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Sustainability of rice production systems: an empirical evaluation to improve policy

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Abstract An evaluation is needed to monitor the progress of sustainable development (SD) in rice production systems. The purpose of this study is to provide policy inputs, examine the sustainability of rice production, and determine major policy areas. A requisite set of 12 indicators of three dimensions of SD, namely economic, was generated by employing an assemblage of top–down and bottom–up approaches. The data were gathered from farm households' survey as well as in-depth discussion with stakeholders from the regions that represent irrigated, rain-fed lowland, rain-fed upland, flood-prone, and saline-prone rice-growing ecosystems in Bangladesh. By constructing composite indicators, the results revealed that 44 % of rice growers were economically viable, environmentally sound, and socially developed. The irrigated rice production system was found to be the most sustainable. The path analysis measured the contribution of the indicators to the index, and results highlighted that rice growers' knowledge, skills, and social networks development, improving land productivity, and integrated nutrient management were essential for promoting sustainable rice production. However, the study findings suggest that pluralistic (i.e., government and non-government) agricultural advisory services can serve as an engine of transition to rice production sustainability in which a multi-year planning and strategy formulation are crucial besides investing in the modernization of extension services. Overall and ecosystem-specific policy implications that emerged from the findings of this study are outlined.

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1 Introduction

Rice is the staple food of about half of the world's population and a principal source of livelihood of the majority of Asian people. Bangladesh is predominantly an agricultural-based country, and rice is the main crop. Rice production occupies almost 77 % of the total cropped area, employs about 50 % of the country's labor force, and contributes to 10 % GDP (BARC 2011). Bangladesh's rice economy has made a notable progress; in particular, the total amount of rice production and cultivating area have increased by 243 and 24 %, respectively, in the last 40 years (BBS 2011). This progress is attributed to rapid expansion of minor irrigation equipments,[1] e.g., shallow tube-wells and introduction of many high-yielding rice varieties (HYVs) (Hossain 2009).

Presently, sustainable rice production and agriculture are the major concerns of policy-makers, and these concerns are reflected in several key documents of the government of Bangladesh, such as National Agriculture Policy 2010 [Ministry of Agriculture (MoA) 2010] and Poverty Reduction Strategic Papers 2008 (Planning Commission 2008). The probable reasons for this concern are as follows: (1) rice farming is highly vulnerable to climate change (e.g., floods) (ActionAid 2011), (2) land is becoming an extremely scarce commodity and declining by 1 % per annum (MoA 2010), (3) the price of fertilizers, pesticides, and fuels for irrigation is gradually increasing (MoA 2006a), (4) irrigation water crisis and groundwater arsenic contamination in the South Western part of the country (Brammer 2009), and (5) rice-based monoculture pushing out the major non-cereal crops such as oilseed and pulse (Hossain 2009).

Moreover, ever-increasing population pressure[2] and soils with poor organic matter content, i.e., most of the soils, have <1.5 % organic matter, whereas a good soil should have at least 2.5 % organic matter (BARC 2011) in rice-producing areas that are the grave threats for rice production sustainability. Based on literature review (e.g., Rasul and Thapa 2004; Gómez-Limón and Sanchez-Fernandez 2010), sustainability refers to preserving and improving natural resources (fostering environmental soundness), enhancing farming productivity and profitability (increasing economic viability), building human and social capital, and provisioning of public goods and services to society (promoting social development).

In Bangladesh, there are five rice-growing ecosystems (IRRI 2013), namely irrigated land (dry 'Boro' season). Rice cultivation is characterized as irrigated and agrochemical (mineral fertilizers and chemical synthesized pesticides)-intensive, and growers are

[1] These equipments are not only dependent on ground water, but also on other numerous water sources. This country is known as 'the land of rivers', i.e., there are 310 rivers in Bangladesh, of these, 57 are trans-boundary rivers. Hence, the sustainability of rice production is not completely dependent on the sustainability of groundwater irrigation.

[2] Based on the data from 1971 to 2005, population increased at a rate of 2.042 million per year, whereas rice production increased at a rate of 0.4582 million tons per year. This figure indicates that if this rate continued, then about 10.50 million tons rice shortage is estimated for its total population demand in 2050 (Basak 2010).

overwhelmingly dominated (89 %) by small and marginal farmers (<1 ha land) (BBS 2013). Despite the fact that rice production has observed a high growth rate, it raises environmental concerns such as soil compactness and acidity (Jahiruddin and Satter 2010). Moreover, declination of agro-biodiversity, rural poverty, and food price speculation exacerbate the growing concerns, indicating that the present rice production trends are not environmentally sound, profitable, and socially responsible (ADB 2004a; Alauddin and Quiggin 2008; Shahid and Behrawan 2008; Chowdhury 2009). Considering the present state of declining land and water resources, as well as increasing rural poverty, addressing the question of how to achieve sustainable rice production and country's food security has become a big challenge.

Considering these challenges, the government has taken initiatives to curb these problems. Many completed and ongoing development projects have been implemented by the Department of Agricultural Extension (DAE) to equip the extension agents and to develop capacity of growers by providing training, logistic, and economic support. However, the achievements obtained by these initiatives are inadequate due to resource constraints, inefficient leadership, weak extension services, and lack of coordination among agencies (MoA 2006b). Mandal (2006) reported that most of the policy documents were prepared based on notional ideas and lack of empirical analysis, largely due to lack of reliable data and ministerial inefficiencies (Roy et al. 2013a). Few years ago, the government had introduced fertilizers and irrigation subsidies, which are negligible, when compared to those implemented in other countries such as India (MoA 2006a). Moreover, studies showed that the subsidies are not so beneficial for marginal and small farmers, and that rather a major share of subsidy benefits is grabbed by the fertilizer traders (Mandal 2006).

Literature on assessing rice production sustainability is not adequate to draw overarching policy inputs. Based on historical data, Baffes and Gautam (2001) examined that the current level of per capita rice production can be sustained by earning increased yields from HYVs. Without taking flood- and saline-prone rice-growing ecosystems into account, Roy et al. (2014) evaluated rice farming sustainability and found that 'Boro' rice is the most sustainable. Developing composite indicators (CIs), Gowda and Jayaramaiah (1998) compared sustainability of rice production systems in India and found that rain-fed lowland rice is the most sustainable, followed by the irrigated system. However, the latter study neither described the methodology in detail nor followed all the steps of CI development, as suggested by the OECD (2008). In the present study, these research gaps have fulfilled in the sense of considering five rice-growing ecosystems and conducting empirical evaluations of rice production sustainability by using detailed CIs development methodologies of the OECD.

