Science of the Total Environment 921 (2024) 170718

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Trigeneration based on the pyrolysis of rural waste in India: Environmental impact, economic feasibility and business model innovation

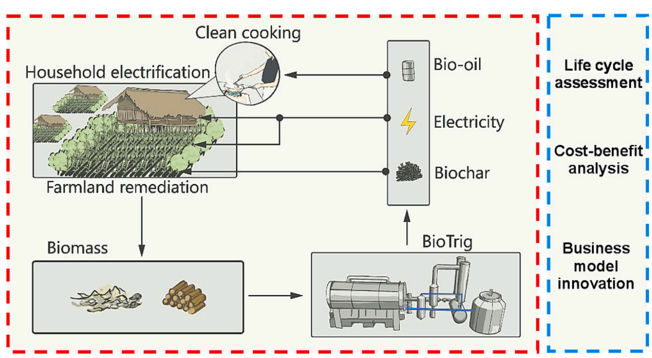
Simon Ascher[a], Jillian Gordon[b,1], Ivano Bongiovanni[c,1], Ian Watson[a], Kristinn Hermannsson[d], Steven Gillespie[e], Supravat Sarangi[f], Bauyrzhan Biakhmetov[a], Preeti Chaturvedi Bhargava[g], Thallada Bhaskar[h,i], Bhavya B. Krishna[h], Ashok Pandey[j,k,l], Siming You[a,*,1]

[a] James Watt School of Engineering, University of Glasgow, G12 8QQ, UK
[b] Adam Smith Business School, University of Glasgow, G12 8QQ, UK
[c] Business School, University of Queensland, Brisbane, QLD, Australia
[d] Robert Owen Centre for Educational Change, School of Education, University of Glasgow, Glasgow, UK
[e] School of Social and Environmental Sustainability, University of Glasgow, Dumfries DG1 4ZL, UK
[f] Gram Utthan, Bhubaneswar, Odisha 752101, India
[g] Aquatic Toxicology Lab, Environmental Toxicology Division, CSIR-Indian Institute of Toxicology Research, Vishvigyan Bhawan, 31, M.G. Marg, Lucknow 226001, India
[h] Material Resource Efficiency Division (MRED), CSIR-Indian Institute of Petroleum, Dehradun 248005, Uttarakhand, India
[i] Academy of Scientific and Innovative Research (AcSIR), CSIR-HRDC Campus, Sector 19, Kamla Nagar, Ghaziabad 210002, India
[j] Sustainability Cluster, School of Engineering, University of Petroleum and Energy Studies, Dehradun 248 007, India
[k] Centre for Innovation and Translational Research, CSIR-Indian Institute of Toxicology Research, Lucknow 226001, India
[l] Kyung Hee University, 26 Kyungheedae-ro, Dongdaemun-gu, Seoul 02447, South Korea

HIGHLIGHTS

- Economic feasibility and environmental impact of bioenergy trigeneration are assessed.
- Field survey is used to determine waste availability and rural household data.
- Monte Carlo simulation is applied to characterise potential analysis uncertainties.
- The trigeneration saves 350 kg of $CO_{2\text{-}eq.}$ per capita per annum.
- Two novel business models lead to an improved benefit-cost ratio of 1.35–1.75.

GRAPHICAL ABSTRACT



ARTICLE INFO

Editor: Damia Barcelo

Keywords:
Bioenergy

ABSTRACT

Pyrolysis-based waste-to-bioenergy development has the potential to resolve some of the major challenges facing rural communities in India such as poor electrification, household air pollution, and farmland degradation and contamination. Existing understanding and analysis of the economic feasibility and environmental impact of

* Corresponding author.
E-mail addresses: jillian.gordon@glasgow.ac.uk (J. Gordon), i.bongiovanni@uq.edu.au (I. Bongiovanni), Siming.You@glasgow.ac.uk (S. You).
[1] The authors have the same contribution to this study.

https://doi.org/10.1016/j.scitotenv.2024.170718
Received 4 November 2023; Received in revised form 10 January 2024; Accepted 3 February 2024
Available online 6 February 2024

