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Sustainable bio-energy production models for eradicating open field burning of paddy straw in Punjab, India

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ABSTRACT

The mechanized harvesting of paddy crop has led into open field burning of paddy straw. Burning of million tonnes of paddy straw releases huge potent greenhouse gases which creates perturbations to regional atmospheric chemistry. This paper presents a case study on utilization of paddy straw for power generation through biomethane and bioethanol production on commercial scale and improved biomass cookstove on domestic scale. Three scenario (biomethane, bioethanol and pellet for improved biomass cookstove) have been compared for their energy economics and emission. It has been revealed that if paddy straw is not being burned, it can be effectively utilized for biomethanation and bioethanol production which can yield energy equivalent of 8.0 GJ/tonne and 5.6 GJ/tonne, respectively, while pelletized paddy straw can be used in improved biomass cookstoves to meet out thermal cooking energy requirement with reduced indoor air pollution. The analysis further revealed that biomethanation of paddy straw reduces net global warming potential by 2750 CO_2e kg emissions/tonne. However, bioethanol production showed net global warming potential reduction of 2549 CO_2e kg emissions/tonne. The pelletization of paddy straw for improved cookstove showed net global warming potential reduction of 2459 CO_2e kg emissions/tonne.

1. Introduction

Rice (*Oryzae sativa*) is most widely consumed crop after sugarcane (*Saccharum officinarum*) and maize (*Zea mays*) globally. About 740.995 million metric tonnes of rice was produced worldwide in year 2013–14. Asia is primary producer of rice with 90.1% share while India itself growing 1/5th of worlds total rice produce [1]. In India paddy is cultivated in about 43.95 million hectares producing about 106.54 million tonnes of rice and approximately 160 million tonnes of straw with a ratio of 1:1.5 for rice grain produced to straw produced [2,3]. The state of Punjab produced 11.27 million tonnes of rice with is 10.6% to all India's total production for the year 2013–14 and producing total of 16.90 million tonnes of paddy straw. Of the paddy straw produced some part is used as a fuel for modern biomass power plants, brick kilns, cardboard makings, mushroom cultivation and to fuel domestic biomass cookstoves in rural areas [4]. Portion of the paddy straw remaining uncollected in the fields due to combine harvesting are not burned and are eventually ploughed back into the fields which serve as beneficial manure for upcoming crops. Mulching of paddy straw in soil provide nutrients for upcoming crop, but this practice also conducts crop diseases and infect next crop quite repeatedly due to nitrogen immobilization. Flooded rice fields also adds up additional methane, a potential greenhouse gas produced by bacterial community under anoxic conditions [5–9]. But, due to surplus paddy straw and problem associated with its storage, farmers sell paddy straw at an uneconomical price of INR 500 ($ 7.50) per metric tonne [10] leading to nearly two–third of it being burned openly in the field to quickly prepare the field for sowing of next wheat crop [11–13].

Researchers suggested that open field burning of paddy straw contributes heavily towards harmful greenhouse gas (GHG) emissions including polycyclic aromatic hydrocarbons (PAHs) [14] as

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well as polychlorinated dibenzo-p- dioxins (PCDDs) and polychlorinated dibenzofurans (PCDFs), referred as dioxins [15]. Experimentally it has been evaluated that one tonne of paddy straw releases 3 kg particulate matter, 60 kg CO, 1460 kg CO_2, 199 kg ash and 2 kg SO_2 [16]. Local paddy straw burning affects the environment as these air pollutants have significant toxicological properties and are notably potential carcinogens [17]. This paper presents experimental evaluation of paddy straw utilization via two bioenergy routes *viz.* biomethanation for power generation and paddy straw pelletization for household cooking needs. Biomethanation of paddy straw has been explained by actual experimental data from a demonstration scale biogas power of capacity 3800–4000 m^3 biogas per day. As an alternative to cattle dung cake for cooking application, paddy straw pellets were made and its potential was experimentally validated at lab scale in micro gasifier based forced draft improved biomass cookstove. Further over citing huge potential of biogas from paddy straw, energy and cost–analysis of demonstration scale biomethanation process is presented. As a part of life cycle assessment of the bioenergy production from paddy straw via biomethanation, cooking fuel and bioethanol (while data for biomethanation and paddy straw pellet for cooking fuel were experimentally evaluated, bioethanol section was derived from literature), global warming potential of these technologies are presented to justify impact of these models on environment.