Broadly, sustainability evaluation is an approximate indication of the extent to which the system is economically viable, environmentally sound, and socially acceptable. The value of the CI, in particular, emerges from the score received by the indicator. A higher index score of any production system commonly refers to the growers belonging to that system presently facing fewer challenges than those with the lower index score. However, this result does not necessarily indicate that the particular system's current production trajectory will be capable of maintaining its long-term ability and resilience of natural resources. An empirical assessment of farming sustainability is a foundation for transition to sustainability. By developing CIs, the present study first assessed the extent of rice production sustainability at the farmer's level. Second, the niche policy areas for promoting it were determined. Finally, important policy implications were recommended.

2 Evaluation of sustainability using composite indicators

Although a common accepted set of indicators has not been identified and defined yet in the literature, sustainability evaluation by using indicators is well established (Dahl 2012), recognizing some operational problems (Gómez-Limón and Sanchez-Fernandez 2010). Specifically, problems exist in interpretation of the whole set of indicators, which provides superficial policy information. It lacks in assessing the trend of changes (e.g., environment) and finding out causes, identifying best practices and optimizing the gains from government investment. However, the life cycle thinking approach is a reliable tool for supporting decision-making process in the assessment of sustainability performance of product (Valdivia et al. 2013). In most cases, policy-makers are too busy to deal with detailed information; they need packaged information to expedite decision-making. In this regard, CIs are well suited in summarizing multidimensional issue to support policy-makers, facilitate communication to the public, media, and other interested parties, and promote accountability. CIs are an aggregated index, comprising the individual indicator based on an underlying model.

Several tools, namely monetary (e.g., contingent valuation method), have been used for sustainability evaluation in the diverse fields, and all approaches have advantages and

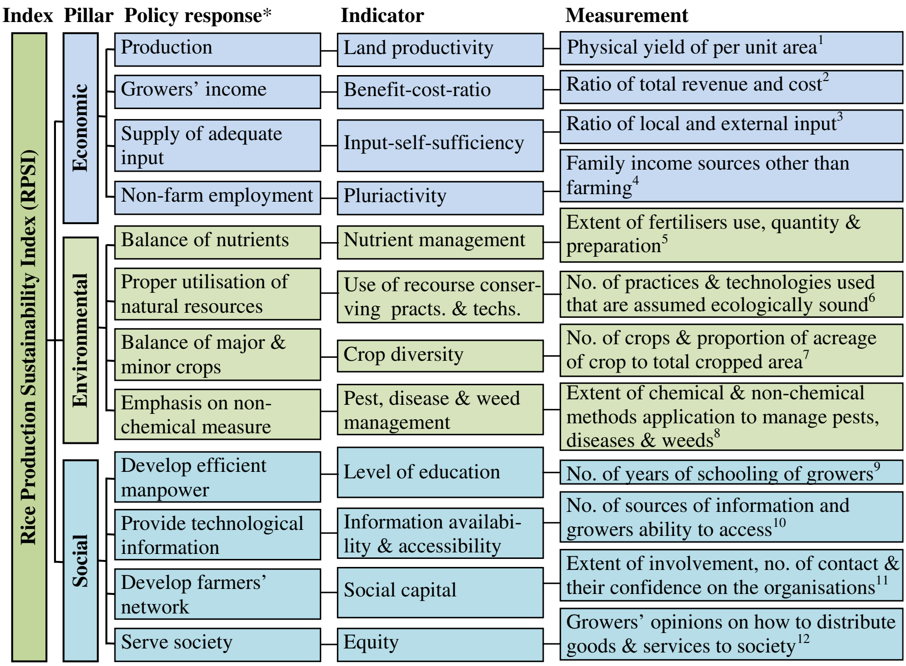

Fig. 1 Conceptual framework for the sustainability of rice production systems. *Policy purpose refers to direct and indirect reflection of the indicators to the particular aspects of policies and strategies of Bangladesh, such as National Agriculture Policy 2013, New Agricultural Extension Policy 1996, Environmental Policy 1992, National Rural Development Policy 2001, Bangladesh Climate Change Strategy and Action Plan 2009, and National Strategy for Accelerated Poverty Reduction 2005. [1, 3] Rasul and Thapa (2004), [2] Zhang (2000), [4, 9] Dantsis et al. (2010), [5] Authors (based on expert opinion), [6] Pretty et al. (2006), [7] Islam and Rahman (2012) and [8, 10, 11, 12] Roy et al. (2014). *Note*: More information on indicators and how they were measured can be found in respective reference of each indicator

disadvantages. For example, biophysical and monetary tools view sustainability problems from different but complementary perspectives. Although they provide complementary snapshots of the same picture, it can be argued that they are unable to capture the whole picture (Gasparatos and Scolobig 2012). In contrast, information is lost during the aggregation step in CIs and cost–benefit analysis, and CIs allow trade-offs between the different sustainability issues (Böhringer et al. 2007). These methodological assumptions are not necessarily major limitations, but careful consideration needs to be taken in constructing indices as well as features that planners and stakeholders must know and be aware of during the planning and decision-making.

CIs are becoming increasingly popular tools for sustainability assessments at various scales. This is because CIs can adopt participatory approach by involving stakeholders in different steps of CIs construction (e.g., indicator generation and weighting measurement). They are flexible to quantify a wide range of issues such as economics, environment, and conduct integrated assessment. CIs have attributes to follow the precautionary principles of assessment and consider subject to certain methodological choices during normalization, weighing, and aggregation as well as capture equity considerations, which largely depend on the choice of indicators (Lee 2006). CI has the ability to summarize multidimensional issues and provide a precise picture (Saisana et al. 2005). It evaluates sustainability performance in an innovative way (Singh et al. 2007), helps in setting policy priorities and monitoring performance (OECD 2008), and accelerates easy communication and interpretation to the public (Kondyli 2010). However, CI may send misleading policy messages if poorly constructed (e.g., lack of a representative set of indicators). In addition, CI may be misused to support a desired policy, if the construction process lacks a sound theoretical foundation. The construction of a CI is not straightforward, and an explicit conceptual framework (Fig. 1) is imperative. Figure 1 is constructed based on review of the literature (e.g., DFID 2003).

