite sustainability score under rainfed conditions. The composite sustainability scores for the composite environmental conditions were found to be 45.58 and 40.03 under rainfed and irrigated conditions, respectively.

Economic indicators

As revealed in the preceding section (steps in the building of composite indicators) performance level indicators tend to be easy to measure and could provide a logical picture of systems economic sustainability. The five principals under economic sustainability were identified; economic viability, efficiency, financial independence, resilience, and transferability. Indicators and sub-indicators for each principle were selected. A comprehensive list of indicators selected to assess economic sustainability as per the procedure given above is presented in Table 1. Weights were obtained based on the opinions of a multidisciplinary group of experts on individual principles and indicators. Further, the weights of the indicators were divided equally among the sub-indicators to obtain a weight for each sub-indicator.

Given the existing and anticipated future energy, climatic, and economic conditions, agro-ecology is one of the most dependable paths to sustainable development. Agro-ecology is currently providing the scientific, methodological, and technical underpinnings for the global agrarian revolution. Robust, effective, biodiverse, and socially acceptable, agro-ecology-based agricultural systems form the basis of the food sovereignty approach. The system is distinguished by an extensive range of tamed plant and animal species, which are preserved and enhanced to guarantee proper biodiversity, soil preservation, and water regime control. These efforts are bolstered by complex traditional knowledge systems. For many generations, these systems have provided for the great majority of people (Marchetti *et al.,* 2020). The competitiveness and profitability of agricultural production that are critical in the short term as well as medium terms and are the main focus of the scientific study on economic sustainability. Besides, some economic indicators such as, farm income, efficiency, financial independence, and transferability also provide details regarding the long-term economic aspect of sustainability. The choice of principles, indicators, and sub-indicators

Table 1: List of economic sustainability indicators and their weights

Principle	Weights	Indicator	Weights	Sub indicator
ECO-1 economic viability	30	ECO-1.1 Productivity	15	Labour Productivity Capital Productivity Land Productivity
		ECO-1.2 Profitability	15	Net Margin Labour Profitability Return on Equity
ECO-2 efficiency	30	ECO-2.1 Technical Efficiency	10	Actual output to the highest output that can be achieved
		ECO-2.2 Allocative Efficiency	10	Output for which the cost of production is equal to the price
		ECO-2.3 Economic Efficiency	10	Presuming to know how effectively the social benefit, or welfare, produced fulfills the interests of the consumer
ECO-3 independence	15	ECO-3.1 Reliance on Subsidies	7	Percentage of subsidy amount to the total cost Percentage of subsidy amount to the net returns
		ECO-3.2 Financial Autonomy	8	Amount of state budget transfers to the total revenues of local government, as well as the percentage of own revenues to the level of total revenues.
ECO-4 resilience	15	ECO-4 Risk Mitigation Mechanisms	15	Continuous planting Crop diversification Staggered planting Tie-up with firms Contract farming Processing Cold storage Different stage of picking Crop insurance IP&D management Direct/self-marketing Distant marketing/export
ECO-5 transferability	10	ECO-5.1 Inter-Generational Continuation of Farming Activity	10	Whether the farmer is growing onion/tomato continuously Whether the objective of farmer taking up onion/tomato production has been fulfilled Whether the farmer is willing to expand his area or at least continue same area under onion/tomato production in future Participation of younger generation production activities

was developed after a review along with is primarily based on the Indicateurs de durabilité des exploitations agricoles (IDEA), response-inducing sustainability evaluation (RISE), sustainability assessment of farming and the environment (SAFE), Sustainable Irrigation water management and River-basin governance: Implementing user-driven services (SIRIUS) and monitoring tool for integrated farm sustainability (MOTIFS) methodologies. Economic indicators were classified under five principles for analysing the economic sustainability of vegetable production in the present study. They are:

1. Economic viability
2. Efficiency
3. Financial independence
4. Resilience
5. Transferability

These five principles give an extensive framework for evaluating the economic viability of vegetable cultivation, including factors of revenue, efficiency of resources, economical flexibility, and reproduction potential in a variety of settings.

ECO-1: Economic viability

The economic function of the agro-ecosystem aims to ensure the agro-ecosystem's economic sustainability by bringing prosperity to the farming community. This principle focuses on determining whether the system for growing vegetables is long-term economically viable and lucrative (Lizińska and Czapiewski, 2018). Variables like earnings are taken into consideration, expenses, and sustainability. An economically viable farm is defined as having the capacity to remunerate family labour on the farm at the average agricultural wage and the capacity to provide an additional return on non-land assets (Latruffe *et al.,* 2016).

ECO-1.1: Productivity

Productivity is the key endeavour to assess the economic performance of agriculture production. Maintaining and enhancing productivity is crucial to accomplish economic sustainability. The assessment of domain is unjust if so focused on a single factor of production, rather than all the factors of production: land, labour and capital. It could be preferable to focus on improving the total factor productivity, which emphasizes utilizing every aspect of production to produce more with each unit of input (Ryan *et al.,* 2016).