Sustainable development
Economics
Life cycle assessment
Business model
Cost-benefit analysis

bioenergy deployment in rural areas is limited by parameter uncertainties, and relevant business model innovation following economic evaluation is even scarcer. This paper uses findings from a new field survey of 1200 rural households to estimate the economic feasibility and environmental impact of a pyrolysis-based bioenergy trigeneration development that was designed to tackle these challenges. Based on the survey results, probability distributions were constructed and used to supply input parameters for cost-benefit analysis and life cycle assessment. Monte Carlo simulation was applied to characterise the uncertainties of economic feasibility and environmental impact accounting. It was shown that the global warming potential of the development was 350 kg of CO_2-eq per capita per annum. Also, the survey identified a significant mismatch between feedstock prices considered in the literature and prices asked for by the surveyed villagers. The results of the cost-benefit analysis and life cycle assessment were then applied to propose two novel business models inspired by the Business Model Canvas, which had the potential to achieve up to 90 % economic profitability and result in a benefit-cost ratio of 1.35–1.75. This is the first study achieving combined environmental and economic analysis and business model innovation for rural bioenergy production in developing countries.

1. Introduction

Significant challenges need to be overcome to improve the living conditions for rural communities in India. Limited electrification, household air pollution, and farmland degradation and contamination are considered three major challenges. These challenges align with the Sustainable Development Goals set out by the United Nations, i.e. “Affordable and Clean Energy”, “Good Health and Well-being”, “Life on Land”, and “Zero Hunger” as well as “End Poverty” (United Nations, 2021). Specifically, >60 million rural households in India do not have access or only have access to electricity for a few hours per day (The World Bank, 2017; Gon Chaudhuri and Krishnan, 2018). Furthermore, 90 % of households in rural India rely on the direct combustion of biomass for cooking. This is a serious public health concern associated with household air pollution. The magnitude of this issue is clear when considering that women and children bear a disproportionate burden of the health effects due to their greater exposure to the resulting pollutants (Patnaik et al., 2017). Finally, the degradation of farmland is a serious threat to an overwhelming majority of the population, as two-thirds rely on agriculture for their living in India (Mythili and Goedecke, 2015). Preventing the decline of farmland is thus essential to ensure that rural communities have sufficient food and a stable income source.

Bioenergy plays an important role in supporting the energy and economic development of rural India. >70 % of India’s rural population depends on biomass for their energy needs in one way or another (Rödl and Partner, n.d.). The country is developing policies which focus on accelerating the deployment of bioenergy (Bosch et al., 2015; El-Chichakli et al., 2016). The Indian government has set a target of blending 20 % of ethanol in petrol by 2025 to encourage domestic biofuel production (Ministry of Petroleum and Natural Gas, 2022). However, current practices in biomass utilisation can take a heavy toll on the environment. For example, around 60 % of rice straw in India is burnt in the field, resulting in the loss of nutrients and significant emissions contributing to climate change and air pollution (Gadde et al., 2009; Bhattacharyya et al., 2020). This makes the development of more sustainable practices essential, especially for a country such as India which is the second-largest producer of rice in the world and where a significant portion of the population relies on agriculture (Soam et al., 2017). However, current bioenergy development in rural India remains weak in addressing all dimensions of sustainability with a lack of awareness and public engagement being a major barrier hindering bioenergy development (Pandey, 2020).