The quantum of energy utilized by a society is regarded as benchmark for social and economic development of the society. Punjab being an agrarian state of India there is an ever–growing requirement of energy and obtaining energy from fossil fuels is becoming difficult and expensive. Also, creating new non–renewable energy generation facilities involves relatively longer gestation periods [18]. Since renewable energy resources vary according to geographical conditions, bio–energy generation from paddy straw has very wide scope in Punjab state [19].

2. Material and methods

2.1. Characterisation of paddy straw

The collected paddy straw from biogas plant site was subjected to proximate and ultimate analysis. Proximate analysis determines the moisture content, total solid, volatile solid and ash content of the paddy straw. Proximate analysis of feed material was carried by standard method reported in APHA [20]. Ultimate analysis which determines the carbon, hydrogen and nitrogen contents of the feed materials, was performed using fully automated instrument 'Vario EL' elemental analyser (Make: Perkin Elmer, USA) [21]. The compositional analysis of paddy straw samples were carried out by the Biomass Research Laboratory, Indian Institute of Technology Delhi using standard method of P. J. Van Soest [22].

2.2. Anaerobic digestion of paddy straw

The anaerobic digestion technology is a most efficient way in term of energy output/input ratio for handling of biomass resources to produce energy and bio-fertilizer [23]. Biomethanation of paddy straw presented here consists of actual field experimental data taken from demonstration scale biomethanation plant at Fazilka district, Punjab, India [24].

2.2.1. Pretreatment of paddy straw

Paddy straw was received in bales from entire region of Fazilka, Punjab and were stored in the storage unit. Further, the paddy straw was manually spread over the width of belt conveyer, to be fed into the pulverisation unit, for its size reduction to a level of 3–5 mm. The average capacity of paddy straw pulverisation unit was 1.0 tonne/h. This unit was powered by an electric motor of 75.0 kW which consumes nearly 94 kWh energy per hour for 10 h operation. This unit also consists of a pulverised paddy straw collection system followed by an aspirator system for the collection of dust generated during the pulverisation process. The aspirator unit was powered through electrical motor of 30.0 kW which consumes 37.5 kW energy per hour of operation.

2.2.2. Anaerobic digestion

Biomethanation was carried out in, two anaerobic digesters of 3400 m^3 water volume capacity. The prepared paddy straw substrate was fed to two digesters through the feeding unit using pumps. No external heating source was provided in the digester as annual mean temperature in the area lies within mesophilic range. Loading rate was kept constant at 6.75 tonne VS/day to maintain 8–10% TS in the digester, while the digester was maintained at a hydraulic retention time (HRT) of 30 days based on previous work done by our group [25–27]. The digested slurry was passed through two horizontal solid–liquid separating machines (Make: WAM, Italy) with a slurry handling capacity of 8.0 m^3/h. The system was able to separate solid material at the rate of 600 kg/h with 65% moisture content. The separated liquid was recycled to prepare paddy straw substrate in blending tank.

2.2.3. Basic parameters of anaerobic digestion study

Table 1 shows initial parameters of conducting continuous feed anaerobic digestion of paddy straw. C/N ratio of the pretreated paddy straw was maintained by adding a nitrogen source such as azolla, urea and de-oiled rice bran at an optimum concentration to maintain C/N ratio equivalent to 20–25. The digester was fully charged with fresh cow dung for start–up and feeding of paddy straw was gradually started. The biogas production measurement was reported once cow dung fed initially was completely replaced by paddy straw. The volumetric biogas measurement was corrected at standard temperature and pressure condition (STP). The detail of theoretical calculations and procedures for measurements of biogas, methane and carbon dioxide production yields, specific biogas and methane production yields has been reported in our previous paper [21].

2.2.4. Hydrogen sulphide removal, power generation and grid feeding unit

Hydrogen sulphide in biogas has deleterious effects on gas engine which has to be reduced below 50 ppm for safer engine operation. Hydrogen sulphide removal was done using mixture of digested slurry and di–ammonium phosphate. Scrubber unit consists of a 5.5 kW electric motor to power a booster pump which pumps raw biogas through the scrubber unit. An electric motor having 5.5 kW power was used to circulate the digested slurry in the scrubbing unit. Total power consumption in hydrogen sulphide scrubbing unit was 11 kW which utilizes 13.75 kW energy per hour of operation. Power generation unit consists of 1.0 MW 100% biogas generator (Make: MWM, Germany). The generator produced

Table 1
Biomethanation parameters.