ECO-1.2: Profitability

Since the maximization of household income is one of the main goals of a farmer, and it plays an important role. Examining profitability involves a cost-benefit analysis of the farming system. In the study, gross margin, net margin, labour profitability and returns on equity were selected to quantify the farm profitability (Alcon *et al.,* 2024). A farmer can acquire a thorough understanding of the profitability of their farming system and pinpoint areas for development by looking at these indicators (Bathaei and Štreimikienė, 2023). For instance, a high gross margin but a low net margin can mean that the farm is not using its resources efficiently or that operational expenses are excessive (Sannou *et al.,* 2023). In a similar vein, a low return on equity can mean that the farm isn't making enough money for the farmers to invest. The indicators would be obtained by subtracting the cost from the value-added.

ECO-2: Efficiency

The indicator that seems to give the best overall picture of economic sustainability is the production process efficiency indicator, which shows the capacity from the farm to develop its own production autonomy (IDEA). To ascertain the efficiency with which resources are employed in the production of vegetables, such as labour, land, and the inputs, effectiveness must be considered. Utilising resources effectively helps maximise productivity while reducing waste (Kumar *et al.,* 2013). Increase in efficiency could increase productivity and profits, without increasing negative environmental consequences (Ryan *et al.,* 2016). From an economic angle, sustainable agricultural system methodologies such as IDEA, MOTIFS, RISE used efficiencies to complete the assessment of economic sustainability.

ECO-2.1: Technical efficiency

Technical efficiency dictates that a farm cannot grow output without increasing inputs because of the way it uses labour, capital, and land resources. Technical efficiency is the capacity of a production process to yield the highest possible output given a specific set of inputs (Lutonja, 2023). Technical (or production) efficiency is achieved when the output is produced at minimum input levels. This minimizes the inappropriate use and waste of inputs, such as fertilizer, pesticides, animal energy, water, mechanical work and labour (Abajue and Gbarakoro, 2023). When there is no resource waste, farming can be considered technically efficient. This has the following advantages: a) lower production costs for farm products, which may result in higher profits; b) resource efficiency minimizes the impact of production processes on the environment, including pollution reduction and natural resource conservation; c) lower prices or higher-quality products; and d) continuous process improvement and waste reduction (Gamage *et al.,* 2023; Samimi and Nouri, 2023). The technical efficiency is a key idea for farms trying to boost productivity and attain long-term growth.

ECO-2.2: Allocative efficiency

Allocative efficiency describes a farm's capacity to generate the assortment of products that consumer's desire at the most affordable price. For the minimize production costs, an allocative efficient farm produces the items that consumers value the most. Allocative efficiency, which is the efficient allocation of resources, or when marginal returns and marginal costs are equal are equal, means that price efficiency is reached for all inputs and outputs. When benefits and marginal expenses are in balance, resources are being used as profitably as possible and cannot be shifted to increase total benefit (Rosegrant *et al.,* 2023). An allocative efficient market guarantees that no resources are wasted and that the economy is running as efficiently as possible. Allocative efficiency, then, is a fundamental idea in economics since it's used to assess if resources are being used as efficiently as possible and gauge a market's overall efficiency (Mivumbi and Yuan, 2023). It can be used to assess whether resources are being distributed in a way that optimizes social welfare, which is the reason why it is frequently used to assess the efficacy of government programs and interventions. The combined technical and allocative efficient farms produce as much as feasible at the lowest possible cost while meeting the highest demands of their customers (Sasaki *et al.,* 2018). This indicates that the farm is optimizing its earnings and making the best use of its resources, and when technical and allocative efficiency are met, the farm is regarded as being economically efficient.

ECO-2.3: Economic efficiency

A key element influencing agricultural output at the crop and farm levels is economic efficiency. When an agricultural operation is technically efficient, then it is generating the most given the resources of labour, capital, and land (Alem *et al.,* 2023). Allocative efficiency, to technical efficiency, makes sure that the farm produces what customer's desire to a lot, optimizing both farm revenue and overall utility for customers. Economic efficiency is attained at the crop level when the right quantity of inputs, such as pesticides, fertilizer, and water, is used to grow the crop. To maximize total farm production, this guarantees that the crop is providing the greatest output possible given the resources employed (Taoumi and Lahrech, 2023).

ECO-3: Financial independence

The capacity for growing vegetables process to earn enough revenue to pay its operating costs without heavily reliant on outside financial support is referred to as financial independence (Bohra and Sharma, 2021). The finance independence guarantees the medium-term future of the farms by making it possible for production systems to have the capacity to invest and to adapt more easily to reductions in public subsidies. A few examples of methodologies are the SAFE, MOTIFS, analysis of farm technical efficiency (AFTE), Impacts on environmental and economic sustainability (IEES), and farm sustainability indicators (FSI). Employed this parameter to evaluate the relevance of public aid on economic performance of crop production.

