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ABSTRACT

There is a close relationship among agriculture, economics, energy and the environment. A comparison was made between conventional and the system of rice intensification (SRI) methods of rice cultivation by conducting two experiments. One field experiment was conducted from 2013 to 2017 at 25 locations across India under the All India Coordinated Rice Improvement Project and another experiment was conducted in 2017 using surveys by collecting data from 262 randomly selected SRI farmers using a personal interview method in the Telangana state of India. The 5-year experimental data revealed that the SRI method of cultivation produced higher rice grain yield (up to 55%) compared to the conventional transplanting method. Survey data revealed that total costs of rice production reduced by 22.71% under SRI. Break even output under SRI was reduced by 58.1%. Adoption of SRI saved total energy inputs by 4350 MJ/ha. The energy productivities were 0.16 kg/MJ and 0.21 kg/MJ for conventional and SRI methods, respectively. Also, SRI resulted the lowest greenhouse gas emissions of 0.280 kg CO_2 e/kg rice grain. Therefore, for ensuring higher productivity, net returns, energy efficiency and sustainable rice production it is recommended to adopt an environmentally friendly SRI method of crop establishment in the Telangana region of India.

KEYWORDS
Crop establishment method; economic analysis; energy use efficiency; global warming potential; greenhouse gas emissions

Introduction

Rice is the staple food crop of India accounting for 40% of the total food grain production. At the global level, India stands first in rice area with 44 million hectares and second in rice production with 111.52 million tons (Ministry of Agriculture, 2018). Rice production needs to be increased to meet future food requirements amid strong competition for limited resources. The so-called ‘Green Revolution’ has provided enough food to meet the current country

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demand. However, concerns have been raised about sustainable rice production, yield stagnation and yield gaps. The gaps between the research station and farmer's fields still exist among various rice growing regions. The yield gaps indicate that the production levels in rice can be increased by bridging the gaps. There are several strategies to bridge the yield gaps and the System of Rice Intensification (SRI) method of rice cultivation is one of the promising approaches for achieving sustainable rice production and increasing food security of small-scale producers. Rice cultivation is in crisis the world over and India is no exception, with a shrinking production area, fluctuating annual production, stagnating yields and escalating input costs. The cost of cultivation of rice paddies has consistently been increasing owing to the escalating costs of seeds, fertilizers and labor. There is a need to grow more rice but with less water and fewer inputs. SRI originated in Madagascar in the early 1980s and the father of this invention is French Priest Henri de Laulanie. He wanted to find ways to enhance the rice productivity of Madagascan farmers who were obtaining rice yields of less than 2 t/ha (Gujja and Thiyagarajan 2009). SRI can increase farmers' rice yields while using less water and lowering production costs (WWF 2007).

Energy use in agricultural production has become more intensive due to the use of fossil fuel, chemical fertilizers, pesticides, machinery and electricity to provide substantial increases in food production (Tuti et al. 2014, 2013, 2012). Hence, energy efficiency has been crucial for sustainable development in agriculture systems. Efficient use of input energy resources not only saves fossil fuel resources but also provides financial savings (Singh, Singh, and Singh 2004). However, more intensive use has created some important human health and environment problems (Yilmaz, Akcaoz, and Ozkan 2005). The energy analysis in rice in general and SRI in particular is essential because of the direct link between energy and rice yields, and food supplies. Among the different indicators of crop performance, energy analysis is one of importance. Several studies have been conducted on energy analysis of rice in developed countries (Canakci et al. 2005; Cetin and Vardar 2008; Hatirli, Ozkan, and Fert 2005; Jianbo 2006; Kuesters and Lammel 1999; Ozkan, Kurklu, and Akcaoz 2004a; Pishgar-Komleh, Safeedpari, and Rafiee 2011; Tuyet et al. 2017). In India, there have been studies on the economics of various rice production technologies. However, comprehensive studies on energy analysis of rice in general and SRI in particular are not available in India. Energy use and energy efficiency analyses could help in comparing energy use at sectoral and operational levels in rice production. Agriculture is an important source of Greenhouse gas (GHG) emissions and is the second highest contributor (17.6%) of the total GHGs in India (Sahai et al. 2011). Agriculture indirectly accounts for another 9% of GHG emissions because it consumes one-fourth of the country's electricity output. Therefore, agriculture is considered one of the main sources of GHG emission in India (Jat et al.

2016). Adoption of SRI can reduce energy use, GHG emissions and global warming potential (GWP) in rice-growing areas of India. Further, for a cleaner environment a detailed study of GWP of this technology may add to the suitability for adoption among farmers. Therefore, economically and environmentally sustainable rice establishment methods are needed to replace the conventional methods of rice cultivation in India. Such a method of cultivation must be based on the knowledge of grain yield under different climatic conditions, economics, energy budget and GWP. Despite the dispute within the academic community, SRI has been disseminated to farmers in more than 40 countries, most in South and Southeast Asia. Although the exact area of adoption has not been officially reported, there is an estimate that SRI has been adopted on 750,000 ha in India, and 17,000 ha in Indonesia (Uphoff and Kassam 2008). A compilation of results from 11 surveys in 8 countries, including 16,000 SRI farmers, has shown, on average, a 47% yield increase, 40% water savings, 23% lower production costs, and 68% increase in farmer income, compared to conventional rice cultivation (Africare 2010; Sato and Uphoff 2007).

The present 5-year study was undertaken (i) to find a better rice crop establishment method for India by comparing SRI and conventional transplanting methods in terms of grain yield, (ii) to confirm/validate the best crop establishment method through surveys using a personal interview method, and (iii) to provide a detailed study to revalidate a better rice establishment method for higher yield, net returns, energy efficiency and low GWP rice production systems for India. We hypothesize that grain yield, profitability, energy ratio, specific energy, energy productivity, energy intensiveness, GWP and yield-scaled GHGs emission will vary between SRI and conventional transplanting methods. If the null hypothesis is rejected, we identify the best crop establishment method in terms of each of the said parameters.

Material and methods

Study site

Experiment-1

This agronomic study was conducted under the All India Coordinated Rice Improvement Project (AICRIP) during *kharif* (wet) season of 2013 (13 locations), 2014 (13 locations), 2015 (10 locations), 2016 (8 locations), and 2017 (12 locations) across India (Figure 1 and Table 1).

All the locations represent different agro-climatic conditions prevailing in each region. Every year several experiments are conducted through AICRIP at various locations of India. To study our objectives we have selected two treatments from those experiments that have similar growing conditions. The treatments were viz., T_1 – System of Rice Intensification and T_2 -

Figure 1. Experiment-1 conducted at various locations of India (from 2013 to 2017).

Manual transplanting in lines followed by crop management for puddled transplanted rice (Flooded rice system). The treatments were replicated thrice under respective experiments. The recommended fertilizer dose for each respective location was applied at the recommended time of applications. The management practices of SRI include the following points: (1) the age of seedlings at transplantation is less than 15 days (two to three leaf stage); (2) seedlings are transplanted with wide spacing, and one seedling per hill; (3) water management is undertaken to maintain paddy soils in mostly aerobic condition, e.g., by small daily applications of water with no flooding, alternate wetting and drying, shallow water management from panicle initiation to harvest, and also active soil aeration through mechanical weeding, and application of organic matter for improving soil structure and function as well as nutrient availability (Dobermann 2004; Thakur 2010; Thakur, Uphoff, and Antony 2010b; Tsujimoto et al. 2009).