Sl. No.	Parameter	Particular detail
1	Operation cycle	Continuous
2	Hydraulic retention time (HRT)	30 days
3	Operating temperature	33–38 ± 1 °C
4	Adjusted C/N ratio	~ 20
5	Substrate concentration	
	Total solids concentration (TS)	10% (100.0 g/L)
	Volatile solids concentration (VS)	7.5% (75.0 g/L)

1.0 MW per hour electrical energy through a three phase 415 V alternator which was further fed into national power grid using a step-up transformer and grid feeder.

2.3. Paddy straw pellet for improved biomass cookstove

2.3.1. Pre–processing of paddy straw

Farm collected paddy straw biomass was dried and pulverised for pelletization. Paddy straw was air dried for 5 days followed by drying in hot air oven at 105 ± 1 °C for 12 h and pulverised [28]. Pulverised paddy straw was mixed with standard binder and pellets were made by pelletizer of capacity 100 kg/h.

2.3.2. Determination of calorific value of paddy straw pellet

Calorific value of paddy straw pellet was estimated using bomb calorimeter (Make: Rico Scientific Industries, New Delhi). 1.0 g pulverised paddy straw was weighed and pellet was made using manual screw press. The pellet was further subjected to standard procedure of estimation of calorific value using bomb calorimeter [28].

2.3.3. Determination of thermal efficiency of paddy straw pellet in cookstove

Water boiling test were conducted in laboratory for estimation of thermal performance of improved biomass cookstove fuelled by paddy straw pellet [28,29]. Thermal efficiency of cookstove was measured as a ratio of use full heat generated by the combustion of pellets in improved cookstove to the theoretically heat produced by complete combustion of a given quantity of pellet in the stove (based on the net calorific value of the fuel).

Hot air oven dried (105 ± 1 °C for 12 h) paddy straw based pellet were used as fuel for testing under standard laboratory conditions. Before commencement of the testing procedures moisture content of the pellet was calculated using infrared moisture analyser (Model: XM 60 – HR; Make: Precisa, Switzerland). Aluminium pot of diameter 260 mm and height 140 mm were used as cooking vessels for water boiling test. Each vessel was filled with 5 kg of water for experiments.

Thermal efficiency estimation was performed under laboratory conditions inside the fume collection hood as mentioned in previous literature by authors [28–30]. The velocity of air inside the duct was kept 2 m/s which allows collections of all the flue gases without interfering the normal combustion of the cookstove. 0.50 kg of paddy straw pellet were used for testing purpose in improved gasifier cookstove (Make: Oorja, India). K- Type thermocouples were used for water and flame temperature measurement.

2.3.4. Smoke emissions performance

The cookstove was tested for its emissions (CO, CO_2 and total particulate matter) simultaneously along with the testing of thermal efficiency. CO and CO_2 measurement was done by multi component gas analyser, Non-dispersive Infra-red (NDIR) based detector system (Make: Horiba, Japan). Measurement of CO and CO_2 values in ppm were performed using standard equations mentioned in previous literature [28–30]. Total particulate matter was monitored through the stack monitoring system (Model PEM-SMS 4; Make: Poltech, India) based on USEPA methodologies [28–30]. Experiments were repeated for six times to receive more reliable results.

2.4. Energy and cost benefit analysis

The energy balance and cost-benefit analysis for paddy straw biomethanation was performed by assuming biogas production chain from bailing, transportation, pretreatment and biogas production. In order to compare the each component an energy balance has been developed, based on the energy input of each step and the final output as biogas, respectively.

The cost-benefit analysis was performed based on the actual prices for bailing, transportation and pretreatment as input and per unit biogas sale price for cooking application and Si–rich manure in India. Further cost benefit analysis for paddy straw based biogas power project was estimated. Since, there isn't any paddy straw based ethanol fermentation plant successfully commissioned in India it was not feasible to calculate cost benefit analysis for the same. The energy input and costs for the biogas process and the pretreatment were calculated as kWh/tonne TS and INR/tonne TS.