ECO-3.1: Reliance on subsidies

This indicator evaluates the economic incidence of government subsidies over farm income and the production expenses. Financial activities should be efficient, that is, the dependency on external finance through credit or subsidies should be optimal, resulting in an optimal debt/equity ratio (solvency) and optimal investment (Langholtz *et al.,* 2021). Subsidies may create a strong dependency inhibiting innovation.

ECO-3.2: Financial autonomy

This indicator proposes for evaluating financial autonomy in crop production by accounting for the total amount of loan availed by the farmer for production of the particular crop (Suresh *et al.,* 2022). A farmer may be severely dependent on outside funding to maintain crop output if they have taken out a large number of loans for that particular crop. This could imply that the farmer has a limited level of financial autonomy for that particular crop. Conversely, it may indicate a greater degree of financial autonomy for that farmer if they have taken out less loans, or none at all, and are depending more on other sources of income (Appiah-Twumasi *et al.,* 2020). It's crucial to remember that a farmer's financial independence and health encompass more than just their level of financial liberty.

ECO-4: Resilience

The resilience is measured by how well it can weather diverse shocks to the economy, market swings, and environmental difficulties. A resilient framework can adjust and carry on even in the face of obstacles (Kim, 2020). Resilience is also important has seldom been directly considered in evaluating economic sustainability (Lien *et al.,* 2006). This indicator reflects the farm's capacity to withstand production and market risk without compromising much on the profits earned. Information on risk mitigation strategies adopted by the farmer was compiled to understand their resilience.

ECO-5: Transferability

Transferability determines if economic behaviours and ideas used in vegetable farming in one environment can be effectively transferred and utilized in other areas or contexts, preserving their significance and efficacy (Fahmi, 2019). Transferability analyses the long-term ability to carry on from one generation to the next. To evaluate the firms a qualitative data on farm features were obtained such as whether the farmer's objective behind growing a particular crop has been met, whether the farmer is growing particular crop continuously, whether the farmer is willing to maintain or extend his area under production of a particular crop and participation of younger generation production activities.

Environmental Indicators

Agronomic and farming activities with an effect on the environment in a wide sense and the ecological part impacting biodiversity were identified. Despite the lack of a clear-cut separation between the principles, enough work has been done to prevent the overlap (Paracchini *et al.,* 2015). This principle is concerned with how farming operations take and the resources that are used. Rotation of crops, conservation of soil, irrigation systems, and fertilizers use are all included (Komatsuzaki, 2017). A comprehensive list of indicators selected to assess environmental sustainability as per the procedure, along with their weights, is presented in Table 2.

Four major principles and eleven indicators surrounding the principles were selected:

1. Farming practices/ Input use
2. Management of resources
3. Organisation of space
4. Diversity

ENV-1: Farming practices

Regarding agricultural input utilization, the growth of overall input use has not changed significantly throughout time, but the makeup of inputs utilized in production has. Either contract labour services or agricultural chemicals like pesticides and fertilizers have taken the place of labour in agricultural operations. Furthermore, as land becomes more limited in comparison to other inputs, the agricultural sector has substituted chemicals for land to improve output. Rising energy prices have also caused the sector to bear rising energy expenses under the producers' budget limitations. Rising and unstable input prices as well as unproductive weather were blamed for the composition shifts in input consumption, which appeared to put pressure on production costs (Suh, 2015).

ENV-1.1: Nutrient management

Concerning the balanced use of nutrients and the choice of their sources, they were proposed as important components by IDEA, and MOTIFS. Balances for nitrogen, phosphorous pentoxide (P_2O_5), and potassium oxide (K_2O) nutrients were calculated as the difference (surplus or deficit) between total nutrients applied from various sources and the recommended dosage of nutrients per unit area. According to Gourley *et al.*, (2012) optimum application of nutrients able to provide the two advantages of reducing the risk of loss of nutrients from farmland while increasing income for the farmer. An essential factor in improving crop output and soil quality is organic matter. By mixing high-quality organic matter into different crop soils, such as composted plant leftovers or barnyard manure, the amount of organic matter in the soil can be raised. In addition to enhancing soil structure and water-holding capacity, organic matter also improves soil biological activity, releases macro- and micronutrients, and increases soil carbon (C) storage. For other macro- and micronutrients, applying 2 t/ha/dry weight of manure would yield approximately 16 kilogram nitrogen (kg N), 14 kg phosphorus (P), 31 kg potassium (K), and 16 kg calcium (Ca). Applying organic matter can raise the soil's cation exchange capacity (CEC) and organic C content from 0.78 percent (%) to 0.83%. Meanwhile, the application of 5 ton per hectare (t/ha) rice straw containing 9 kg N and 26 kg potassium (K) enhanced the rice grain production from 2.39 t/ha to 4.14 t/ha in comparison to plots without rice straw recycling.