The practical implementation of a bioenergy project is highly contingent upon its economic viability and environmental impact. There have been extensive studies on the economics and environmental impacts of bioenergy systems in India and beyond, which showed that renewable and bioenergy solutions are strongly influenced by local factors, making a one-size-fits-all approach unfeasible (Yang et al., 2022). You et al. (2017) studied the feasibility of decentralised oil palm biomass gasification for the electrification of rural Indonesia. The proposed scheme led to carbon savings of 7.7 kg CO_2-eq kWh^{-1} compared to diesel generators (You et al., 2017). In comparison, the replacement of diesel generators with micro-scale marine hydrokinetic devices was shown to be promising for rural regions of Alaska, USA which has long rivers and coastline (McCallum et al., 2021). Yang et al. (2021) studied the global warming potential of corn straw-based bioenergy on a regional level by assessing seven conversion pathways across 30 Chinese provinces. Most conversion pathways led to the mitigation of greenhouse gas emissions, with a maximum mitigation potential of 253 million tonnes of CO_2-eq, across all provinces (Yang et al., 2022). Short rotation willow biomass was found to be one promising biofuel crop for Canada which can reduce greenhouse gas emissions by 85 % relative to natural gas and light fuel oil (Dias et al., 2017). Liu et al. (2017) found that switch grass may lead to lower greenhouse gas emissions, whereas coppiced hybrid poplar was found to be more economical, making it ultimately the more feasible option. In total, the use of marginal land for energy crop production could lead to a replacement of 30 % of transport gasoline, resulting in emission reductions of 29 million tonnes of CO_2-eq per year (Liu et al., 2017).

However, existing economic and environmental impact assessment studies focused on bioenergy and/or biofertilizer generation based on the designs of single-generation or co-generation. For example, Hiloidhari et al. (2021) evaluated the carbon footprints of sugarcane bagasse-based co-generation (electricity and heat) using high-pressure boilers in the state of Maharashtra, India, and found the carbon footprints varied between 0.075 and 0.2 kg CO_2-eq kWh^{-1} depending on the districts where the systems were deployed (Hiloidhari et al., 2021). Soam et al. (2017) evaluated the environmental impacts of different practices of rice straw utilisation in India including use as a fertiliser, conversion into animal fodder, electricity (using combustion boilers) production, and biogas production (using anaerobic digestion) (Soam et al., 2017). You et al. (2017) evaluated the economic feasibility and carbon-saving potential of a gasification-based system to electrify rural communities in Indonesia (You et al., 2017).

Bioenergy trigeneration becomes technically feasible for a thermochemical technology – pyrolysis based on recent research findings. Pyrolysis is a thermochemical process that can convert carbonaceous materials like virgin biomass (e.g., energy crops, grasses, and algae) or waste biomass (e.g., crop residues, food waste, and animal manure in rural areas) into biochar and pyrolysis bio-oil under an oxygen-free environment, which can contribute to the generation of a soil conditioner, electricity and a fuel for cooking. In rural areas, typical waste biomass suitable for pyrolysis that has been extensively studied includes animal manure, crop residue, etc. Specifically, there is substantial evidence that supports the use of biochar as a soil conditioner to improve soil quality while achieving carbon abatement (You et al., 2020). Experiments have also been carried out to demonstrate the use of pyrolysis bio-oil (with/out being blended with e.g., diesel or vegetable oil) in turbines for electricity production with efficiencies depending on the ratios of mixture and pyrolysis bio-oil production conditions (Kalargaris et al., 2017; Buffi et al., 2018). The heating value of pyrolysis bio-oil from lignocellulosic biomass was normally less than half of that of petroleum fuels, and its ignition was found to be more difficult than that of petroleum fuels due to high heat of evaporation of water; however, it could be burned steadily once ignited which can be facilitated with the help of pilot flames or ignition improvers (Lehto et al., 2014). Moreover, the emissions from pyrolysis bio-oil combustion were reported to be less than that from light oil and typically did not include SO_x (Yao et al., 2018). All these suggest that it can be used as a fuel for cooking to mitigate the air quality deterioration issue caused by biomass combustion-based cooking in Indian villages (Oasmaa et al., 2008). However, there is limited understanding of the economics and environmental impacts of the pyrolysis-based trigeneration development in rural communities to the energy and environmental challenges.

Limited profitability has been recognised as one of the major hurdles against sustainable renewable energy development in rural communities. For example, out of the nine middle and large-scale biogas production plants in rural Gansu, China, only two were economically feasible by a narrow margin (Niu et al., 2021). Governmental subsidies and incentives were essential requirements for promoting biogas development in rural areas. Another study on electrifying rural Ghana showed that decentralised electricity generation using waste gasification was not economically feasible based on 100 % private funding (Arranz-Piera et al., 2018). In India, a similar financial difficulty was observed for a bioenergy project (biomass energy for rural India) supported by the United Nations Development Program even with the presence of subsidies from the Ministry of New and Renewable Energy (MNRE) (Kothari et al., 2020).