2.5. Global warming potential

As a part of life cycle assessment of the technologies for utilization of paddy straw for bioenergy production, the global warming potential for biogas (power), improved biomass cookstove and bioethanol was calculated. Global warming potential (GWP) is an index defined as the cumulative radiative forcing between the present and a chosen later time ‘horizon’ caused by a unit mass of gas emitted now [31]. It is being used to compare the effectiveness of greenhouse gases to trap head in the atmosphere relative to standard gas, generally CO_2. The GWP for CH_4 (based on a 100 year time horizon) is 21 [32], N_2O is 310 [32], CO is 2 [33] and Particulates (PM) is 190 [34]. The GWP of the calculated GHG emission reduction was calculated using the following equation.

$$GWP = \{(CH_4 \times 21) + (N_2O \times 310) + (PM \times 190) + (CO \times 2) + (CO_2 \times 1)\}$$

2.6. Total energy yield

Total energy yield from paddy straw was estimated, based on total surplus paddy straw generation potential and yield of biomethane and bioethanol per tonne of dry paddy straw. Biomethane yield was experimentally evaluated which is based on actual data obtained from 1 MW paddy straw based biogas power plant while bioethanol yield was refereed from recent work by Soam et al. [35].

3. Results and discussion

3.1. Properties of paddy straw biomass

The proximate analysis revealed that untreated paddy straw contains up to 10.0% moisture and 90.0% total solids on wet weight basis, while 84.0% and 16.0% volatile solid matter and ash matter respectively, on dry weight basis. The ultimate analysis resulted into 40.00% carbon, 5.50% hydrogen, and 0.75% nitrogen contents on dry weight basis. Upon elemental analysis, it was found that the amount of nitrogen content present in rice straw biomass is very low, C/N ratio = 54.0. Compositional analysis of paddy straw revealed 39.90% cellulose, 24.0% hemicellulose and 5.6% lignin.

3.2. Methane production parameters

3.2.1. Cumulative biogas and methane production yields

10 tonne/d of paddy straw was pulverised and fed to anaerobic digesters which produced nearly 3800–4000 m^3 of biogas per day with methane and carbon dioxide content in the range of 50–55% and 40–45%, respectively. The hydrogen sulphide content in

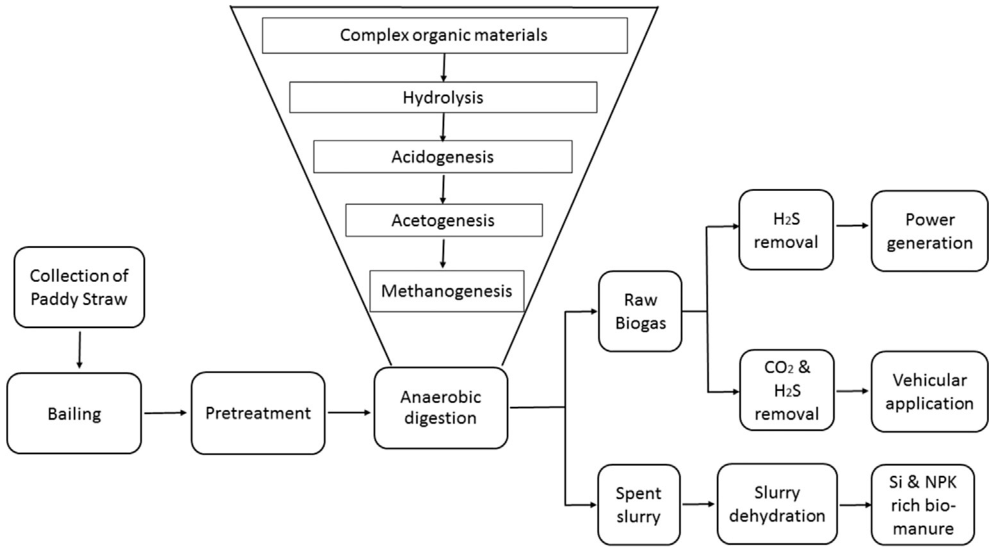

Fig. 1. Process flow diagram of biogas production from paddy straw.

produced biogas varied from 500 to 600 ppm. Average specific biogas production has been found in the range of 390–440 m^3/tonne of total solids fed to the plant. Specific methane production yield has been observed in the range of 200–220 m^3/tonne of total solids for standard operation of 12 months. Fig. 1 shows process flow diagram of paddy straw to biogas generation.