All variables were analyzed following an RBD model. The least significant difference (LSD) test was carried out for analyzed mean square errors. The procedure provides for a single LSD value at 5%level of significance, which serves as a boundary between significant and non-significant differences

Table 1. Comparative grain yield (t/ha) performance under SRI and conventional methods of transplanting across different locations of India from 2013 to 2017.

S.No.	Location	SRI (t/ha)	Conventional method (t/ha)	% higher grain yield over conventional method
	2013			
1	Aduthurai	6.77	5.61	21
2	Chatha	3.03	2.62	16
3	Coimbatore	6.95	6.33	10
4	Khudwani	6.85	6.50	5
5	Mandya	6.69	5.61	19
6	Navsari	3.51	3.35	5
7	Nawagam	5.68	4.45	28
8	Patna	5.09	3.33	53
9	Raipur	4.68	3.97	18
10	Ranchi	4.59	4.29	7
11	Varanasi	7.36	6.81	8
12	Hyderabad	5.96	5.15	16
13	Arundhatinagar	9.48	6.11	55
	2014			
1	Aduthurai	5.27	4.34	21
2	Arundhatinagar	5.54	5.93	−7
3	Chatha	2.39	1.82	31
4	Coimbatore	6.51	5.83	12
5	Giridih	3.34	3.73	−10
6	Khudwani	4.96	4.74	5
7	Mandya	5.96	5.02	19
8	Navsari	4.2	4.11	2
9	Nawagam	5.61	4.83	16
10	Raipur	5.06	4.84	5
11	Ranchi	4.5	4.34	4
12	Wangbal	4.39	4.33	1
13	Hyderabad	5.93	5.12	16
	2015			
1	Aduthurai	5.29	4.34	22
2	Cuttack	5.68	4.64	22
3	Khudwani	5.83	5.72	2
4	Navsari	4.11	3.75	10
5	Nawagam	4.77	4.36	9
6	Patna	6.7	6.12	9
7	Raipur	4.77	4.39	9
8	Ranchi	4.76	4.13	15
9	Wangbal	4.17	4.19	−0.1
10	Hyderabad	5.6	5.00	12
	2016			
1	Chiplima	7.77	7.16	9
2	Gangavathi	4.43	4.03	10
3	Mandya	5.29	4.81	10
4	Puducherry	2.5	2.37	5
5	Pantnagar	4.58	4.73	−3
6	Samastipur	6.64	6.16	8
7	Ranchi	4.85	4.51	8
8	Raipur	5.34	5.49	−3
	2017			
1	Aduthurai	4.91	4.89	0.1
2	Arundhatinagar	5.68	4.89	16
3	Gangavathi	6.15	5.69	8
4	Ludhiana	6.91	6.49	6
5	Nagina	5.39	5.30	2
6	Pantnagar	5.23	5.23	0
7	Samastipur	6.28	5.62	12
8	Puducherry	5.97	5.62	6
9	Raipur	5.05	4.98	1
10	Rajendranagar	6.82	5.70	20
11	Moncompu	5.84	5.33	10
12	Varanasi	4.86	4.61	5

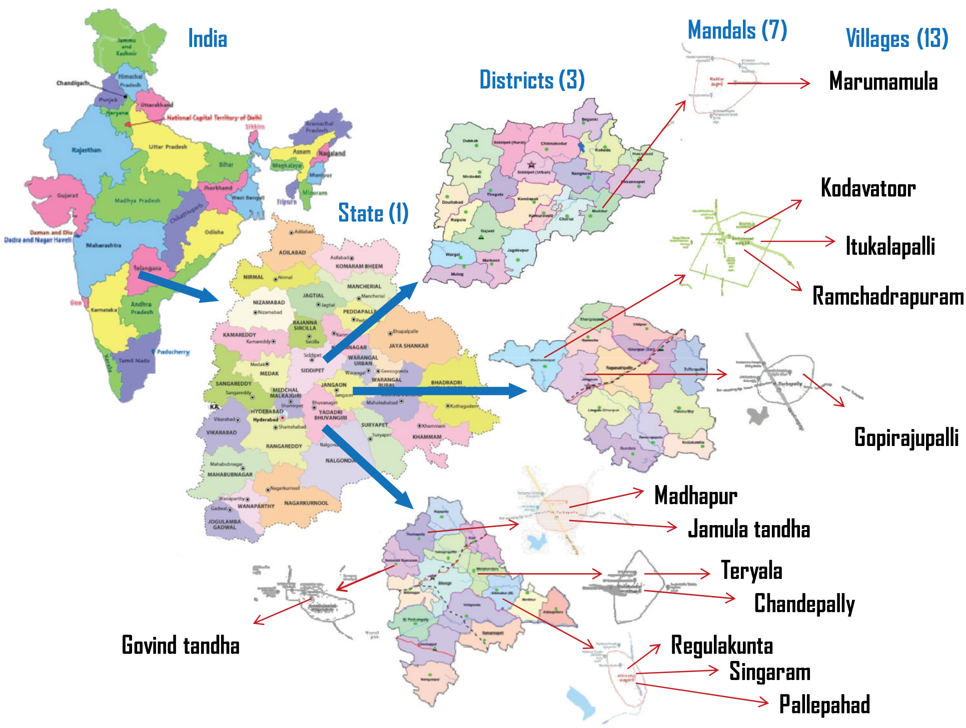

Figure 2. Map showing location of the survey.

between any pair of treatment means. Mean rice grain yields recorded at various locations from 2013 to 2017 are presented in Table 1.

Experiment-2

The study was undertaken in the Telangana State of India (Figure 2). A multistage sampling procedure was adopted in getting primary data from farmers. In the first stage, Telangana State was selected. In the second stage three districts viz., Yadadri Buvanagiri, Siddipet and Janagaon districts were selected. In the third stage, 13 villages were selected purposively for a total of 760 demonstrations on SRI conducted in these villages in *kharif* (wet) and *rabi* (winter) seasons during 2017–18.

These demonstrations were organized by the non-government organization (NGO), BLESS under its flagship program 'Food and Nutritional Security Project' with the technical expertise provided by scientists of each parent institute. Finally, the data were collected from 262 randomly selected SRI farmers in 2017 using a personal interview method. The collected data pertains to the *kharif* 2017–18. To determine the number of sample farmers to be approached for data collection, the Yamane method was applied. Yamane (1967) suggested the formula for calculation of sample size from a population. Sample size for the present study was determined by employing Yamane's formula for a 95% confidence level and e = 0 .05 as:

$$n = \frac{\mathrm{N}}{1 + \mathrm{N}(\mathrm{e}^2)}$$

where
N = Population under study
n = Sample size
e = margin error

To calculate the sample size, a permissible error of 5% within the confidence level of 95% was used. Therefore, the size of 262 was considered as sampling size and accordingly, 262 SRI farmers were selected randomly. Data from farmers who were growing rice by both the conventional method and the SRI method were collected through personal interviews. The sample farmers were selected in such a way that they grew rice both by conventional and SRI methods side by side on the same land area (some area under conventional method and some under SRI) during the same crop season under similar agro-climatic, biophysical, and socioeconomic conditions.