3 Research methods

3.1 Indicator development

Indicators are increasingly becoming a holistic and long-ranged strategic tool for sustainability evaluation. Nearly two decades earlier, researchers started to develop indicators for diverse disciplines using many of the indicator-generating methods, frameworks, approaches, and criteria at different levels. This perspective has been described as 'indicator explosion' (Riley 2001) and 'indicator zoo' (Pintér et al. 2005). However, there is a considerable debate regarding the effectiveness of the indicators. As an example, Pintér et al. (2011) opined that the recent economic and food crises indicate the inability of the indicators in diagnosing problems as well as providing early warning to take necessary preventive actions. This is partly a problem of methodological shortcomings. 'Author's appraisals' and 'expert judgments' are the most common methods for indicator generation. From the implementation perspective, indicator derived using the top–down approach might be difficult to apply at the local level (Binder et al. 2010). Conversely, indicators derived using the bottom–up approaches are usually easy to apply, but are sometimes not objective enough (Freebairn and King 2003). However, multi-stakeholder and multidisciplinary involvement has reflected positively on sustainability evaluation, and it has been reported that the results have been fit-for-purpose, efficient, and effective in decision-making and providing sustainable solutions (Roy and Chan 2012).

According to the above-mentioned understandings, the present study has adopted an assemblage of top–down and bottom–up approaches comprising four episodes, namely establishing the study context, information gathering and brainstorming, validation of the indicator by farmer's focus group discussion (FGD), and generation of the indicator. Initially, a review of the literature was carried out to get potential indicators, and then online surveys (Dillman 2006) employing the Delphi technique (Linstone and Turoff 2002) were administered to capture expert's opinions. Experts were selected based on distinct criteria, e.g., having 20 years of professional expertise on that particular issue. Two rounds of survey of experts were conducted, and questionnaires comprised of close- and open-ended questions that provided freedom for proposing new indicator of the three dimensions

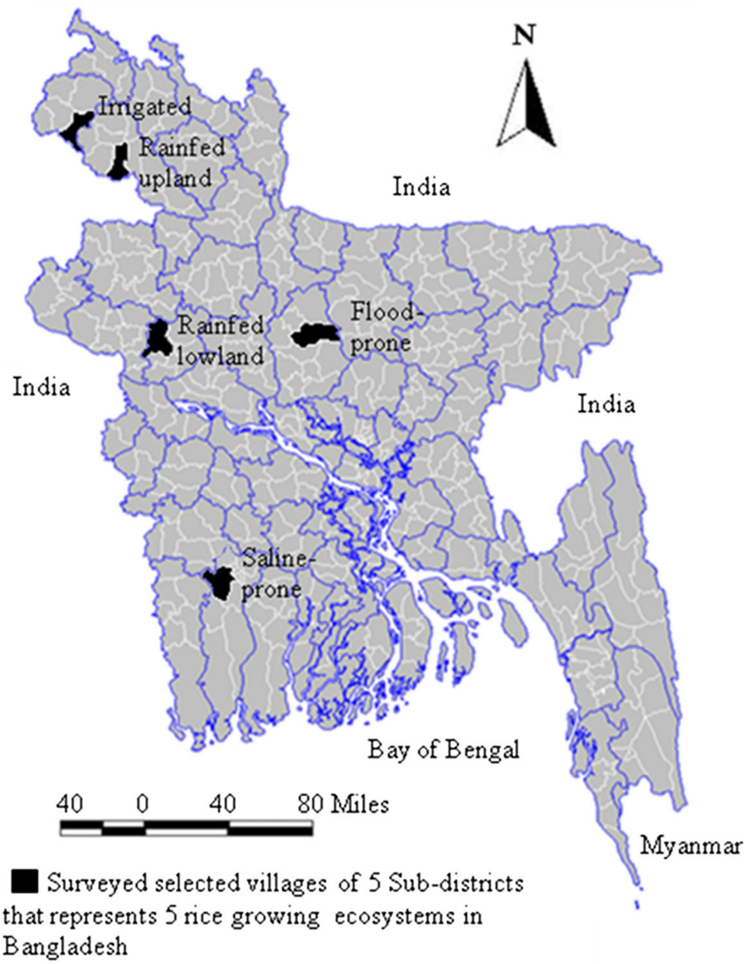

Fig. 2 Map of Bangladesh shows the location of five Sub-districts, namely Pirganj (irrigated rice), Dinajpur Sadar (rain-fed upland rice), Natore Sadar (rain-fed lowland rice), Ghatail (deepwater or flood-prone rice) and Dumuria (saline-prone rice) where farm households' data were collected

of sustainable rice farming. After achieving a satisfactory consensus of indicators, 10 FGDs (Bloor et al. 2001) were conducted with the growers of five rice-growing ecosystems, e.g., irrigated. The purpose of the FGDs was to evaluate the indicator's data availability, representative, and communicability. Finally, 12 indicators were derived for assessment. Methodological explanations on how and why a set of indicators were developed can be found elsewhere (Roy et al. 2013b).

Table 1 Brief description of rice-growing ecosystems

Name	Description	Yield
Irrigated	Irrigated rice is cultivated in dry season and is completely irrigated. In terms of yield and the total production this rice has higher contribution to livelihood than other rice. About 60 % of the country's rice area is irrigated and adoption of HYVs is around 94 % (Bhuiyan et al. 2004). It constitutes 40 % of the total land area	Yield: 4.0–4.2 Mt/ha
Rain-fed lowland	Rain-fed lowland ecosystem is mainly known as monsoon 'Aman' season rice, which is widely cultivated across the country. This rice is non-irrigated or partially irrigated. Aman season rice accounts for about 51 % of total land area in Bangladesh	Yield: 2.0–3.0 Mt/ha
Rain-fed upland	Rice of this ecosystem is characterized as rain-fed or partially irrigated, drought tolerant, broadcast or transplanted, short growth duration (105–110 days) and photoperiod insensitive[a]. Rice cultivation encounters unfavorable environmental conditions; particularly, it rains intensively with hot temperature at that time, and the intermittent intense sunlight makes favorable environment for pest, disease, and weed infestations. It constitutes nearly 7 % of the total land area	Yield: 2.0–2.4 Mt/ha
Flood-prone	This ecosystem[b] consist the depressed basins and lowland areas adjacent to rivers and the coastal areas. Flooding conditions vary from submergence of 1–10 days to stagnant water of varying depth for several months. It characterizes by a great diversity of growing conditions such as depth and duration of flooding and frequency and time of flooding. Rice of this ecosystem suffers from multiple constraints including biotic (e.g., tall seedlings) and abiotic (e.g., duration of submergence). It constitutes about 1 % of the total land area	Average yield: 1.5–2.0 Mt/ha
Saline-prone	About 400–950 million ha of land around the world (Lin et al. 1998) and 1 million ha in Bangladesh (Seraj et al. 2002) are affected by different levels (2- > 16 ds/meter) of salinity. Rice is one of the most suitable crops for saline soil[c]. Farmers usually grow 13 local rice varieties, namely Ashfall, Jotabalam in that soil. Low productivity, tasteless rice and immature rice grain are observed problems due to salinity. It constitutes approximately 1 % of the total land area	Yield: 2.0–2.2 Mt/ha