Table 2 below shows biomethane production from various other pretreatment routes. Maximum and minimum biogas generated per tonne of total solids in present case is 390 and 440 m^3 respectively after providing mechanical pretreatment for short duration, i.e., 5–10 min, while the maximum biogas production yield from literature said to be 479.4 m^3 after fungal pretreatment for 3 weeks.

3.2.2. Hydrogen sulphide removal

Hydrogen sulphide was removed from biogas before power generation unit using hydrogen sulphide scrubber. Scrubber contain 1 kg of di–ammonium phosphate mixed to 0.5 m^3 of biogas spent slurry. The biogas produced from anaerobic digesters was passed through this scrubber at a flow rate of nearly 500 m^3/h to reduce the concentration of hydrogen sulphide gas from the biogas. It is an essential requirement to reduce the hydrogen sulphide level in biogas below 50 ppm so that biogas can be used for engine operation. In this unit the hydrogen sulphide gets converted into ammonium sulphide and phosphoric acid with the help of DAP (di-ammonium phosphate) through recirculation of slurry. The obtained product is having a large potential application for rejuvenation of saline soils.

3.3. Energy and cost–benefit analysis of biogas production

For the energy balance calculations were made from the point of paddy straw pretreatment for biogas production. The energy needed for pulverisation, feeding, hydrogen sulphide scrubbing and slurry dewatering was taken as input energy of the system and the total energy output in the form of actual electrical power generation methane in the biogas plant was taken into account. The cost-benefit analysis calculations are based on the profits from selling electricity produced from the biogas and Si–rich manure and OPEX for operating biogas production processes.

From Tables 3 and 4, it is evident that conversion of paddy straw to biogas via pulverisation achieve a net positive energy of 655 kWh/tonne and cost benefit of INR 6916/tonne of paddy straw. Table 5 shows the cost benefit analysis for installation of such project over a period of 5 years. It is evident from the table that with a capital investment of 80.55 Million INR the project breakeven meets in between 3 and 4 year which makes paddy straw based biogas power project an economically positive project. The results obtained in this study is in agreement with the study Nguyen et al., 2016 which shows net energy output of 3400–3700 MJ/tonne of

Table 2
Biogas yield from paddy straw post different pre-treatments.

S. No	Pretreatment	Biogas Yield L/kg TS	Biogas Yield L/kg VS	Reference
1	*Pleurotus florida* cultivation for 40–45 day	148.00	–	[36]
2	*Pleurotus sajor–caju* cultivation for 40–45 day	110.00	–	[37]
3	Fungal pretreatment white rot fungus *Phanerochaete chrysosporium* for 3 weeks	479.40	–	[38]
4	Fungal pretreatment brown rot fungus *Polyporus ostreiformis* for 3 weeks	430.95	–	[38]
5	Mechanical milling (0.84 mm) followed by white-rot fungi pretreatment	147.70	–	[39]
6	Extrusion pretreatment with an ISR of 0.4	–	227.3	[40]
7	3% H_2O_2 for 7 days	–	319.70	[41]
8	3% NaOH for 120 h at 37 °C	–	184.80	[25]
9	5% NaOH for 48 h	375.84	–	[42]
10	Hydrothermal pretreatment for 10 min at 200 °C	–	315.90	[25]

Table 3
Energy analysis of paddy straw based biogas power production.

Unit	Power consumption (kWh/h)	Operating time, h	Total power consumption, kWh/10 tonne
Energy input			
Paddy straw pretreatment (pulverisation)	94.00	10.00	940.00
Substrate feeding unit	23.00	10.00	230.00
Hydrogen sulphide scrubbing unit	13.75	10.00	137.50
Bio-fertilizer unit	13.75	10.00	137.50
Total energy input (kWh)			1445
Energy output (kWh)			8000
Net energy gain (kWh)			6555
Output/Input			5.5

Table 4
Cost–benefit analysis of paddy straw based biogas power production.

	INR/10 Tonne paddy straw	Rate (INR/Unit)
Output electricity (8000 kWh)	60000	7.5. kWh
Bio-fertilizer (5.0 t)	35000	7.0/kg
Input		
Paddy straw cost	−15000	1500/ton
Paddy straw pretreatment (pulverisation)	−7050	
Substrate feeding unit	−1725	
Hydrogen sulphide scrubbing unit	−1031	
Bio-fertilizer unit	−1031	
Net benefit	69163	
Output/Input	3.6	

paddy straw. They revealed that the use of rice straw for biogas production can generate a positive net energy balance of between 70% and 80% [43].