Economics of rice cultivation through conventional and SRI methods

The data on inputs used and output obtained were collected from the sample farmers. The cost of cultivation was worked out on a hectare basis in two parts, namely variable cost and fixed cost. Variable cost was based on the actual amount paid by the farmers and the prevailing cost in the region for human labor, hourly hiring charges for tractors, expenditure incurred for seed, manures and fertilizers, and pesticides. The prevailing bank rate of interest (7%) was used to work out the interest on working capital. Fixed costs were worked out based on the prevailing rental value of land, land revenue and interest on fixed costs. Interest on fixed costs was calculated in the same way as in case of interest on working capital at the bank interest rate of 10%. Returns were worked out based on the paddy and straw yield obtained and the price realized for the same during 2017–18. Break even analysis was carried out to assess the viability of paddy cultivation. Break-even output (BEO) is the output level at which the total revenue received by a farmer just matches the total cost incurred. It is computed at the hectare level using the formula:

$$\text{Break even output(kg/ha)} = \frac{\text{Fixedcost}}{\text{Price per unit} - \text{Variable cost per unit}}$$

$$\text{Break} - \text{evenprice(\$/kg)} = \frac{\text{Fixedcost}}{\text{Production volume}} + \text{Variable costs per unit}$$

Energy equivalents of inputs and outputs

The energy use efficiency of rice cultivation using conventional and SRI methods was evaluated by energy indices based on output and input source data collected through the farmer surveys. In the survey region, inputs for rice cultivation were human labor, machinery, Farm Yard Manure (FYM), chemical fertilizers, plant protection chemicals, herbicides, and electricity. Human labor was mainly used for transplanting, weeding, irrigation, FYM and fertilizer and pesticide application. Machine labor was used for land preparation and harvesting. The outputs were paddy grain and paddy straw. The quantity of various inputs used and the outputs were calculated per hectare, based on the information obtained from the farmers through the personal interviews.

For comparing the consumption of all inputs with each other and also with output, all of them should use the same units. By converting the amount of inputs and outputs to energy units we can more easily evaluate them (Ramedani, Rafiee, and Heidari 2011). Hence, the input and output data were multiplied by the corresponding coefficients of energy equivalents (Table 2) to calculate the total input and output energy per hectare.

Total energy input was calculated based on the energy inputs for various operations from primary tillage to harvest, and output was based on the grain and straw yield. These data were entered into Excel spreadsheets and energy indicators were calculated as follows:

$$\text{Energyefficiency} = \frac{\text{Total Energy Output}(\text{MJ}/\text{ha})}{\text{Total Energy Input}(\text{MJ}/\text{ha})}$$

Table 2. Energy equivalents of inputs and outputs in agriculture.

Particulars	Unit	Energy equivalents (MJ Unit $^{-1}$)	References
Inputs			
Human labor			
Men	H	1.96	Moradi, Azarpour, and Ziaeidoustan 2011
Women	H	1.57	Mohammadi et al. 2008
Diesel	L	51.33	Muhr et al. 1965
Electricity	Kwh	11.93	Gundogmus 2006
Farm machinery	H	62.7	Rafiee, Mousavi Avval, and Mohammadi 2010
Chemical Fertilizer			
N	kg	60.60	Mittal, Mittal, and Dhawan 1985; Devasenapathy, Senthilkumar, and Shanmugam 2009
P_2O_5	kg	11.10	Mittal, Mittal, and Dhawan 1985; Devasenapathy, Senthilkumar, and Shanmugam 2009
K_2O	kg	6.70	Mittal, Mittal, and Dhawan 1985; Devasenapathy, Senthilkumar, and Shanmugam 2009
Farm Yard Manure	Kg	0.3	Heidari and Omid 2011; Mousavi-Avval et al. 2011
Chemicals (Pesticide)	L	120	Erdal et al. 2007; Banaeian and Namdari 2011
Herbicide	L	85	Helsel 1992
Seed	kg	14	Kitani 1999
Output			
Paddy	kg	14.7	Ozkan, Akcaoz, and Fert 2004b, Alam, Alam, and Islam 2005
Straw	kg	12.5	Ozkan, Akcaoz, and Fert 2004b

$$\text{Energy productivity} = \frac{\text{Grain Yield(Kg/ha)}}{\text{Total Energy Input(MJ/ha)}}$$

$$\text{Specific energy} = \frac{\text{Total Energy Input(MJ/ha)}}{\text{Grain Yield(Kg/ha)}}$$

$$\text{Net energy gain(MJ)} = \text{Energy output(MJ/ha)} - - \text{Energy input(MJ/ha)}$$

$$\text{Energy intensiveness}\left(\text{MJ\$}^{-1}\right) = \frac{\text{Input Energy(MJ/ha)}}{\text{Total Production Cost(\$/ha)}}$$

Calculation of global warming potential (GWP) and greenhouse gas intensity (GHGI)

Environmental impact of conventional and SRI methods of rice cultivation was assessed by calculating the energy requirement and GWP. The GHG emissions (CO_2, N_2O, and CH_4) were estimated indirectly during crop production in terms of CO_2 equivalent. The CO_2, N_2O, and CH_4 were converted into CO_2 equivalent by using GWP equivalent factors of 1.0, 265 and 28 for CO_2 and N_2O and CH_4, respectively, for the time frame of 100 years (IPCC, 2013). The GHG emissions from farm operations (tillage, herbicide application, insecticide, planting and fertilizer application and harvest) and for the production of fertilizer and seeds were calculated by multiplying the input with its corresponding emission co-efficient (Lal 2004; West and Marland 2002). The CH_4 from rice cultivation and N_2 O emissions from applied nitrogen fertilizer, manure, and crop residue was calculated by the formula given by Tubiello et al. (2015) with some modifications. CH_4 emissions from rice cultivation were calculated as given below.

$$CH_4 \text{ emissions} = \text{EFxSF}_o\text{x(Aj+[AjxSFj])/10}$$

where

CH_4 Emissions (kg/ha/year) = Methane emissions from rice paddy

EF = Seasonal methane emission factor,10 g/m^2/year for India

Aij = Rice paddy area harvested, ha/year

SF_o = 1.4 correction factor for organic amendments

SFj = 0.7 scaling factor for Aj

Similarly, N_2O emissions were calculated based on nitrogen applied through synthetic fertilizer, manure, and crop residue:

$$N_2O \text{ emissions} = \text{NxEF}_1\text{x44/28}$$

where

N_2O emissions = N_2O emissions from synthetic nitrogen/manure, crop residue additions to the managed soils, kg N_2O/year

N = Consumption of nitrogen from fertilizers, manure, crop residue, etc., kg N input/year

EF_1 = Emission factor 0.01 for N_2O emissions from N inputs, kg N_2O-N/kg N input

Greenhouse gas intensity (GHGI) was estimated by dividing GWP by rice grain yield and is expressed as kg CO_2 e/kg rice grain yield (Pratibha et al. 2016).