Source: Bhuiyan et al. (2004), MoA (2006b), Hossain (2009), BBS (2013), Roy et al. (2014)

[a] The timing of both the light and dark periods has little effects on the developmental responses of the rice plants

[b] Globally, the flood-prone ecosystem accounts for about 9 % of total rice lands but, in South and Southeast Asia countries including Bangladesh, flood-prone rice ecosystem represents about 25 % of total rice lands

[c] The soil where the salinity range is 4 dsys/m or more is termed saline soil

3.2 Study area and survey

This study was conducted in five Sub-districts, namely Pirganj, Natore Sadar, Dinajpur Sadar, Ghatail, and Dumuria (Fig. 2), which represent irrigated, rain-fed lowland, rain-fed upland, flood-prone and saline-prone rice-growing ecosystems (Table 1), respectively. The selection of the study area was based on two criteria: (1) in terms of yield (i.e., crop per unit area of land) and total production, the sub-districts are geographically recognized for rice cultivation area and (2) in terms of socioeconomic and biophysical condition, the areas exhibit general situation of the respective ecosystems (Agriculture Census 1996). Based on the ecosystems, districts, sub-districts, and villages were selected by applying a multistage random sampling technique. A total of 450 farm households were selected from 18 villages for household survey, and this sample size represents about 26 % of rice growers. Considering the number of sub-districts with different rice-growing ecosystems, 6 (2 × 3) villages were taken from flood- and saline-prone ecosystems and 12 (3 × 4) villages were from other 3 ecosystems. Following a random sampling method, 25 households were selected from each village by taking the proportional size of the farms into consideration, i.e., large, medium, and small. Detailed information on rice yield of per unit area, fertilizer use, agricultural information, cost and revenue of farming, and organization involvement was collected through the farm households' survey. The data were checked and cross-checked by multiple sources to obtain a complete and good quality data set. It was done by the following ways: Data collection was repeated when it seems that there were inconsistencies, and collected information was cross-checked by informal discussion with stakeholders.

Moreover, supplementary information was collected through observations and in-depth discussions with extension agents, input dealers, local leaders, NGO workers, and policy-makers. Secondary data were provided by the concerned sub-districts Agricultural

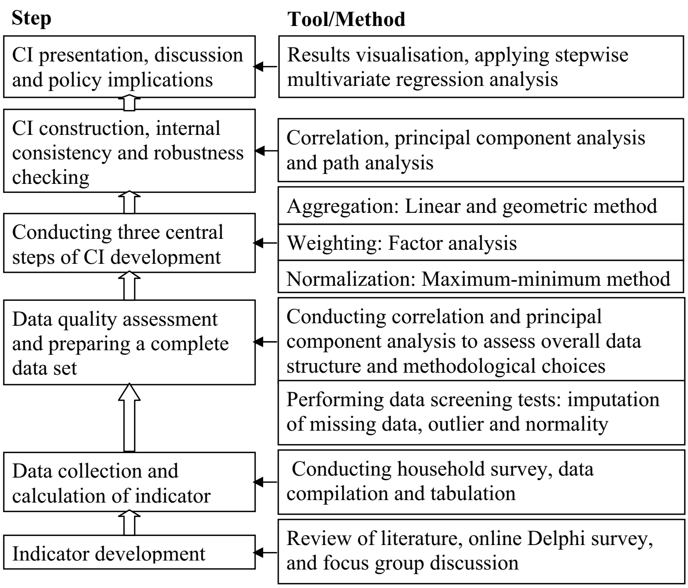

Fig. 3 Steps and tools employed for composite indicator (CI) development

Extension Office (AEO). Figure 1 presents the purpose of indicators and how they were measured. The majority of the indicators were measured following previous study such as following Rasul and Thapa (2004) where land productivity was measured by estimating the physical yield of rice per unit area, and yield data (HYV and local rice) were collected by survey as well as from the AEO. Expert opinion was taken to measure some of the indicators, e.g., equity. Equity measures farmer's opinion on how to distribute goods and services across society, particularly thinking on gender issues (Roy et al. 2014).

Sustainability is a multi-scalar concept that has both temporal and spatial dimensions. Spatial aspects were assessed by conducting a survey of on-farm rice-related information in five rice-growing ecosystems. Temporal aspects of sustainability are addressed by (1) utilizing 'systems of indicator' (Gómez-Limón and Sanchez-Fernandez 2010; Bell and Morse 2008) that approaches particular indicators (e.g., use of resource-conserving practices and technologies), which deal with problems of protecting and enhancing the environment at present and provide sustenance for future generations and (2) using time series data of rice yields for measuring indicators.

3.3 Data preparations

Figure 3 presents the construction process of CI. A good care was taken for maintaining data quality, which was accomplished in two ways, namely applying data-screening tests and bivariate and multivariate analysis to examine the overall structure and suitability of the data set for subsequent methodological choices. Two data-screening tests, namely outlier checking and normality of data set, were performed. The outliers were checked by observing z-score and dealt by employing the next highest score plus one, and the mean plus two standard deviations. The assumption of normality is important in research using regression analysis (Field 2009), for which, skewness and kurtosis value was estimated (Table 2).

Following data-screening tests, the correlation analysis was conducted to observe the interrelationships of the indicators. This method is a widely used statistical tool for confirming the mathematical design of index. The index is overwhelmed, confused, and implicit in communicating when there is a poor interrelationship among the indicators (OECD 2008). Correlation analysis showed that about 85 % indicators had moderate to high association between indicators. The results also indicated that multicollinearity was not a problem among the indicators. Moreover, it fulfilled the major assumption of principal component analysis (PCA), which is essential to investigate the multidimensionality of the data set (Nardo et al. 2005). Another important condition of PCA is sample adequacy, for which the Kaiser–Meyer–Olkin (KMO) statistic should be 0.60 or higher; otherwise, the application of PCA is questionable (OECD 2008). In our case, the KMO statistic was 0.68, and the other condition, namely the Bartlett's test of Sphericity, was satisfied. The PCA revealed that the indicators had five common components and explained 78 % variance of the entire data set. However, when we forced a desired structure of three dimensions, it accounted for 71 % of the variance of the full data set by using varimax rotation (see Saisana 2008 for details).