Table 2: List of environmental sustainability indicators and their weights

Principle	Weights	Indicator	Weights	Sub-indicator
ENV-1 Farming Practices	40	Env-1.1Nutrient management	12	Nutrient imbalance indicator Portion of nutrients derived from organic sources Practices for integrated nutrient management were used Applying fertilizer after conducting a soil test
		ENV-1.2 Pest management	12	Active ingredient of PPC used per unit of cropland The use of integrated pest management techniques
		ENV-1.3 Farm Machinery Operation	8	Heavy machineries entered in the field Land that is ploughed conventionally
		ENV-1.4 Material degradability	8	Disposal of non-degradable material
ENV-2 Management of resources	30	ENV-2.1Water resource management	10	Source of irrigation Method of irrigation Existence of irrigation water scarcity Pressure on freshwater resources due to irrigation
		ENV-2.2 Soil conservation	10	Period with live plant cover in a year Application of silt/red soil/sand Conservation Tillage Drainage Practices
		ENV-2.3 Energy consumption	10	Total energy used per unit of land Share of renewable energy used on farm.
ENV-3 Organization of space	20	ENV-3.1 Cropping intensity	**9**	The quantity of crops cultivated by a farmer in a specific agricultural year on the same field
		ENV-3.2 Crop rotation	11	Rotating crops with deeply rooted plants Farmers grown different crop in previous and subsequent season Legumes in crop rotation to fix nitrogen Rotating crops using green manure Crop rotation to break life cycle of pests and soil borne disease Use cover crops in crop rotation to scavenge nutrients
ENV-4 Diversity	10	ENV-4.1 Diversity of annual crops	5	One might use the Herfindahl, Simpson, Margalef, and Entropy indices to determine the diversity of annual crops, as well as their quantity.
		ENV-4.2 Diversity in the genotype	5	Variations in the base sequence of DNA or the amino acid sequence of proteins can be used to quantify variation within a species.

ENV-1.2: Pest management

Agrochemicals form a major component of pest, disease, and weed management in traditional methods of farming. The practice of using non-chemical plant protection measures is considered environmentally friendly. The indicator on agrochemicals concentrates on the adoption of integrated pest, disease, and weed management practices and the quantity of active ingredient (AI) of chemicals per unit area of crop. Along with the actual AI used, the potential harm caused by a specific chemical was considered to calculate the value of this indicator (Apon and Nongmaithem, 2022). In broad-acre crops, there are a range of effective, locally validated integrated pest management (IPM) alternatives, including biological control, decision-support tools, innovative pesticide delivery modes (e.g., attract-and-kill), or agronomic measures such as diversified crop sequences, the implementation of cover crops, and inter-cropping. The technological progress and implementation readiness of various biological control and biopesticide approaches bodes well for ongoing efforts to phase out these compounds in a range of agriculture crops (Veres *et al.*, 2020).

ENV-1.3: Farm machinery operation

Excessive use of heavy machinery leads to soil compaction, which is thought to be among the most significant environmental issues brought on by traditional farming (Hamza and Anderson, 2005). Soil compaction, which may arise from an excessive use of heavy equipment in agriculture, is really one of the major environmental issues associated with current agricultural practices (Yang *et al.,* 2023). Compacted soil disrupt soil structure and reduce permeability, intense tillage methods like harrowing and ploughing may contribute to soil compaction worse (Šarauskis *et al.,* 2018). The pore area in soil is diminished and the ability of soils to take in nutrients, water, and air is limited, when soil particles are compressed (Yang *et al.,* 2023). The indicator of farm machinery operation takes into account the total number of hours machinery worked in the tillage field (fertilization, pesticide application, and harvest), to traditional land preparation techniques using bullock pairs.

ENV-1.4: Material degradability

Several external inputs and their packaging materials have environmental risks at their disposal, especially the non-biodegradables. Materials such as drip or sprinkler irrigation structures, mulching materials, staking materials, and containers of agrochemicals are the foremost wastes generated in the agriculture production process (Sivakumar *et al.,* 2022; Maraveas, 2020). There are serious environmental dangers associated with disposing of external inputs and the materials used to package them, particularly those that are not biodegradable. These inputs include agrochemicals that are often utilized in contemporary agricultural methods, such as plastic mulches, insecticides, herbicides, and fertilizers (Silva *et al.,* 2019). Soil contamination, water pollution, plastic waste pollution, and long-term environmental persistence are the risk linked elements (Mosa *et al.,* 2023; Samimi and Mansouri, 2024; Cheraghipoor *et al.,* 2024).

ENV-2: Management of resources

Natural resources are becoming more and more limited due to climate change since their rate of regeneration outpaces their rate of consumption. This is especially apparent in the case of water. Climate change is a decrease in precipitation, and when it does occur, it does so with extreme intensity and temporal concentration. Agriculture must create new methods and practices to deal with this problem. One such method is known as “dry farming” or “dryland farming” which is the process of producing crops without irrigation during dry seasons. This method is particularly important in areas where annual rainfall is limited to 50 centimeter (cm). Surprisingly, wealthy countries tend to have a larger prevalence of drylands, which are more susceptible to desertification. For instance, desertification has been a problem in thirteen European countries (Samuel *et al.,* 2021). Management of resources involves the efficient and the prudent utilization of natural resources. It entails practices that reduce waste and encourage conservation. Indicators could include: i) effective utilization of water sources; ii) energy conservation; and iii) environmentally friendly utilization of fertilizers; and iv) lowering greenhouse gas emissions (Karki and Rao, 2023). This principle aims at evaluating practices in the control of natural resources like water and soil. The crop production practices that affect the air quality at farm level were not studied as they are relevant to greater spatial levels such as regional or higher (RISE and SIRIUS).