Results

Experiment-1

Field experiment

In 2013, the highest rice grain yield was recorded at Arundhatinagar (9.48 t/ha) under the SRI method of cultivation, which was 55% higher than the transplanting method (Table 1). SRI resulted in higher grain yield than those under transplanting plots at all the 13 locations. A similar trend was also followed in 2014 except for two locations (Arundhatinagar and Giridih) where the SRI method yielded lesser grain yield (−7% and −10%, respectively) than those under transplanted plots. In 2015, all 10 locations recorded higher grain yield under the SRI method except at Wangbal. In 2016, all 8 locations recorded higher grain yield under the SRI method except at Pantnagar and Raipur. In 2017, the SRI method resulted in higher grain yield at all 12 locations.

Experiment-2

Demographic characteristics of sample farmers

The average family size of the surveyed households was five members per household (Table 3). The average age of sample farmers was 42.8 years. The

Table 3. Demographic characteristics of sample farmers *n = 262.*

Sl.No.	Particulars	
1	Average Family size	5
2	Mean Age of sample farmers (Years)	42.8
	<30 years	45 (17%)
	31–50 years	137 (52%)
	>51 years	80 (31%)
3	Education (Years of schooling)	4.5
4	Land holding size (ha)	0.98
	Marginal Farmers (<1hectare)	175 (67%)
	Small farmers (1–2 hectares)	79 (30%)
	Medium farmers (2–4 hectares)	8 (3%)
	Large farmers (>4 hectares)	0
5	Paddy area (ha)	0.76
	SRI method (ha)	0.34
	Conventional method (ha)	0.42
6	Experience in SRI (Years)	2

Table 4. Comparison of costs on inputs in SRI and transplanted method ($/ha).

Sl.No.	Inputs/operation	Conventional method	SRI	Difference(%)
1	Land preparation	186.05	167.44	−11.11
3	Seed	46.51	3.10	−1400
4	Transplanting	137.21	88.37	−55.26
5	Farm Yard Manure	21.77	22.55	3.48
6	Fertilizer	183.66	151.07	−21.57
7	Plant protection chemicals	30.69	17.17	−78.73
8	Weeding	124.03	81.40	−52.38
9	Harvesting	78.57	82.98	5.32
10	Interest on working capital	28.00	21.58	−29.72
	Total Variable Costs (A)	836.48	635.67	−31.59
11	Rental value of land	224.81	224.81	
12	Land revenue	0.87	0.87	
13	Interest on fixed capital	22.57	22.57	
	Total Fixed Costs (B)	248.25	248.25	
	Gross/Total costs (A + B)	1084.73	883.92	−22.71

majority of the sample farmers were middle-aged followed by young-aged, which indicates that young- and middle-aged farmers have a strong preference for adoption of new technologies such as SRI.

Education plays an important role in the adoption of innovations/new technologies. The education level (number of schooling years) was 4.5 years. The size distribution of landholdings showed that sample farmers had less than 1 ha (0.98 ha) of land for cultivation. The study found that 67% of sample farmers had less than 1 ha of land, thus belonging to the marginal farmers category. The farmers who belonged to small and medium categories were 30% and 3%, respectively. Data also shows that none of the selected sample farmers had large land holdings (>4 hectares).

Economic analysis

The fixed costs were the same for both the methods since the components of fixed costs, *viz.*, rental value of land, land revenue paid by the farmers to the Government and the interest on the fixed capital remain the same for both methods (Table 4). However, variable cost was higher in the conventional method (836.48 US$/ha) than the SRI method (635.67 US$/ha).

The Gross returns were US$ 1108.55 and US$ 1295.74, respectively, for conventional and SRI methods (Table 5). Higher Gross returns in SRI could be attributed to higher yield (5700 kg/ha) in SRI in comparison with the

Table 5. Comparative economics of rice production under SRI and transplanted methods.

Particulars	Conventional method	SRI
Yield (kg/ha)	4880	5700
Price ($/kg)	0.21	0.21
Gross Returns ($/ha)	1108.55	1295.74
Net Returns ($/ha)	23.82	411.82
BCR	1.02	1.46
Break Even Output (kg/ha)	5751	2409
Break Even Price ($/kg)	0.22	0.15

Table 6. Energy inputs and output in rice production.

Items	CM* (Qty**/ha)	Energy (MJ/ha)	%	SRI (Qty/ha)	Energy (MJ/ha)	%	Difference (%)
Seed (kg)	75	1050	3.4	5	70	0.3	−93.33
Human labor (hrs)							
Male	208.00	407.68	1.3	200.00	392.00	1.5	−3.85
Female	568.00	891.76	2.9	280.00	439.60	1.6	−50.70
Total human labor (hrs)	776.00	1299.44	4.2	480.00	831.60	3.1	−36.00
Machine labor (hrs)	23.45	1470.32	4.7	21.75	1363.73	5.1	−7.25
Diesel (l)	79.73	4092.54	13.2	73.95	3795.85	14.2	−7.25
Fertilizers (kg)							
N	181.65	11008.13		152.50	9241.50		−16.05
P	143.75	1595.63		102.97	1142.96		−28.37
K	33.05	221.41		9.10	60.97		−72.46
		12825.16	41.3		10445.43	39.1	−18.56
FYM (kg)	31200	9360	30.1	32325	9697.50	36.3	3.61
Pesticides (l)	6.18	741	2.4	3.50	420	1.6	−43.32
Herbicide (l)	0.61	51.85	0.2	0.62	52.70	0.2	1.64
Electricity (Kwh)	16.80	200.42	0.6	5.40	64.42	0.2	−67.86
Total energy input (MJ/ha)		31090.73			26741.23		−13.98
Output							
Grain	4880	71736		5700	83790		16.80
Straw	6344	79300		7410	92625		16.80
Total energy output (MJ/ha)		151036			176415		16.80

*CM: Conventional method; **Qty: Quantity

conventional method of rice production (4880 kg/ha). The Benefit Cost Ratio (BCR) which was obtained by dividing the gross returns per hectare by total cost of production per hectare for the conventional method of rice production was 1.02 and was lower than the SRI method (1.46). The Break-even output for both the methods of rice cultivation was worked out. Break-even output indicates the level of output that is required to cover the total costs, consisting of both fixed and variable costs. Total profit at the Break-even output is zero. The total revenue received by the farmers at the break-even output just matches the total costs incurred. The results revealed that Break-even output required for the conventional method was 5751 kg/ha, and this was reduced by 58.1% for the SRI method, with a break-even output requirement of 2409 kg/ha. Similarly, Break-even price was calculated for both methods of rice production. The break-even price represents the sales price that must be received for an output unit so that the revenues meet the expenses. It is the price point at which a product will earn zero profit. The Break-even price was higher for the SRI (0.22 $/kg) than that of the conventional method (0.15 $/kg) of rice cultivation, indicating that SRI is more profitable.

Energy analysis

The results revealed that the SRI method contributes to significant reduction in energy inputs in comparison to the conventional method (Table 6). Seed requirement in SRI is much lower (5 kg/ha vs.75 kg/ha). This resulted in a 93.33% reduction in energy input for seed with adoption of SRI. The

Table 8. Energy indices in rice production.