In fact, it is difficult to find acceptable explanations for the five components in sustainability evaluation of rice production systems. The significance, balance, and compactness of the three dimensions in sustainability assessment and management have been established in the literature (e.g., DFID 2003), and the decision was corroborated by expert opinions. Furthermore, pertinent measurement errors such as correlation (assumed not to be spurious due to representative sample) were overcome, and data qualities were managed

Table 2 Descriptive statistics of the indicators

Indicator	Min. Score	Max. score	Mean	SD	Skewness	Kurtosis
Land productivity (productivity)	2396.94	8297.10	4617.31	1617.38	0.787	−0.742
Benefit–cost ratio (BCR)	0.74	1.47	1.04	0.14	0.503	0.270
Input self-sufficiency (InputSufficiency)	0.37	0.70	0.54	0.07	0.023	−0.737
Pluriactivity	0.00	5.00	2.43	1.54	−0.479	−0.980
Integrated nutrient management (NutrientMgt)	6.00	26.00	13.56	3.31	0.365	0.188
Resource-conserving practice & technology (RCPracTech)	20.00	52.00	36.44	5.10	0.620	0.896
Cropping diversity (Cropdiversity)	0.20	0.89	0.62	0.13	−0.327	−0.395
Pest, disease, and weed management (PDWMgt)	7.00	18.00	12.01	2.49	0.060	−0.765
Education	2.00	16.00	9.50	3.65	−0.440	−0.502
Information availability and accessibility (InfoAvailAcess)	2.00	13.00	7.13	2.30	0.114	−0.437
Social capital (SCapital)	11.00	39.00	20.98	4.68	0.764	0.447
Equity	21.00	44.00	32.37	4.20	−0.361	−0.432

Abbreviated name of indicators name in the parentheses will be referred hereafter

by statistics. The observed features of PCA, such as indicators not being redundant, being partially overlapping, and not being entirely separable in each component, further reinforced our justification of the presence of three dimensions in data set.

3.4 Normalization, weighting, and aggregation

In general, indicators have different measurement units, and prior to data aggregation, it is required to remove the scale effects of units of measurement to render them comparable. Several normalization methods have been described, and the selection of suitable method depends on both data properties (e.g., the presence of extreme values) and theoretical foundations (OECD 2008). Considering the pros (e.g., simplicity) and cons (e.g., presence of outliers) of several normalization techniques, the 'max–min' normalization method was used (Eq. 1).

$$\mathrm{Ii} = \frac{x - \min(\mathrm{x})}{\max(x) - \min(x)} \tag{1}$$

where Ii is the normalized value of the individual indicator, x is the raw value of individual indicator, and max (x) and min (x) are the maximum and minimum value of x.

There is no consensus for the appropriate weighting method (OECD 2008). A number of subjective and objective weighting methods exist. However, each method has been reported to have several merits and demerits. Equal weighting (EW) is the most widely used method and has the risk of double counting (i.e., when two or more indicators partially measure the same behavior) and ignores the statistical and empirical basis, implying a judgment on the weights being equal (Nardo et al. 2005). From the policy perspective, public opinion-based weighting has been established. Although it is a legitimate choice, it is not unique and its arbitrary characteristic raises criticism. According to Munda (2007), these methods are justifiable only when there is a well-defined basis for national policy. With the development of statistical tools (e.g., PCA), weighting measurement is being frequently used because the statistical approaches are transparent, methodologically sound, unbiased, and thoroughly data-driven. Factor analysis (FA) was applied for weighting measurement (for details see Nicoletti et al. 2000).

Aggregation influences compensation among variables. Therefore, it is a very delicate part of the construction of an index that needs particular care. A number of aggregation methods exist, and the choice of a suitable method depends on the purpose of CI, and the nature of the subject is being measured. OECD (2008) reported that the aggregation technique is strongly related to the method used to normalize the raw data, and Zhou et al. (2006) found that the geometric aggregation technique results in the minimum loss of information between three commonly used aggregation techniques. Based on conceptual and methodological suitability, arithmetic average (Eq. 2) was used in this study to combine indicators within dimensions (to minimize measurement error and capture inconsistencies), and geometric average[3] (Eq. 3) was employed to combine the dimensions (to give more effort to improve those areas where it is relatively weak) (Saisana 2010).

$$\mathrm{RPSI} = \sum_{i=1}^{n} \mathrm{Ii} \cdot \mathrm{wi} \qquad (2)$$

$$\mathrm{RPSI} = \prod_{i=1}^{n} \mathrm{li} \cdot \mathrm{wi} \qquad (3)$$

where RPSI is the rice production sustainability index, Ii is the normalized individual indicator, and wi is the weight associated with individual indicator.

4 Assessing internal consistency of index

The goal of assessing internal consistency is to observe how far CIs are internally sound and consistent from a statistical and conceptual point of view. It is evaluated by PCA (Saisana et al. 2009), which identifies the statistical dimension of data set, and by correlation analysis between the index and its pillar. In the Methodology section, a brief discussion on PCA has been provided and the presence of three dimensions in PCA has justified by statistically (see the second paragraph of Sect. 3.3) and review of literature, e.g., DFID 2003. In addition, Table 3 shows the positive and moderately strong associations between the index (RPSI) and pillars, and that the correlation coefficient was >0.61. The index value had the highest correlation with social pillar, followed by economic pillar. The relationships among the pillars varied. The most closely associated ($r = 0.58$) was the environmental and social pillars, and the least association was observed between the economic and environmental pillar. This result implies that the pillars may account differently, somewhat partially, and may not be fully separable. Moreover, the positive correlation coefficient indicates that the three pillars and overall index measure are in the same direction. Furthermore, the associations between the index/dimensions and underlying indicators were all significant at 1 % level of significance and showed the expected sign (Table 4). These are the desirable features from the perspective of

[3] The geometric mean refers the central tendency of a set of numbers by using the product of their values. It is expressed as the nth root of the product of n numbers.

Table 3 Pearson's correlation coefficients for the index and its pillar

	Pillar		
	Social	Environmental	Economic
Rice production sustainability index (RPSI)	0.79	0.61	0.68
Pillar			
Social	1		
Environmental	0.58	1	
Economic	0.40	0.31	1

All coefficients are significant ($p < 0.01$, $n = 450$)

theoretical justifications, and their absence indicates the existence of trade-offs between the index and pillar.

5 Results

Figure 4 presents the result of sustainability assessment of rice production systems. The average sustainability index score was 0.44 in a scale from 0 to 1, signifying the least and most sustainable condition, respectively. Thus, the higher the index score, the lower is the possibility of the occurrence of grower's environmental degradation, economic loss, and deterioration of social circumstances. Irrigated system achieved the highest score (0.54), followed by rain-fed lowland (0.52), rain-fed upland (0.46), flood-prone (0.36), and saline-prone (0.34) system. At the pillar level, an indifferent picture was observed; for example, in terms of economic gain, the irrigated system outperformed (0.22), whereas the scores of other ecosystems were much lower, specifically, flood-prone (0.12) and saline-prone (0.11) system. In the case of social aspects, growers belonging to the irrigated, rain-fed lowland, and upland system were almost the same. In addition, rain-fed lowland system was more environmentally sound (0.18), followed by rain-fed upland (0.15) and irrigated (0.14) rice. However, growers of flood and saline-prone systems were in marginal condition in terms of gaining economic outputs, developing social aspects, and maintaining environmental soundness. Rice production of the irrigated system was fairly economically profitable[4] and socially progressive in terms of organization involvement, access to education, and others aspects.