ENV-2.1: Management of water resources

Water resource conservation is essential component of the overarching goal of sustainability. Irrigation is the dominant form of water use in a production system, and measures that raise the water’s efficiency application are of paramount importance. Though water resource management entails both quantitative and qualitative parameters, this framework considers only quantification as the quality is more of a state parameter of sustainability (IDEA, MOTIFS, and RISE). Indicators used to account for the sustainability of water resources were identified following SIRIUS. The source of irrigation, method of irrigation, and pressure exerted on water resources due to irrigation were considered under this indicator (Polemio and Voudouris, 2022).

ENV-2.2: Soil conservation

Cropping systems and tillage related operations affect the soil’s physical, chemical, and biological properties both in the short and long run. The healthy soil management is essential to soil conservation. Following RISE, IDEA, and SIRIUS, parameters such as live cover, conservative tillage operations, and soil rejuvenation through the application of silt or red earth were considered under this indicator. To prevent soil erosion and add nutrients back to soil, crop residue incorporation is ideal, which is also referred to as conservative tillage. The crop residue could be disposed of by burning, incorporated, or used for preparing farm manure. The method of disposal of crop residue from the particular crop and its previous crop was measured for this indicator (Flower *et al.,* 2022). In many parts of the world, crop rotations are not complete without the use of the cover cropping system, a conservation agriculture (CA) strategy that provides a multitude of advantages and ecosystem services, including water retention, weed control, nitrate leaching mitigation, and N supply and retention. Furthermore, cover crops have the potential to increase soil organic C and nitrogen over time while reducing net N_2O and CO_2 emissions, all of which can help mitigate climate change. Enhancing soil organic C reserves through cover crops may help ensure food security and stability in the environment. In a similar vein, the application of CA strategies to improve soil water management and soil C storage is essential in rainfed agro ecosystems (Cates *et al.,* 2019).

ENV-2.3: Energy consumption

Indicators concerning the calculation of total energy input were adopted by SIRIUS and RISE. Further use of renewable sources of energy to measure environmental sustainability was suggested by MOTIFS and Gaviglio *et al.*, (2017). The entire energy input was calculated by converting the physical units of inputs such as manures, fertilizers, chemicals for plant protection, human and machine labour, machines, fuel, and electricity based on scientific facts retrieved. Renewable energy sources are the ones that can be replenished, such as organic manures, human and animal labour. Sources of energy that are not quickly replenishable, such as fossil fuels, electricity, chemical fertilizers, agrochemicals, and machinery used in crop production, are grouped as non-renewable energy sources (Overland *et al.,* 2022).

ENV-3: Organisation of space

The methodologies or indicators used to characterize agricultural land use intensity, as well as its effects on the ecological environment, social-economic development, and so on, have been the main topics. A new system has been developed utilizing farm accounting network data to characterize agricultural land use intensity. This system includes land usage, socioeconomic characteristics, local climate, and government subsidies to determine the unit land cost input. The spatial distribution of agricultural intensity in France has been determined using polynomial regression models, which serve as a crucial point of reference for the execution of relevant agricultural policies and are based on conventional agricultural statistics to measure agricultural intensification using indicators of inputs or outputs. While indicators of the outputs include cereal and animal husbandry products, they have only been used to analyse the features of agricultural land use and their informative significance, rather than focusing on the innovation of characterization methods. Indicators of the inputs include fertilizers, levels of intercropping, nitrogen input (for arable land and permanent grassland), livestock unit density, and pesticide amounts (herbicide, insecticide, and flame-retardant herbicide and insecticide) (Jiang *et al.,* 2016). The spatial arrangement of agricultural activities and their impact on the environment are addressed by spatial organization. It may take into account the design of land use, agroforestry, and the preservation of biodiversity (Yoshida and Kono, 2022). This principle is a proxy for farmers' choice regarding use of the land, which is further associated with a reduction of soil erosion, improving soil health, ensuring an optimum population of beneficial fauna, and maintaining of natural habitat (RISE, IDEA, and SIRIUS). Indicators related to this issue are cropping intensity, crop rotation, and management of crop residues.

ENV-3.1: Cropping intensity

Cropping intensity indicates the pressure exerted on natural resources. The quantity of crops produced over a period of one year and agricultural land that is subsequently sown with different crops were considered under this indicator (Giunta *et al.,* 2019). Cropping intensity is a crucial indicator for assessing the burden agricultural systems make on natural resources (Shen *et al.,* 2023). A popular way to quantify it is the ratio of arable land to cropped area. This indicates how much agricultural activity occurs on a specific plot of land over a specific time period. Important data on resource consumption, land use intensity, and potential environmental implications of agricultural practices are provided by cropping intensity (Tsue *et al.,* 2021).