Business model innovation involves the creation of new value propositions and their value delivery and value capture systems for greater economic value (Baldassarre et al., 2017). It has the potential to improve the economics of renewable energy development in rural areas. For example, it was shown that business model innovation (combining solar photovoltaics (PVs) and agricultural greenhouses) could improve the economics of PV-greenhouse systems in rural China by diversifying revenue sources to offset the declining revenue from power production-related feed-in-tariff policy changes and attracting new PV agricultural companies and investors (Li and Shen, 2019). Holguín et al. (2019) proposed a new business model to facilitate the full electrification of the rural areas of Perú based on the available energy resources and consideration of the demands of rural communities. The business model took a community-driven approach with community members being owners of the assets, which served to ensure a stable energy supply and reduce the operation and maintenance costs (Holguín et al., 2019). However, there has been no business innovation to improve the economic feasibility and practical development of pyrolysis-based trigeneration so far.

This work aims to fill the existing knowledge gaps about the economics, carbon-saving potential and business model innovation of pyrolysis-based bio-trigeneration in rural India. To ensure the analysis closely reflects the real demands (user-centric) and waste biomass availability in rural India, questionnaire-based household surveys (13 villages and 1200 households) were carried out to gather such critical information as current usage of electricity and electrical items in households, cooking and farming practices, technological penetration, and production of biomass, etc. The data were applied in associated life cycle assessment (LCA) and economic analysis for evaluating the global warming potential and benefit-cost ratio of the trigeneration development. Specifically, end-user-specific data were applied to reduce the potential uncertainties of the analysis. Probability density distributions were fitted to the survey results to accurately model the fluctuations and uncertainty involved in local waste production. Successively, the obtained distributions were employed within a Monte Carlo simulation to capture the effect of fluctuations in waste production on the outputs. To improve the economic viability, two alternative business models are proposed, and their economic attractiveness is scrutinised to guide practical business operations.

2. Methodology

2.1. Survey design and implementation

A household survey was conducted to collect information from a sample of 13 villages in 6 identified districts: Jajpur (Kuanar pur and Bindhan), Dhenkanal (Kaisiadihi and Balaram pur), Angul (Sarangapur and Kandasara), Bhadrak (Sapakatia and Nuabandha), Cuttack (Budhapanka and Panchgaon), and Khordha (Paidapatna Balipatana, Paidapatna Banamalipur, and Odakhanda). In total, the responses of 1200 households were collected. Fig. 1 (a) shows the location of the surveyed villages. It is worth noting that all 13 surveyed villages are located in the Odisha state in India, where 83 % of the population lives in rural areas, and more than half of its total workforce is engaged in the agriculture sector (Arriaga and Paolo, 2022). Considerable agricultural waste is generated and burned, causing serious air pollution issues. Additionally, reliable electricity supply is still a great challenge for a large part of the rural area in in this state (Arriaga and Paolo, 2022). Hence, the villages selected are representative and appropriate for evaluate the potential of trigeneration to mitigating these issues.

The survey was organised in categories aimed at unpacking topics such as current usage of electricity, waste/biomass production and their treatment/utilisation, cooking and farming practices, awareness of sustainable practices, willingness to adopt more sustainable methods, etc. that centre around the implementation of bioenergy projects (see the supplementary material for the survey). More specifically, villagers were asked questions such as “How much do you pay for electricity per year?”, “What energy source do you use for household cooking?”, “To what extent, do you want to change your cooking practice to make it healthier?”, “How important is it for households to have access to an organic soil additive?”, and “How important is it for a household to have clean cooking fuel?” in the form of a questionnaire. A key stakeholder in implementing the research project was a partnership with a local NGO Gram Utthan, which assisted in administering the survey and collecting the data in July 2020 (Fig. 1 (b)). The survey was administered in English, and staff from Gram Utthan assisted villagers by translating where necessary. The gathered data was analysed using Microsoft Excel and MATLAB.