The irrigated rice production system was found to be the most sustainable, which is also substantiated by Fig. 5. Specifically, more than half of the indicators of the irrigated system received higher score such as land productivity (5.21) and level of education (5.30). Growers belonging to rain-fed lowland system were the best in diversification of crop cultivation, and maintaining input self-sufficiency (i.e., the ratio of local inputs cost to the total inputs cost). In addition, in case of rain-fed upland system, growers were more judicious than others in applying non-chemical and chemical measures for pest, disease, and weed management, assumed to be efficient and environmentally non-degrading and applying resource-conserving practices (5.0). However, most of the indicators of flood- and

[4] The price of fertilizers, labor and rice was collected from the Sub-district Agricultural Extension Office and irrigation water price was taken from the Barind Multipurpose Development Authority (www.bmda.gov.bd), an organization that manages deep tube-wells in Bangladesh.

Table 4 Pearson's correlation coefficients between the index/pillars and the underlying indicators

Pillar	Indicator	Desired direction	Correlation with		Direct and indirect effect of indicator to index (%)
			Index	Pillar	
Economic	Productivity	+	.611	.776	**9.98**
	BCR	+	.473	.519	8.25
	InputSufficiency	+	.373	.557	7.00
	Pluriactivity	+	.487	.556	7.12
Environmental	NutrientMgt	+	.621	.612	**9.32**
	RCPracTech	+	.608	.524	**9.00**
	Cropdiversity	+	.372	.671	8.11
	PDWMgt	+	.310	.553	7.34
Social	Education	+	.715	.790	**10.00**
	InfoAvailAcess	+	.656	.801	8.25
	SCapital	+	.563	.866	**9.08**
	Equity	+	.516	.710	6.55

All coefficients are significant ($p < 0.01$, $n = 450$)

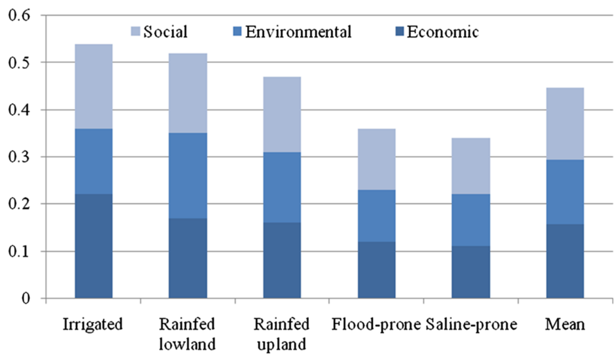

Fig. 4 Result of sustainability of rice production systems

saline-prone ecosystems achieved the lowest scores except farmer's 'education level,' and building 'social capital' indicator received fair scores in comparison with indicators belonging to other ecosystems. Irrespective of the production systems, several indicators had nearly the average score, such as equity and pluriactivity.

6 Assessing the total effect of the indicators on the index

By taking into account the correlation structure and regression coefficients, path analysis could identify direct and indirect effects of the individual indicator on the index (OECD 2008; Esty et al. 2005). The results (Table 4) show that the index score was not dominated by the small number of indicators, and that the contribution of the three pillars was approximately of the same magnitude (adding up the influences of respective indicators). Nearly 75 % of the indicators individually influenced the RPSI (by about 8 %), and five of

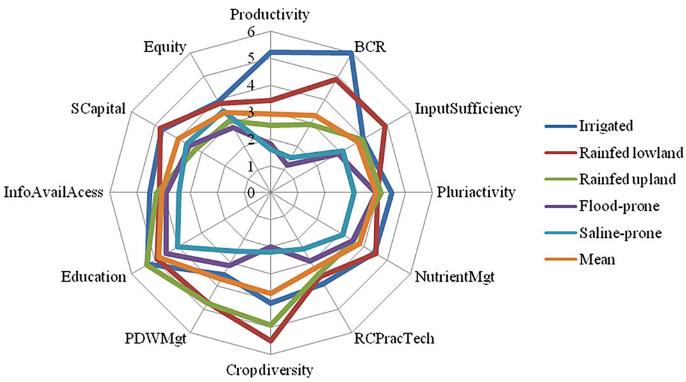

Fig. 5 Result (indicator level) of sustainability of rice production systems

them exceeded 9 %, such as land productivity (9.98 %) and education (10 %). It can be stated that (1) neither any pillar nor a single indicator dominated the RPSI; almost six indicators had a contribution of about 10 %, implying a balanced structure; (2) the index is internally sound and robust; and (3) the methodological choices such as normalization and others were hitherto legitimate. These results provide valuable insights for discussions.

7 Discussion

The index score (0.44 out of 1) signifies that 44 % of the growers of the five rice production systems were sustainable in terms of increasing economical viability, fostering environmental soundness, and promoting social development. According to the RPSI score, irrigated and saline-prone systems were the most and least sustainable (Fig. 4). This result is, in part, consistent with the national data; for instance, the irrigated rice area has been increased by 30 % over the last decade (BBS 2011). SAARC Meteorology Research Centre found that tidal level is increasing (means salinity also increasing) in the coastal areas, e.g., Hiron Point (4 mm/year)—a place of few kilometers away from Dumuria subdistrict (Rahman 2011). Rain-fed upland and lowland rice areas have been reduced by 39 and 21 %, respectively. It was observed from the discussions with the growers that they were overwhelmingly dependent on irrigated rice production for their income and household food security, due to productivity and production ability of irrigated rice. Besides, several initiatives of the government, specifically availability of chemical fertilizers, and high-yielding seeds, uninterrupted irrigation facilities, and rapid dissemination of urea deep placement technology, have helped growers to make a progress in irrigated rice production (Roy et al. 2013c). For example, from 1979 to 2001, the annual rate of an increase in irrigated area was over 4 % (MoA 2006b). This expansion has triggered the transformation of rice production from rain-fed and monsoon-dependent to irrigated and diversified systems.