ENV-3.2: Crop rotation

Rotation of crop is a practice of planting different crops successively within the same area. Four sub-indicators, i.e., suitability of the previous crop, suitability of the subsequent crop, and two methods of crop rotation using legumes and green manure, were compiled under this indicator. Crop rotation is an underpinning for any sustainable production system. It is a planned system of growing different crops in recurrent succession on the same land. Benefits of crop rotation include weed, pest, and disease management, increased soil moisture and nutrients, and higher yields (Parvana, 2022). Numerous crop types, such as grains, legumes, root crops, and oil crops, can be utilized as vegetative covers, and each has a unique set of benefits to maintain soil health. Increased soil organic C and accessible soil nutrients, decreased soil compaction, increased soil structure and particle aggregation, and improved microbial activity, abundance, and diversity are some of the advantages associated with cover crop adoption in agricultural areas. Specifically, some species of cover crops like *Vicia sativa* L. may improve the soil with nitrogen because of their capacity to fix atmospheric nitrogen (Adetunji *et al.,* 2020).

ENV-4: Diversity

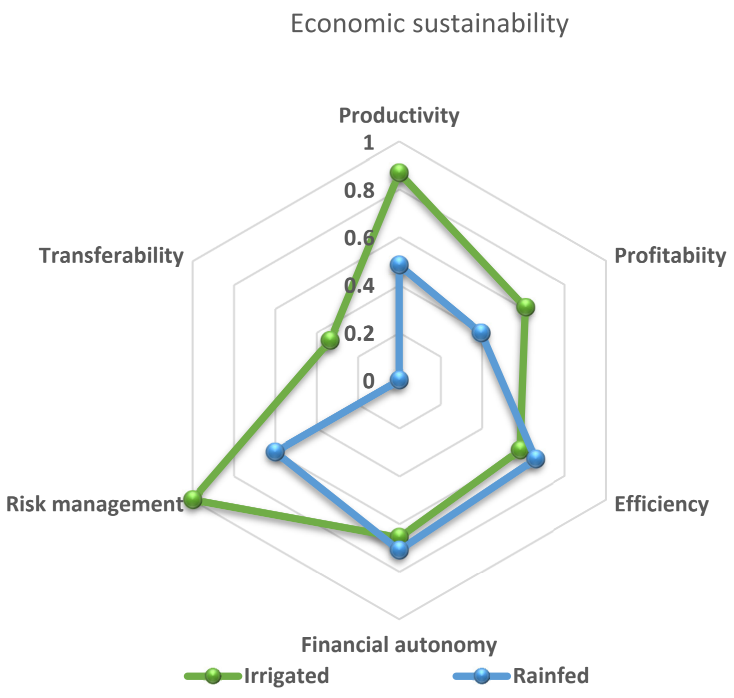
Agriculture diversity entails sustaining a diverse range of livestock, crops, and habitats. It helps with the resilience of ecosystems and dietary safety (Geldenhuys *et al.,* 2021). The process of growing multiple crop varieties, either from the same or different species, in a specific area through intercropping or rotation is known as crop diversification. Diversification of crop has several roles in the sustainability of the agriculture system, such as being cost-effective, increasing resilience, and lowering agricultural uncertainty. Katie *et al.,* (2014) stated that Crop diversification promotes health, stability in yield, variety in nutrition, and control over pests and diseases. It also improves soil fertility. In agriculture, biodiversity can be quantified on three levels: diversity in communities within the local environment, the quantity of species present in the area, and the genetic variety within a single species (Salgotra and Chauhan, 2023). Given that the current study evaluates a farm-level assessment of sustainability, measuring diversity exclusively on the farm and the genetic variety of a particular vegetable is feasible.

Application of the framework for an Indian case study

Tomato farming in India is used to illustrate the proposed framework for evaluating the sustainability of agricultural production at the crop level. All farmers for cultivating tomatoes under rainfed, and irrigated conditions, was inter viewed for required details on tomato cultivation aspects (Mehta *et al.,* 2020). The production practices were analysed to obtain values for individual indicators and sub indicators of economic and environmental sustainability. For each component of sustainability, scores are displayed like a radar diagram (Fig. 2).

Farmers growing tomatoes under irrigated conditions had better performance in terms of productivity, profitability, and risk management. Rainfed farmers had zero scores for transferability, indicating their poor performance in terms of intergenerational transferability of tomato cultivation (Tsusaka *et al.,* 2015). Rainfed farmers had better performance in components of environmental sustainability such as external material disposability, farm machinery operations, and space organization compared to irrigated farmers. The pest management had better scores under irrigated conditions, as they were following more integrated pest management practices (Sharifzadeh *et al.,* 2023). Overall, both farmers had better economic sustainability than environmental sustainability, which is apparent from the composite sustainability scores provided in Table 3.