This shows that pretreatment of paddy straw is necessary to reap higher methane yield. The pretreatment followed by bio-methanation will enable the economically competitive use of paddy straw for energy generation. This will lower the negative environmental impact during burning of paddy straw in open fields.

3.4. Total energy yield

It is evident from Table 6 that total obtainable energy yield from biomethanation route is 30% more than bioethanol route. If all the surplus paddy straw biomass which accounts to 11.70 MMT in Punjab is brought to biomethane production it will produce energy equivalent to 2.238 Mtoe and upon converting it to bioethanol it will produce give energy equivalent to 1.564 Mtoe. Additionally biomethanation process provides Si–rich manure for cultivation of paddy crop.

3.5. Paddy straw pellet performance in improved biomass cookstove

Thermal effitpgoto "ciency of the improved biomass cookstove was found to be 36.11 ± 0.38% when fuelled by paddy straw pellets which is equivalent when same stove is fuelled with other fuels. Emissions were calculated on total CO_2 equivalent per tonne of paddy straw pellet fuelled in aforementioned biomass cookstove. Fig. 2 presents the trends in thermal efficiency during laboratory testing and CO_2 equivalent emissions when 1 tonne paddy straw pellets will be combusted in improved cookstove. The average value for CO_2 equivalent was found to be 648.76 kg/tonne of paddy straw pellet. The value shows significant decrease in emissions when compared to CO_2 equivalent emissions from burning 1 tonne

Table 5
Estimate of the capital and operating cost and profit for the paddy straw based biogas operated power generation plant.

Entity	Unit		1st Y	2nd Y	3rd Y	4th Y	5th Y
Capital cost (CAPEX)							
Digester	M INR	29.05	0.00	0.00	0.00	0.00	0.00
Scrubber, compressor, storage and piping	M INR	6.50	0.00	0.00	0.00	0.00	0.00
Biogas generation system	M INR	30.00	0.00	0.00	0.00	0.00	0.00
Pumps, heat exchanger, slurry dehydrator and control system	M INR	10.00	0.00	0.00	0.00	0.00	0.00
Land preparation and building expenses	M INR	5.00	0.00	0.00	0.00	0.00	0.00
Total Capital Cost	M INR	80.55	0.00	0.00	0.00	0.00	0.00
Operational cost (OPEX)							
Paddy straw requirement	kg/m^3		4	4	4	4	4
Annual feed requirement	MT		5600	5600	5600	5600	5600
Paddy straw cost	INR/MT		1500	1575	1654	1736	1823
Annual feed cost	M INR		8.40	8.82	9.26	9.72	10.21
Transportation cost	INR/MT		150.00	158.55	167.59	177.14	187.24
Annual transportation cost	M INR		0.84	0.89	0.94	0.99	1.05
Operation and maintenance	M INR		8.00	8.46	8.94	9.45	9.99
Total operational cost	M INR		17.24	18.16	19.14	20.16	21.24
Annual profit							
Electrical power	M INR		17.62	18.06	18.51	18.97	19.45
Organic manure	M INR		19.60	21.56	23.72	26.09	28.70
Total annual sales	M INR		37.22	39.62	42.23	45.06	48.15
Total annual OPEX	M INR		17.24	18.16	19.14	20.16	21.24
Net profit	M INR		19.98	21.46	23.09	24.90	26.90

M INR is stands for million Indian rupees.

Table 6
Biomethane and bioethanol potential of paddy straw.

S. No.	Energy route	Yield/ton paddy straw (kg/t)	Total energy yield (GJ/t)	Electricity equivalent[a] (kWh/t)	Petrol equivalent (L/t)
1.	Biomethane	144.32	8.000	777.00	166.60
2.	Bioethanol	188.57	5.600	544.25	116.60

[a] Power generation efficiency is 35.0%.