Irrigated rice is more dependent on external inputs, which accrues the cost for irrigation and fertilization, but its per-unit return surpasses the cost. For instance, deriving from the survey, the average yields of irrigated rice was almost double than other ecosystems (Table 1). In addition, consistent with the findings of Sen (2004), survey results showed that area covered by modern varieties of irrigated, rain-fed lowland, and rain-fed upland were 96, 49, and 35 %, respectively. However, the figures for flood- and saline-prone ecosystems were much lower. These were about 13 and 10 %, albeit Bangladesh Rice Research Institute (BRRI) has developed 17 climate-resilient rice varieties such as submergence (e.g., BR52) and saline tolerant (e.g., BR47). These results fairly indicate the weakness of DAE, which is mainly responsible for crop-related information and technology dissemination at the farmers' level. This phenomenon was rather worse in the coastal areas where no official awareness and capacity building program to promote saline tolerant varieties were found (Sen 2004). In this case, the role of agricultural extension services is very crucial for creating awareness, educating, and leading for the change in resilient farming. Realizing the present context, overhaul of the extension system is not enough, but fundamentally, the approach of extension services should be changed from the agents/consultants to facilitators/supporters for farming sustainability transitions (Dogliotti et al. 2014).

Despite the fact that the growers of the irrigated rice production system were economically most viable, they were not environmentally sound in comparison with rain-fed lowland and upland rice (Fig. 4). It can be justified that the high dependency of the irrigated rice on external inputs negatively affects agro-environmental system such as deterioration of soil fertility, water pollution, and erosion of biodiversity (MEA 2005). A number of growers reported that a general conception regarding the irrigated rice production is 'more investment and more benefits.' Here, investment refers to the use of an increased amount of chemical fertilizers, pesticides, and herbicides. The environmental condition of flood- and saline-prone ecosystems is in fragile state due to the flash and tidal floods. Researchers (e.g., Mirza 2011) indicated that pluvial as well as fluvial flooding could increase in Bangladesh with climate change, and flooding is one of the major constraints to yield and crop production (Wassmann et al. 2009).

Salinity intrusion poses a serious threat to rice production in the coastal areas that constitute nearly 30 % of the cultivable land in this country (Hossain 2010). The largely harvested type rice 'rain-fed lowland' is commonly non-irrigated, when compared to irrigated rice and is less dependent on agrochemicals. Discussion with stakeholders revealed that: (1) this rice is less susceptible to pests, diseases, and weeds infestations; (2) it produces average yield using a minimal amount of external inputs; and (3) higher production of this rice is not strongly associated with increased amounts of external inputs application. These characteristics seem suitable for environmentally sound production to a partial extent. Rain-fed upland rice is almost dependent on natural spring and needs fewer amounts of fertilizers because it receives nutrients from previous irrigated rice crop. However, its cultivation period from April to August falls on adverse climatic conditions (i.e., raining and hot temperature) (Table 1). Consequently, increased amount of pesticides application hampers environmental qualities of farming systems and adds financial burden to farmers.

A common scenario observed in social dimension was that growers of irrigated, rain-fed lowland, and rain-fed upland ecosystems have near to average access to education, information, and social capital (Fig. 5), which indicates that a particular production system does not contribute to the development of the grower's communal issues to a large degree. However, growers who belong to the irrigated system were found to be one step ahead; their educational level was comparatively a little higher; they had access to agricultural information sources and were involved with organizations. All these factors contribute to increase in social development. Consistent with other research findings (World Bank 2008), it was found a greater association between education and sustainable rice production and development (Table 4). The grower's level of education is a highly influential indicator to promote this association. This phenomenon can be explained by the three present conditions: most of the farmers are less educated, public-funded agricultural extension service is ineffective, and very little opportunities exist for non-formal education. To approach farming sustainability transition, grower's literacy level, training, and empowerment are fundamental to develop their knowledge, skill, attitude, and decision-making in the adoption of rice farming innovation.

Like economical and environmental dimension, farmers of flood- and saline-prone areas were in marginal conditions owing to their poor socioeconomic background, least access to public services, and markets (Fig. 4). This country ranks sixth among the most vulnerable country to flood in the world (GoB 2010). About 20 % of the country's areas are experiencing flooding in every year due to its topography and position. It has been seen that the flooding becomes severe in almost an interval to 4–5 years. The floods brought a severe impact of different sectors and overall development, for instance, ADB (2004b) estimated that the total loss for the floods in 2004 was $2.2 billion or 3.9 % of GDP. The coastal districts encounter cyclones and salinity besides flooding; as a corollary, managing natural resources, cultivating rice (main crops in the coastal area), and livelihoods of coastal people are highly vulnerable to the confluence of these factors.

Consistent with the report by the MoA (2010), land productivity was found a vital issue for sustainable rice production. Bangladesh is a densely populated country with a growth rate of 1.59 % (2013 est.) per annum and has no scope for agricultural land expansion. Besides, agrarian land is shrinking primarily due to two reasons: (1) increasingly, agricultural land is being used for non-agricultural purposes such as urbanization and (2) land declines by riverbank erosion of major rivers, namely the Padma, Meghna, and Jamuna, and a large area is under water due to sea-level rise in the Southern part. Therefore, increasing land productivity is an urgent need for agricultural development and food security.

Nutrient management is found to be a contributing indicator of the sustainability of rice production. It is increasingly a growing concern that intensified use of agrochemicals has caused adverse impacts (e.g., eutrophication) on the quality of water (Mateo-Sagasta and Burke 2012). In Bangladesh, farmers use hazardous pesticides, such as Bashudin 10 G, which have already been banned in other countries (Parveen and Nakagoshi 2001). ADB (2004a) found agrochemicals (mainly mineral fertilizers) are the second vital sources of water pollution in Bangladesh, followed by industrial effluents. In this condition, integrated or combined nutrient management is essential to curb pollution, which increases farming productivity, enhances the biological, physical, and hydrological properties of soil, and promotes sustainable production.

The first objective of 'National Agricultural policy 2013' was 'to develop and harness improved technologies.' Undoubtedly, embracing technological advancement in this sector is significant to feed a growing population and achieve food security. However, the chosen technologies should be environmentally sound and socially feasible. Resource-conserving practices (e.g., crop rotations) and technologies (e.g., deep urea placement) have negligible adverse effects on environmental goods and services and lead to raise in the input use efficiency, enhance productivity, provide environmental benefits, and improve poor farmer's livelihood (Pretty et al. 2006). These practices and technologies have observed significant associations with rice production sustainability and hence are influential in fostering it.

Pretty (2009) stated that SA is a social learning process rather than a precise set of technologies. Findings reveal that effective involvement with local organizations serves several purposes for farming development: (1) it enhances social bonds and norms that reinforce social cohesion, mental landscape, mutualism, and confidence; (2) it creates an avenue for knowledge, idea, and technology generations, as well as stimulates members for sharing, comparing, prioritizing, and debating on innovation from the localized perspective to determine its relative importance, feasibility, compatibility, and applicability; and (3) it develops a channel for linkage, cooperation, and collaboration with other stakeholders such as NGO workers and civil societies.