Irrigated farmers had better economic sustainability performance, and rainfed farmers performed well for environmental sustainability. In both rainfed and irrigated situations, there is much potential for improvement for the environment and farmers alike (Ullah *et al.,* 2022). Adopting sustainable agricultural practices is crucial to reducing these environmental risks. These practices should minimize the use of external inputs, encourage integrated pest management, improve soil fertility and health through organic farming, and lessen dependency on synthetic fertilizers and pesticides. Furthermore, the environmental effects of agricultural inputs can be reduced by using biodegradable substitutes and properly disposing of and reusing packaging materials. Reducing the environmental footprint of agrochemicals and promoting environmentally responsible agriculture methods are also aided by government legislation, industry standards, and consumer awareness efforts.



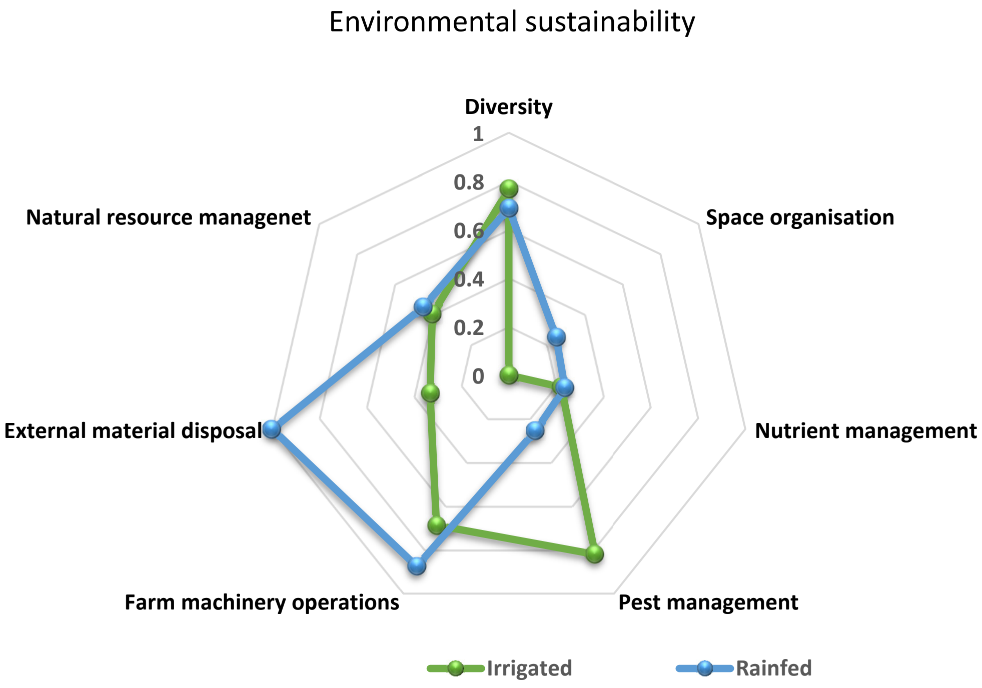


Fig. 2: Sustainability scores of sample farmers cultivating tomatoes cultivation under rainfed and irrigated conditions

Table 3: Composite sustainability scores of sample farmers

Sample farmers	Composite economic indicator	Composite environmental indicator
Rainfed	50.99	45.58
Irrigated	67.65	40.03