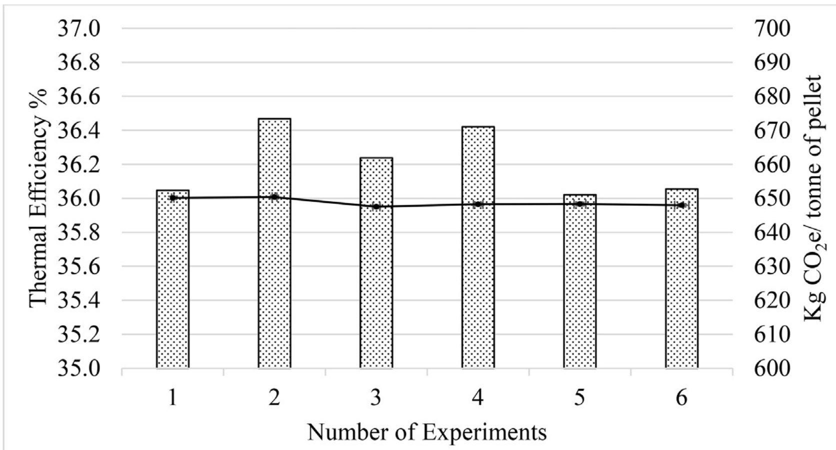

Fig. 2. Thermal efficiency and emissions as kg CO_2e/tonne of paddy straw pellet in improved biomass cookstove.

of paddy straw in open field which comes to be 2150 kg CO_2e/tonne as mentioned in Table 6.

3.6. Global warming potential

The greenhouse gas emissions in term of kg CO_2e/tonne of paddy straw is presented in Table 7 below. Emissions from open field burning was considered to be a base case and accordingly calculations were made for each activities. It was found that 1 tonne of paddy straw if diverted from burning in open field can produce 8 GJ for biogas, 5.6 GJ for ethanol (refer Table 6) and 5.0 GJ when used as paddy straw pellet with 36% biomass cookstove efficiency. The system boundary taken into considerations while making calculations is depicted in Fig. 3.

Global warming potential of all three technologies as mentioned in Table 7, suggests that significant emissions can be controlled by diverting paddy straw from open field burning. Since all three routes mentioned here have nearly same net GWP,

Table 7
Impacts on global warming potential (kg CO_2 e/tonne paddy straw) for biogas, paddy straw pellet and bioethanol.

	Biogas (Power)	Paddy straw pellet (cookstove)	Bioethanol
CO_2e emissions (in kg) for activities (for 1.0 tonne of paddy straw)			
Bailing[a]	165.00	165.00	165.00
Transportation (15 km)[b]	14.35	14.35	14.35
Paddy straw pretreatment[c] (pulverisation)	81.78	81.78	81.78
Substrate feeding unit[c]	20.01	N/A	N/A
Hydrogen sulphide scrubber[c]	11.96	N/A	N/A
Biofertilizer unit[c]	11.96	N/A	N/A
Pelleting[c]	N/A	78.00	N/A
Dilute acid pretreatment[d]	N/A	N/A	32.00
Milling and enzymatic hydrolysis[d]	N/A	N/A	32.00
Fermentation and distillation[d]	N/A	N/A	8.00
Total GHG emissions (kg CO_2e/ton PS)	305.06	339.13	333.13
GHG Credits			
Avoidance of open field burning	−2150	−2150	−2150
Electricity	−870	N/A	N/A
Emissions from cookstove	N/A	−648	N/A
Vehicular emissions from ethanol	N/A	N/A	−377
Emission from petrol vehicles	N/A	N/A	−355
Total GHG credits	−3020	−2798	−2882
Net GWP	−2715	−2459	−2549

[a] kg/tonne CO_2e emissions for bailing paddy straw is taken from a document of International Rice Research Institute Database [44].
[b] kg/km CO_2e emissions for tractor is calculated by calculating total diesel consumption in unloaded and 1.0 tonne load conditions [43,45].
[c] kg/kWh of CO_2e emissions are calculated using CO_{2e} emission factor 0.87 kg/kWh. Power consumption of these units are mentioned in Table 3.
[d] kg/tonne CO_2e emission estimations are based on literature data [35].