Item	Unit	Conventional method	SRI
Energy ratio		4.86	6.6
Energy productivity	kg/MJ	0.16	0.21
Specific energy	MJ/kg	6.37	4.69
Net energy	MJ/ha	119945.27	149673.77
Energy intensiveness	MJ/$	28.66	30.25

machine labor energy consumed was reduced by 7.25% in SRI. SRI contributes to reducing a significant amount of chemical fertilizers and pesticides. SRI contributes to a reduction of 19% in total energy consumed in fertilizers, within which energy consumption for N, P, and K is cut down by 16.05%, 28.37%, and 72.46%, respectively. Total chemical fertilizer applications in the SRI method decreased by 2378 MJ. Similarly, the energy consumed on pesticides decreased by 43.32%. The total energy output for SRI and conventional method were calculated as 176415 MJ/ha and 151036 MJ/ha, respectively. This was mainly because of higher yield in SRI (5.70 t/ha) than that of the conventional method (4.77 t/ha). A greater number of effective tillers per meter square in SRI results in more yield per unit area. The price realized was same for both methods, which implies that there was no effect on the grain quality. The quantity of straw harvested is 1.3 times the weight of rough rice; therefore, the straw contains a large amount of energy, which is much higher than the energy of paddy output. The energy output increased by 25379 MJ with adoption of SRI.

Operation-wise energy input analysis

It is evident that land preparation required the highest energy input, 4846.36 MJ/ha, which accounted for 75.39% for the conventional method and 4371.92 MJ/ha accounting for 76.72% of the total energy on various operations in rice cultivation (Table 7).

The second highest energy input-requiring operation was harvesting, accounting for 15.74% and 12.84% of the total energy of the various operations in rice cultivation in SRI and conventional methods of rice production, respectively. The operations weeding and transplanting accounted for 6.25% and 5.52%, respectively, in the conventional method, whereas they accounted for 3.58% and 3.97$ in the SRI method. It could be observed that adoption of the SRI resulted in a reduction of 11% of the total energy input of various operations in rice cultivation. Energy indices such as energy ratio for the conventional and SRI methods of rice cultivation were 4.86 and 6.6, respectively, indicating that SRI is a more energy efficient method of rice production (Table 8).

The energy productivity (the amount of rice produced per MJ of energy consumed) was calculated as 0.16 kg/MJ and 0.21 kg/MJ for conventional

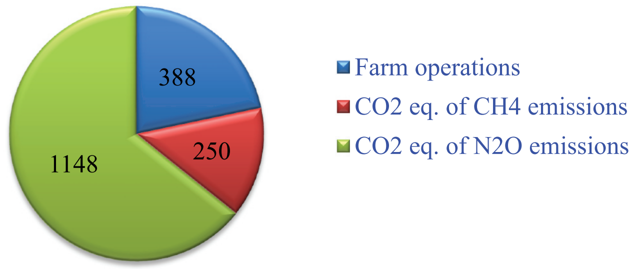

Figure 3. GWP (CO_2 e kg/ha/year) of conventional method of rice cultivation.

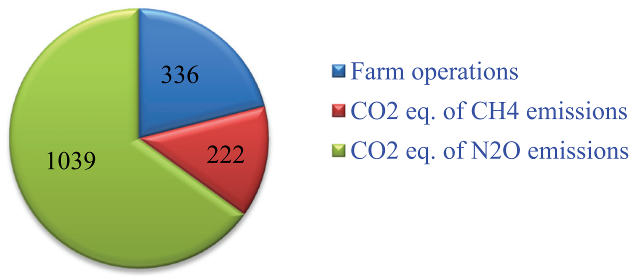

Figure 4. GWP (CO_2 e kg/ha/year) of SRI method of rice cultivation.

and SRI methods, respectively. Specific energy is an index which shows how much energy was used to produce one unit of disposable product. In this study, the specific energy for each method was calculated as 6.37 MJ/kg and 4.69 MJ/kg, respectively. For producing 1 kg of paddy, 6.37 and 4.67 MJ of energy was spent in the conventional method and in SRI, respectively. This means that each kilogram of paddy produced by the SRI method can save approximately 1.7 MJ compared with the conventional method of rice production. The energy intensiveness of rice production for conventional and SRI methods of rice production were 28.66 MJ/$ and 30.25 MJ/$, respectively.

Global warming potential (GWP) and greenhouse gas intensity (GHGI)

The SRI method of rice cultivation had lower GWP than the conventional method (Figs. 3 and 4). Farm operations, CH_4 and N_2O in the SRI method had lower GWPs of 336, 222, and 1039 CO_2e kg/ha/yr, respectively, than the conventional method (388, 250, and 1148 CO_2e kg/ha/yr, respectively). Energy consumption was the highest for manure and fertilizer application (Table 6). Therefore, GWP potential of these operations is also more than that of other practices. The data on GHGI (Figure 5) showed that the SRI method had the lowest GHGI (0.280 kg CO_2e/kg rice grain) as compared to 0.366 for the conventional method.

Discussion

Yield

The SRI method of crop establishment consistently (2013–17) resulted in higher grain yield compared to that of the conventional method across all the study locations in India. Thakur et al. (2010a) also reported 40% higher grain yield under SRI compared to that of recommended management practices. Better growth and yield parameters are likely to have contributed to the yield improvements registered with SRI and the same reason has been reported in many countries (Kassam, Stoop, and Uphoff 2011). Various individual practices associated with SRI management have already been identified as conducive for increasing rice yields under irrigated production systems, i.e., single seedlings/hill (San-oh et al. 2006), young seedlings (Menete et al. 2008; Pasuquin, Lafarge, and Tubana 2008), and moderate wetting and drying (moist) soil conditions (Wang et al. 2011; Yang et al. 2004; Yang and Zhang 2010; Zhang et al. 2009). With SRI the transplanting of young seedlings results in a prolonged period (by nearly 2 weeks) for more root development and tillering. Moreover, with young seedlings transplanting shock will be minimal, while greatly reduced plant density (25 in SRI vs. 150 plants/m^2 in the conventional transplanting method) favors the development of a distinctly different plant phenotype. These factors in combination contributed to the increase in rice grain yield under the SRI method of crop establishment.

Demographic characters

It may be concluded that the majority of the sample farmers were marginal farmers having less than 1 ha of agricultural land. Similar data of 44% marginal farmers in Husnabad Mandal, Karimnagar district of Telangana state in India was reported by Macharla and Lal (2017). This is due to the fact that in India, small and marginal farmers constitute about 82% of the total farm holdings. The other reason may be fragmentation of the holdings due to the nuclear family system. The average area was 0.34 and 0.42 hectares under SRI and conventional methods, respectively. The selected farmers had, on average, 2 years of experience in SRI.

Economics

Nursery seedlings required for 1 ha under SRI used 5 kg/ha seed as against 75 kg/ha for the conventional method. Hence, the expenditure incurred for seed was 3.1 USD as against 46.51 USD. The significant seed saving can promote seed multiplication rates, purity of seed (single seedling planting), and faster availability and spread of released varieties. It was observed that there was a reduction in costs of all inputs except FYM. The amount spent on FYM was a little high in the case of SRI as compared to the conventional method as more quantities of FYM are recommended for application in the SRI. The amount spent on harvesting was high in SRI, which could be due to more grain yield, which required more time using a hired combine harvester. The results of the study revealed that the total cost of production was US $1084.73 and US$883.92 for the conventional and the SRI methods, respectively, indicating that the adoption of SRI resulted in a reduction in total costs by 22.71%. Higher BCR indicates more profitability with SRI over the conventional method.