A farm should be productive and profitable without the need for taking economic risk to make it sustainable (Gafsi and Favreau 2010). Benefit–cost ratio is the financial term that measures farming profitability, and in the present study, it was found to be a contributing indicator to the sustainable rice production system (Table 4). Poverty is a vital concern of farmers, and farming is a principal source of their income. It was realized that due to lack of hard cash during the peak season, many growers could not purchase quality seeds, adequate fertilizers, and irrigation, which hamper expected yield. Adoption of innovation involves cost and risks, and grower's financial conditions are always a dominant determinant in the innovation decision process (Rogers 2003). Therefore, non-farm income sources (i.e., pluriactivity) are an important impetus for adopting various sustainable approaches of farming, namely crop diversification and livestock integration into farming systems. The significances of non-agricultural income sources are strongly reflected in the country's Poverty Reduction Strategy Paper (Planning commission 2008) to accelerate growth and bring a pro-poor orientation in the sustainable socioeconomic growth process.

Irrigated rice was observed to be less self-sufficient with respect to inputs than rain-fed lowland, and this finding is consistent with that of Altieri (2000) who pointed out that the dependency on external inputs in sustainable production should be minimum. Indicators such as information availability and accessibility and equity were not significantly different from one system to another (Fig. 5). Similarly, the available sources of information and user access ability are a cornerstone for development because poor information has become the resource of poor in the world. In addition, from the survey, it was found that sustainability is possible if it addresses the core part of equality. Growers voiced their concerns about the issue of equality. However, most of them expressed their financial inability.

8 Policy implications

Besides drawing the significance of pluralistic agricultural advisory services, the following overall policy implications were drawn with rationale and practical reference for sustainable rice production in Bangladesh. Then rice-growing ecosystem-specific policy implication matrix is drawn in Table 5.

- Improve farmer's knowledge, skill, and capacity development to enable and prepare them to face the challenges of the twenty-first century.

In Bangladesh, farmers face enormous challenges of shortage of natural resources (BARC 2011). More investment is needed to improve the ability of growers for best management and decision-making in this country. The present study also found that the grower's level of education is the most contributing factor for sustainable production. The Commission on Sustainable Agriculture and Climate Change stresses the significance of knowledge management in combating future agrarian challenges (Beddington et al. 2012). Land and

Table 5 A policy implication matrix of sustainability of rice production systems

Ecosystems	Policy areas		
	Economic	Environmental	Social
Irrigated	Increasing non-farm incomes	Promoting integrated nutrient management Diversifying crop production	Increasing growers' human capital Promoting social capital
Rain-fed lowland	Improving local inputs (minimizing external inputs cost) Increasing land productivity	Disseminating resource-conserving practices and technologies Promoting integrated nutrient management	Increasing growers' human capital
Rain-fed upland	Increasing non-farm incomes Increasing land productivity	Promoting integrated pest, disease, and weeds management Disseminating resource-conserving practices and technologies	Increasing information availability and accessibility
Flood-prone	Increasing non-farm incomes Increasing land productivity	Promoting integrated nutrient management	Promoting social capital Increasing growers' human capital Increasing information availability and accessibility
Saline-prone	Increasing land productivity	Disseminating resource-conserving practices and technologies	Increasing growers' human capital Increasing information availability and accessibility Improving farming equity

Ecosystem-specific policy implications are deduced following the same procedure (path analysis) of deducing the overall policy implications (see Table 4)

water resource management-driven agricultural extension services and modern information systems can play a central role in farmer's capacity building.

- Increasing land productivity needs a multi-year planning and strategies.

In Bangladesh, land productivity is much lowered than other rice-cultivating countries, with no scope for horizontal expansion of agricultural land. Hence, effective initiatives are needed to increase productivity, such as increasing irrigation coverage, providing high-quality hybrid seeds, improving irrigation efficiency, minimizing yield gaps, and developing flood and salinity resistance rice varieties. World Bank (2008) recognized that increasing land productivity is one of the key strategies for improving the livelihoods of subsistence farming communities.

- Establish and support a feasible integrated or combined nutrient management for keeping the soil productive.

Nutrient management is a key issue for maintaining soil health. Most of the country's soils suffer from organic matter depletion (BARC 2011). Therefore, according to the findings of the present study, policy should give importance to integrated and mixed nutrients management. Government should reduce subsidies on urea fertilizer and introduce economic interventions on ideal form of balanced or mixed fertilizers, similar to that implemented in

West Bengal, India, where subsidies on a better mix of nutrients and cutting the old subsidy provision on urea have already been adopted (Anand et al. 2010).

- Disseminate and utilize existing resource-conserving practices and technologies and explore further environmental sustainability.

Achieving food security is a national mandate, and in the context of resource constraint, intensification of sustainable farming would be a potential solution. Resource-conserving practices and technologies not only increase production (NCB 2004), but also preserve and enhance land, biodiversity, and water resources (Singh et al. 2011). Hence, policies should pay attention to pervasive dissemination and utilization of resource-conserving practices and technologies. In that situation, price support, financial incentive, or giving direct subsidy to certain classes of farmers is a beneficial strategy. For instance, the Chinese government provides incentive and subsidy to farmers to stimulate the technology choices and adoption (IFAD 2010).

9 Conclusions

Sustainability evaluation is contested. However, an empirical evaluation is a better way to examine the key component, drivers, and essential actions that accelerate sustainability transition. Results of the study show 56 % of rice growers face several environmental, social, and economic challenges of rice production, and these challenges will be reasonably aggravated in the context of climate change. Presently, irrigated rice production is more sustainable than rain-fed, flood-prone, and saline-prone rice ecosystems, and concerted policy actions, as drawn above, can open more trajectories of sustainability of these ecosystems. Thus, it can be concluded that (1) farmer's knowledge, skills, and social networks development are imperative for fostering sustainable rice production; (2) there is still scopes for increasing land productivity; meticulous planning, strategies (e.g., narrowing yield gaps), and investments are required; (3) government patronization is needed for adopting site-specific, integrated, and mixed form of nutrient management that is key for long-term productivity of land; and (4) proper adoption of existing resource-conserving practices and technologies, and facilitating growers and local organizations to involve 'agricultural innovation system' are equally important.

Overall, demand-led, effective and efficient agricultural advisory services can play a leading role in resolving the multitude of challenges of rice growers. This study is based on a set of indicators, which were developed by employing participatory approaches. The exclusion of indicators related to particular environmental issue such as salinity and flooding is a limitation of this study, since indicators that represent five rice-growing ecosystems were chosen. The determination of an essential set of indicators of climate-smart farming and sustainability evaluation in the context of sustainable development and poverty alleviation is a potential area for future research.

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