CONCLUSIONS

Studies and evaluations of sustainability in agriculture are commonly conducted at many levels, such as the regional, national, state, and farm levels. Understanding the existing situation of agricultural sustainability, monitoring changes over time, and identifying areas for development are the goals of these researches. Researchers, decision-makers, and interested parties may obtain a thorough grasp of the intricate relationships between agricultural systems and their larger social, economic, and environmental settings by examining sustainability at several levels. Creating methods that effectively support sustainable agriculture and guarantee the long-term survival of food systems requires a multi-level approach. Enhancing the overall sustainability of agricultural systems requires comparing the sustainability of several crops or variations of the same crop. The objectives of these studies are to comprehend the current state of agricultural sustainability, track changes over time, and pinpoint areas in need of improvement. By looking at sustainability from multiple angles, policymakers, and interested parties can gain a comprehensive understanding of the complex interactions that exist between agricultural systems and their broader social, economic, and environmental contexts. A multi-level strategy is needed to develop techniques that reliably support sustainable agriculture and ensure the long-term sustainability of food systems. It is necessary to compare the sustainability of several crops or varieties of the same crop to improve the overall sustainability of agricultural systems. The farmers, and policymakers may determine which crops or kinds perform best in terms of indicators related to social, environmental, and economic sustainability by using this comparative study. Stakeholders can find possibilities for innovation, funding, and policy assistance to promote the sustainability of agricultural production systems by systematically comparing the sustainability of different crops and variations. This comparison method makes it easier to make decisions based on facts and addresses the intricate problems that the world's food systems face. Yet, comparisons of sustainability among crops and/or varieties of the same crop are essential to increase the agriculture system's overall sustainability. The proposed framework to evaluate each crop's sustainability individually has considered the two major pillars of sustainability, viz., environmental and economic pillars, as social or governance aspects are less significant for individual crops. The indications at several levels were used to build composite indicators for each pillar. It is common practice to create composite indicators for measuring sustainability across various pillars (economic, environmental, and social) using indicators at multiple levels, including regional, national, state, and farm levels. These measures cover key aspects of sustainability and offer a comprehensive framework for evaluation. Indicators such as agricultural production and output, resource use efficiency, land use change and agricultural expansion, water quality, and soil health indicators at the regional and national levels offer macro-level insights into wider trends and patterns connected to sustainability. State- or provincial-level indicators offer a more focused viewpoint on sustainability since they account for local variances and unique difficulties. Examples of these indicators include state-specific policies and regulations related to agriculture and the environment; regional variations in climate and weather patterns; soil conservation and erosion control measures; and water management practices and regulations. Agro-ecological practices adoption, input usage efficiency, crop yield and productivity, and other farm-level metrics are aimed at evaluating the sustainability of specific farms or agricultural businesses. These indicators offer in-depth understanding of management choices and practices in the field. Composite sustainability indices, which incorporate information from many levels, offer a thorough evaluation of agricultural sustainability by illustrating the interaction between the social, environmental, and economic facets. For the environmental pillar, indicators at the practice stage and indictors at performance stage were obtained to supply reliable outcomes illustrating a system's sustainability from below. An appropriate hierarchy was followed in developing the framework to avoid overlapping indictors between the components. The sustainability scores of farmers were found to be 50.99 and 67.65 under the composite sustainability score under rainfed conditions. The composite sustainability scores for the composite environmental conditions were found to be 45.58 and 40.03 under rainfed and irrigated conditions, respectively. The economic sustainability indicator weights were found to be 30, 30, 15, 15, and 10 for the ECO-1, ECO-2, ECO-3, ECO-4, and ECO-5 principles. It started with the identification of principles for both the pillars under study, followed by selecting relevant indicators regarding every principle and assigning weights to them based on experts' opinions. Economic indicators were divided into nine indicators and sub-indicators as needed, using five categories to classify them. Eleven indicators that were categorized into four principles were also acquired and, as needed, sub-classified into indicators. The social or institutional pillars of sustainability still need to be investigated; the developed framework limits the study to the environmental and economic pillars of sustainability. Furthermore, there is never a consensus on how to understand the concept of sustainability. A wide range of problems, including climate change, a high rate of biodiversity loss, land degradation due to soil erosion, compaction, salinization, depletion, and pollution of water resources, rising production costs, a steadily declining number of farms, poverty, and a decline in the rural population, pose a threat to agriculture's ability to meet human needs both now and in the future. The goal of sustainable agriculture is to raise the standard of living for farmers and the public while simultaneously providing food and fiber to meet the needs of people both now and in the future. Sustainability needs to be applied to all facets of agriculture in order to achieve this. The developed framework, however, is confined to the economic and environmental pillars of sustainability, as the relevance of social or investigating the institutional pillars of sustainability is still necessary. Furthermore, there always exists conflict in perceiving the concept of sustainability itself.

AUTHOR CONTRIBUTIONS

A.Z. Bi conducted the literature review, analysis, and interpretation of the data. K.B. Umesh compiled the data and completed some of the manuscript writing. B. Md Abdul contributed to some of the manuscript preparation as well as the literature review preparation. D. Sivakumar contributed critical thought to make the manuscript technically sound. P. Srikanth oversaw the writing of the review and edited it.

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CONFLICT OF INTEREST

The authors declare that there are no conflict of interest regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancy, were observed by the authors.

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PUBLISHER'S NOTE

ABBREVIATIONS	DEFINITION
%	Percent
AFTE	Analysis of farm technical efficiency
AI	Active ingredient
CA	Conservation agriculture
Ca	Calcium
CEC	Cation exchange capacity
cm	Centimeter
CO_2	Carbon dioxide
DEA	Data envelopment analysis
EPI	Environmental performance index
FA	Factor analysis
FAO	Food and Agriculture Organization
FSI	Farm Sustainability Indicators
ha	Hectare
ICT	Information and communication technology
IDEA	Indicateurs de durabilité des exploitations agricoles
IEES	Impacts on environmental and economic sustainability
IPM	Integrated pest management
K	Potassium
K_2O	Potassium oxide
kg	Kilogram
MCA	Multi-criteria analysis
MOTIFS	Monitoring tool for integrated farm sustainability
N	Nitrogen
N_2O	Nitrogen oxide
P	Phosphorus
P_2O_5	Phosphorous pentoxide
PCA	Principal components analysis
RISE	Response-inducing sustainability evaluation
SAFE	Sustainability assessment of farming and the environment
SDG	Sustainable development goals
SIRIUS	Sustainable irrigation water management and river-basin governance: Implementing user-driven services
t/ha	Ton per hectare
UCM	Unobserved component models

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