Energy analysis

Of all the energy inputs, fertilizers and farm yard manure had the highest share of the total energy inputs in both the methods of rice cultivation (Table 6). These results are similar to the findings of Kazemi et al. (2015) and Pishgar-Komleh, Safeedpari, and Rafiee (2011) who reported that the fertilizers had the highest share among all the inputs in rice production. Similarly, Aghaalikhani, Kazemi-Poshtmasari, and Habibzadeh (2013) also reported that chemical fertilizers were the second highest share within the total energy input in both conventional and mechanized methods of rice production. The energy input on labor was significantly reduced by 36% in SRI. This was mainly due to less labor involved for management of short duration nursery (8 to 12 days) (Reuben et al. 2016) as compared to the conventional method (25 days) and also less labor was required for transplanting single seedlings in SRI as compared to the conventional method (Satyanarayana, Thiyagarajan, and Uphoff 2007).

However, the energy consumed for FYM was slightly higher in SRI, mainly because of comparatively higher recommended application of FYM in the SRI method of cultivation. The herbicide applied was almost the same for both the methods. Truong et al. (2017) also found that the SRI method can save around 23% of energy inputs while increasing energy outputs by 11%. Total energy inputs were reduced by 4350 MJ. This is equivalent to approximately 0.104 tons of oil and 1210 kWh of electric power consumption saved. These results corroborate with the findings of Tuyet et al. (2017) who reported that the adoption of SRI could reduce energy inputs by 7429 MJ which is equivalent to approximately 0.18 t of oil and 2060 Kwhr electricity power consumption saved. Yadav et al. (2013) also reported that land preparation required the highest energy input in rice cultivation. Similar detailed discussion between

Table 7. Operation wise energy input in rice cultivation.

	Conventional method		SRI	
Operation	MJ/ha	%	MJ/ha	%
Land preparation	4846.36	75.39	4371.92	76.72
Transplanting	354.72	5.52	226.00	3.97
Weeding	401.92	6.25	204.00	3.58
Harvesting	825.18	12.84	896.93	15.74
Total	6428.18		5698.85	

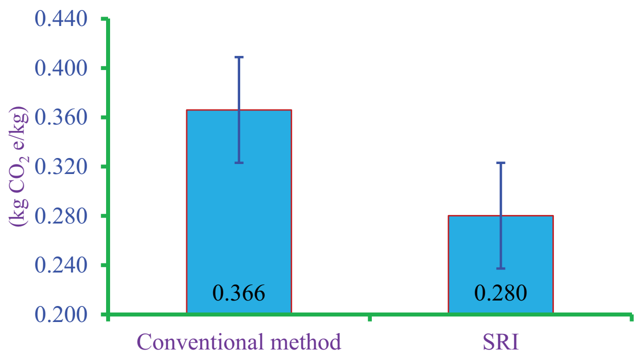

Figure 5. GHGI (kg CO_2e/kg of rice) of conventional and SRI method of rice cultivation.

mechanized SRI and conventional transplanting methods in India have been reported by Sudhakara et al. (2017).

Global warming potential

The GWP of both the methods of rice cultivation was assessed by estimating CO_2e emission from different agricultural operations (e.g., tillage, land preparation, manure, fertilizer, crop residue, irrigation, fossil fuel consumption) (Pryor et al. 2017). The CO_2e emission under both cultivation methods indicated a strong positive relationship with energy use, indicating that the amount of energy used under both methods is directly related to GWP of the respective form of operations (Pishgar-Komleh, Ghahderijani, and Sefeedpari 2012). Fertilizer N use and N_2O emissions were the two main emission sources of CO_2e (Gao et al. 2015). The SRI method requiring less fertilizer, irrigation, and minimal tillage has lower GWP. With low N fertilizer and reduced crop duration, the SRI method has a strong potential to reduce energy use and GWP while maintaining more net economic benefits than the conventional transplanting method. Further, the GWP from the SRI method can be kept low by following conservation practices on the basis of an energy budgeting approach for maximizing crop biomass, increasing N and water use efficiencies, decreasing N_2O emissions and building up SOC from the return of crop residues (Adviento-Borbe et al. 2007). Among the farm operations that can contribute to the reduction of emissions are the reduced use of fertilizer and increase in rice grain yield under the SRI production system. There is a strong need for energy efficient rice establishment methods that must reduce the GWP. Thus, the SRI method can reduce the dependence on fossil fuels and chemical fertilizers while promoting sustainability and a cleaner environment. Hence, it is imperative to design policies and incentives to expand and promote the SRI cultivation method especially in irrigated parts of India. Gathorne-Hardy et al. (2016) also reported that the SRI production systems offer substantial environmental benefits-reducing water and energy use by 60% and 74% per kg, respectively, reducing GHG emissions by 40% per kg, reducing reliance on nutrient inputs-as well as improving farmer returns by over 400% through increasing yields while reducing costs.

Conclusions

This five-year field experimentation at 25 locations across India followed by a survey of farmers conducted in the Telangana state of India, compared and contrasted the economics and energy efficiency between conventional and SRI methods of rice production. Rice production with the SRI method resulted in 55% (field experiments) and 17% (survey) higher grain yield thus producing a higher energy output of 176415 MJ/ha and net energy benefit of 149674 MJ/ha as compared to conventional practice. Higher energy use efficiency (6.6), energy productivity (0.21) and less specific energy (4.69) were also observed in the SRI method. The higher energy efficiency in SRI is due to a significant reduction in inputs accompanied by higher output. Adoption of SRI produced higher net returns (411.82 US$/ha) and BC ratio (1.46). Further, the SRI method had lower GHGI (0.280 kg CO_2e/kg rice grain) than 0.366 for the conventional method. Availability of labor in agriculture is declining. Hence, development of appropriate machinery for substituting or enhancing human energy is important for rice production. SRI can play an important role in improving agricultural productivity and sustainability, besides saving energy and reducing GHG emissions. In consideration of grain yield, net benefits, energy use, and GWP, the experiments and surveys reported in this study show that the SRI method of rice cultivation is a suitable system and strongly recommended for irrigated rice zones of India.

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References

Adviento-Borbe, M. A. A., M. L. Haddix, D. L. Binder, D. T. Walters, and A. Dobermann. 2007. Soil greenhouse gas fluxes and global warming potential in four high yielding maize systems. *Global Change Biology* 13:1972–88.

Africare. 2010. Oxfarm America, WWF-ICRISAT Project 2010. More rice for people, more water for planet. WWF-ICRISAT Project, Hyderabad, India.

Aghaalikhani, M., H. Kazemi-Poshtmasari, and F. Habibzadeh. 2013. Energy use pattern in rice production: A case study from Mazandaran province, Iran. *Energy Conversion and Management* 69:157–62.

Alam, M. S., M. R. Alam, and K. K. Islam. 2005. Energy flow in agriculture: Bangladesh. *American Journal of Environmental Sciences* 1:213–20.

Banaeian, N., and M. Namdari. 2011. Effect of ownership on energy use efficiency in water-melon farms: A data envelopment analysis approach. *International Journal of Renewable Energy Resources* 1:75–82.