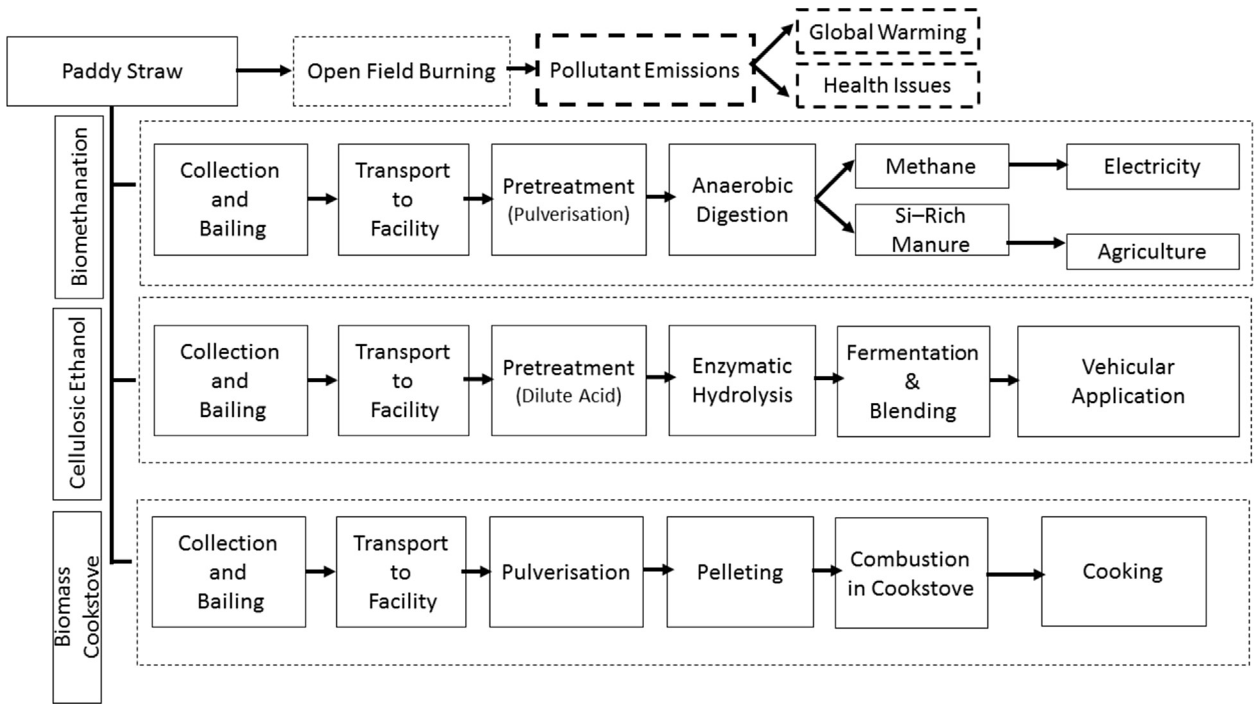

Fig. 3. System boundary of paddy straw utilization for energy generation in this assessment.

these technologies has to be used based on requirement since one technology can't be the solution provider for mitigating open field burning.

4. Conclusions

Paddy straw burning being a serious concern in India and has been driving attention of policy makers and researchers. Through this paper authors did in–depth study for best utilization of paddy straw for sustainable energy production and to reduce resulting emissions in term of greenhouse gases equivalent. The analysis of biomethane production from paddy straw revealed that this route of energy conversion is most efficient in terms of obtainable useful energy and global warming potential. The power generation data showed that the biomethane results into electricity generation of 777.0 kWh/tonne of paddy straw with output/input energy ratio of 5.5. However, bioethanol production potential analysis showed an electricity equivalent of 544.25 kWh/tonne of paddy straw. Nevertheless bioethanol is a ray of hope in competing with existing petrol based motor vehicles but biomethane provides an added advantage of reaping extra energy from same amount of paddy straw and on the other hand providing valuable manure for sustainable agriculture. The pelletized paddy straw can be used in improved biomass cookstoves to meet out thermal cooking energy requirement, the results showed in reduction of indoor air pollution compared to open field burning. The analysis further revealed that biomethanation of paddy straw reduces net global warming potential by 2750 CO_2e kg emissions/tonne. However, bioethanol production showed net global warming potential reduction of 2549 CO_2e kg emissions/tonne. The pelletization of paddy straw for improved cookstove showed net global warming potential reduction of 2459 CO_2e kg emissions/tonne. The overall analysis of conducted study reveals that the utilization of paddy straw for biomethane production through anaerobic digestion route is a best way in terms of energy and environmental economics. Decentralized and centralized system of biogas production commercial plants can be suitably setup at a cluster level of villages to minimize logistic cost. The available energy can be suitably used to supply clean and green cooking fuel, power generation and as well as vehicular fuel applications depending upon the need in the vicinity of area.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.energy.2017.03.138.

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