Canakci, M., M. Topakci, I. Akinci, and A. Ozmerzi. 2005. Energy use pattern of some field crops and vegetable production: Case study for Antalya region, Turkey. *Energy Conversion And. Management* 46:655–66.

Cetin, B., and A. Vardar. 2008. An economic analysis of energy requirements and input costs for tomato production in Turkey. *Renewable Energy* 33:428–33.

Devasenapathy, P., G. Senthilkumar, and P. M. Shanmugam. 2009. Energy management in crop production. *Indian Journal of Agronomy* 54:80–90.

Dobermann, A. 2004. A critical assessment of the system of rice intensification (SRI). *Agricultural Systems* 79:261–81.

Erdal, G., K. Esengun, H. Erdal, and O. Gunduz. 2007. Energy use and economic analysis of sugar beet production in Tokat province of Turkey. *Energy* 32:35–41.

Gao, B., X. Ju, Q. Meng, Z. Cui, P. Christie, X. Chen, and F. Zhang. 2015. The impact of alternative cropping systems on global warming potential, grain yield and ground water use. *Agriculture, Ecosystems & Environment* 203:46–54.

Gathorne-Hardy, A., D. Narasimha Reddy, M. Venkatanarayana, and B. Harriss-Whitea. 2016. System of Rice Intensification provides environmental and economic gains but at the expense of social sustainability - A multidisciplinary analysis in India. *Agricultural Systems* 143:159–68.

Gujja, B., and T. M. Thiyagarajan, 2009. New hope for indian food security? The system of rice intensification: Gatekeeper: 143.

Gundogmus, E. 2006. Energy use on organic farming: A comparative analysis on organic vs. Conventional apricot production on small holdings in Turkey. *Energy Conversion and Management* 47:3351–59.

Hatirli, S. A., B. Ozkan, and C. Fert. 2005. An econometric analysis of energy input-output in Turkish agriculture. *Renewable and Sustainable Energy Reviews* 9:608–23.

Heidari, M. D., and M. Omid. 2011. Energy use patterns and econometric models of major greenhouse vegetable productions in Iran. *Energy* 36:220–25.

Helsel, Z. R. 1992. Energy and alternatives for fertilizer and pesticide use. In *Energy in world agriculture*, ed. R. C. Fluck., Vol. 6, 177–201. Amsterdam: Elsevier.

IPCC, Climate change. 2013. The physical science basis. In *Contribution of working group I to the Fifth assessment report of the intergovernmental panel on climate change*, ed. T. F. Stocker,

D. Qin, G. K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, and P. M. Midglev, 710–16, Cambridge and New York: Cambridge University Press.
Jat, M. L., J. C. Dagar, T. B. Sapkota, B. Govaerts, S. L. Ridaura, Y. S. Saharawat, R. K. Sharma, J. P. Tetarwal, R. K. Jat, H. Hobbs, et al. 2016. Chapter three: Climate change and agriculture: Adaptation strategies and mitigation opportunities for food security in South Asia and Latin America. *Advances in Agronomy* 137:127–235.
Jianbo, L. 2006. Energy balance and economic benefits of two agro-forestry systems in northern and southern China. *Agriculture, Ecosystems & Environment* 116:255–62.
Kassam, A., W. Stoop, and N. Uphoff. 2011. Review of SRI modifications in rice crop and water management and research issues for making further improvements in agricultural and water productivity. *Paddy and Water Environment* 9:163–80.
Kazemi, H., B. Kamkar, S. Lakzaei, M. Badsar, and M. Shahbyki. 2015. Energy flow analysis for rice production in different geographical regions of Iran. *Energy* 84:390–96.
Kitani, O. 1999. Energy and Biomass engineering. *CGIAR handbook of agricultural engineering*, Vol. V, 330. St. Joseph MI: ASAE Publication.
Kuesters, J., and J. Lammel. 1999. Investigations of the energy efficiency of the production of winter wheat and sugarbeet in Europe. *European Journal of Agronomy* 11:35–43.
Lal, R. 2004. Carbon emission from farm operations. *Environment International* 30:981–90.
Macharla, I., and B. S. Lal. 2017. Issues and problems of small and marginal farmer: A study in Karimnagar District. *International Journal of Academic Research* 4:203–10.
Menete, M. Z. L., H. M. van Es, R. M. L. Brito, S. D. DeGloria, and S. Famba. 2008. Evaluation of system of rice intensification (SRI) component practices and their synergies on salt-affected soils. *Field Crops Research* 109:34–44.
Ministry of Agriculture & Farmers Welfare, Govt. of India. 2018. Third advanced estimates of crop production.
Mittal, V. K., J. P. Mittal, and K. C. Dhawan, 1985. Research digest on energy requirements in agricultural sector. Coordinating cell, AICRP on energy requirements in Agricultural sector. Punjab Agricultural university, Ludhiana.
Mohammadi, A., A. Tabatabaeefar, S. Shahin, S. Rafiee, and A. Keyhani. 2008. Energy use and economic analysis of potato production in Iran: A case study: Ardabil province. *Energy Conversion and Management* 49:3566–70.
Moradi, M., E. Azarpour, and H. Ziaeidoustan. 2011. Study of energy indices for native and breed rice varieties production in Iran. *World Applied Science Journal* 13:137–41.
Mousavi-Avval, S. H., S. Rafiee, A. Jafari, and A. Mohammadi. 2011. Energy flow modelling and sensitivity analysis of inputs for canola production in Iran. *Journal of Cleaner Production* 19:1464–70.
Muhr, G. R., N. P. Datta, H. Shankaranbramoney, V. P. Levy, and R. L. Donahaue. 1965. *Soil testing in India*, 39–41. New Delhi: USAID.
Ozkan, B., H. Akcaoz, and C. Fert. 2004b. Energy input-output analysis in Turkish agriculture. *Renewable Energy* 29:39–51.
Ozkan, B., A. Kurklu, and H. Akcaoz. 2004a. An input-output energy analysis in greenhouse vegetable production: A case study for Antalya region of Turkey. *Biomass & Bioenergy* 26:89–95.
Pasuquin, E., T. Lafarge, and B. Tubana. 2008. Transplanting young seedlings in irrigated rice fields: Early and high tiller production enhanced grain yield. *Field Crops Research* 105:141–55.
Pishgar-Komleh, S. H., M. Ghahderijani, and P. Sefeedpari. 2012. Energy consumption and CO_2 emissions analysis of potato production based on different farm size levels in Iran. *Journal of Cleaner Production* 33:183–91.

Pishgar-Komleh, S. H., P. Safeedpari, and S. Rafiee. 2011. Energy and economic analysis of rice production under different farm levels in Guilin province of Iran. *Energy* 36:5824–31.
Pratibha, G., I. Srinivas, K. V. Rao, A. K. Shanker, B. M. K. Raju, D. K. Choudhary, K. S. Rao, C. Srinivasarao, and M. Maheswari. 2016. Net global warming potential and greenhouse gas intensity of conventional and conservation agriculture system in rainfed semi-arid tropics of India. *Atmospheric Environment* 145:239–50.
Pryor, S. W., J. Smithers, P. Lyne, and R. van,Antwerpen. 2017. Impact of agricultural practices on energy use and greenhouse gas emissions for South African sugarcane production. *Journal of Cleaner Production* 141:137–45.
Rafiee, S., S. H. Mousavi Avval, and A. Mohammadi. 2010. Modelling and sensitivity analysis of energy inputs for apple production in Iran. *Energy* 35:3301–06.
Ramedani, Z., S. Rafiee, and M. D. Heidari. 2011. An investigation on energy consumption and sensitivity analysis of soybean production farms. *Energy* 36:6340–434.
Reuben, P., Z. Katambara, F. C. Kahimba, H. F. Mahoo, W. B. Mbungu, F. Mhenga, A. Nyarubamba, and M. Maugo. 2016. Influence of transplanting age on paddy yield under the system of rice intensification. *Agriculture Science* 7:154–63.
Sahai, S., C. Sharma, S. K. Singh, and P. K. Gupta. 2011. Assessment of trace gases, carbon and nitrogen emissions from field burning of agricultural residues in India. *Nutrient Cycling in Agroecosystems* 89:143–57.
San-oh, Y., T. Sugiyama, D. Yoshita, T. Ookawa, and T. Hirasawa. 2006. The effect of planting pattern on the rate of photosynthesis and related processes during ripening in rice plants. *Field Crops Research* 96:113–24.
Sato, S., and N. Uphoff, 2007. A review of on-farm evaluation of system of rice intensification (SRI) methods in eastern Indonesia. CAB Reviews: Perspectives in Agriculture, Veterinary Science, Nutrition and Natural Resources, 2. Commonwealth Agricultural Bureau International, Wallingford, UK.
Satyanarayana, A., T. M. Thiyagarajan, and N. Uphoff. 2007. Opportunities for water saving with higher yield from the system of rice intensification. *Irrigation Science* 25:99–115.
Singh, G., S. Singh, and J. Singh. 2004. Optimisation of energy impacts for wheat crop in Punjab. *Energy Conversion and Management* 45:453–65.
Sudhakara, T. M., A. Srinvas, R. M. Kumar, T. Ram Prakash, and G. A. Rajanna. 2017. Energy saving and profitability of rice (*Oryza sativa*) under mechanized and conventional system of rice intensification. *Indian Journal of Agronomy* 62:57–62.
Thakur, A. K. 2010. Critiquing SRI criticism: Beyond scepticism with empiricism. *Current Science* 98:1294–99.
Thakur, A. K., S. Rath, S. Roychowdhury, and N. Uphoff. 2010a. Comparative performance of rice with system of rice intensification (SRI) and conventional management using different plant spacing. *Journal of Agronomic Crop Science* 196:146–59.
Thakur, A. K., N. Uphoff, and E. Antony. 2010b. An assessment of physiological effects of system of rice intensification (SRI) practices compared with recommended rice cultivation practices in India. *Experimental Agriculture* 46:77–98.
Truong, T. T. A., J. Fry, P. V. Hoang, and H. H. Ha. 2017. Comparative energy and economic analyses of conventional and system of rice intensification (SRI) methods of rice production in Thai Nguyen Province, Vietnam. *Paddy Water Environment* 15:931–41.
Tsujimoto, Y., T. Horie, H. Randriamihary, T. Shiraiwa, and K. Homma. 2009. Soil management: The key factors for higher productivity in the fields utilizing the system of rice intensification (SRI) in the central highland of Madagascar. *Agricultural Systems* 100:61–71.
Tubiello, F. N., R. D. Condor-Golec, M. Salvatore, A. Piersante, S. Federici, A. Ferrara, S. Rossi, A. Flammini, P. Cardenas, R. Biancalani, et al., 2015. Estimating greenhouse gas emissions in

agriculture: A manual to address data requirements for developing countries. Estimating Greenhouse Gas Emissions in Agriculture: a Manual to Address Data Requirements for Developing Countries. Food and Agriculture Organization of the United Nations, Rome. www.fao.org/publications.

Tuti, M. D., N. K. Hedau, J. K. Bisht, and J. C. Bhatt. 2014. Effect of organic and inorganic sources of nutrients on yield, economics, and energetics of pepper and soil properties in naturally ventilated polyhouse. *Archives of Agronomy and Soil Science* 60:1005–14.

Tuti, M. D., D. Mahanta, R. Bhattacharyya, B. M. Pandey, J. K. Bisht, and J. C. Bhatt. 2013. Productivity, economics and energetics of pigeonpea (*Cajanuscajan*)-based cropping systems in mid-hills of north–west Himalaya. *Indian Journal of Agronomy* 58:303–08.

Tuti, M. D., V. Prakash, B. M. Pandey, R. Bhattacharyya, D. Mahanta, J. K. Bisht, M. Kumar, B. L. Mina, N. Kumar, J. C. Bhatt, et al. 2012. Energy budgeting of colocasia-based cropping systems in the Indian sub-Himalayas. *Energy* 45:986–93.

Tuyet, T. A. T., F. John, V. H. Phu, and H. H. Hoang. 2017. Comparative energy and economic analyses of conventional and system of rice intensification (SRI) methods of rice production in Thai Nguyen province, Vietnam. *Paddy Water Environment* 15:931–41.

Uphoff, N., and A. Kassam. 2008. A critical assessment of a desk study comparing crop production systems: The example of the "system of rice intensification" versus "best management practice". *Field Crops Research* 108:109–14.

Wang, X., Y. Suo, Y. Feng, M. J. I. Shohag, J. Gao, Q. Zhang, S. Xie, and X. Lin. 2011. Recovery of 15N-labeled urea and soil nitrogen dynamics as affected by irrigation management and nitrogen application rate in a double rice cropping system. *Plant and Soil* 343:195–208.

West, T. O., and G. A. Marland. 2002. A synthesis of carbon sequestration, carbon emissions, and net carbon flux in agriculture: Comparing tillage practices in the United States. *Agriculture, Ecosystems & Environment* 91:217–32.

WWF. 2007. More rice with less water - system of rice intensification, World Wide Fund for Nature, Gland. www.panda.org.

Yadav, S. K., S. Babu, Y. Singh, G. S. Yadav, K. Singh, R. Singh, and H. Singh. 2013. Effect of organic nitrogen sources and biofertilizers on production potential and energy budgeting of rice (*Oryza sativa*)-based cropping systems. *Indian Journal of Agronomy* 58:459–64.

Yamane, T. 1967. *Statistics: An introductory analysis*. 2nd ed. New York: Harper and Row.

Yang, C., L. Yang, Y. Yang, and Z. Ouyang. 2004. Rice root growth and nutrient uptake as influenced by organic manure in continuously and alternately flooded paddy soils. *Agricultural Water Management* 70:67–81.

Yang, J., and J. Zhang. 2010. Crop management techniques to enhance harvest index in rice. *Journal of Experimental Botany* 61:3177–89.

Yilmaz, I., H. Akcaoz, and B. Ozkan. 2005. Analysis of energy use and input costs for cotton production in Turkey. *Renewable Energy* 30:145–55.

Zhang, H., Y. Xue, Z. Wang, J. Yang, and J. Zhang. 2009. An alternate wetting and moderate soil drying regime improves root and shoot growth in rice. *Crop Science* 49:2246–60.