Factors such as waste generation and electricity usage can widely vary depending on local factors. By using information obtained as part of the conducted survey, the authors attempt to address some of these uncertainties. As previously mentioned, Monte Carlo simulation methodology is employed to account for fluctuations in key parameters – namely local waste/biomass production. Ultimately, the employed methodology may result in outcomes more tailored to local conditions. Combined with the employed uncertainty analysis this allows investors and policymakers to make more educated decisions.

2.2. Bioenergy development design

Based on the survey, three different types of waste suitable for pyrolysis were considered, namely dung, wood waste, and agricultural waste. All three wastes have successfully been treated by pyrolysis in the past and can produce suitable pyrolysis products (bio-oil, syngas and biochar) for the desired applications (Shackley et al., 2012; Cantrell et al., 2012; Ro et al., 2010). For example, the biochar produced from these wastes is suitable for soil application. Shackley et al. (2012) tested biochar from rice straw for potentially toxic elements and found that the tested samples did not exceed the level recommended by the UK government (Shackley et al., 2012). Ro et al. (2010) found that manure-derived biochar contained high concentrations of P and K, making it a good fertiliser option. The co-pyrolysis of manure and dried and energy-dense biomass was found to minimise the need for external energy supply (Ro et al., 2010). This project aims to solve the challenges of poor electrification, household air pollution, and farmland degradation based on the consideration of a bioenergy trigeneration system that converts

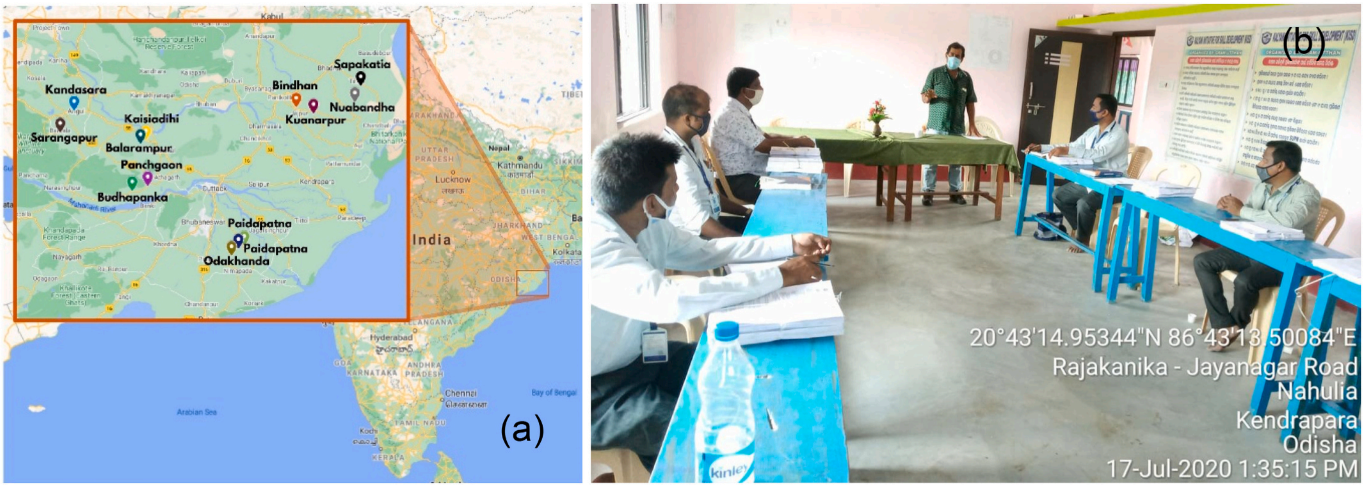


Fig. 1. (a) Location of the 13 surveyed villages. (b) Gram Utthan survey staff training.

wastes into biochar, bio-oil and combustible gas (BioTRIG in Fig. 1). The biochar is used as a soil conditioner. Part of the bio-oil is used in a turbine for electricity generation and the remaining is used a fuel for cooking. The gas is combusted in a boiler to supply heat to sustain the pyrolysis process.

The system model considers the use of bio-oil for the following three purposes: (1) for electricity generation by a turbine to cover auxiliary demands (10 %) for the pyrolysis and engine unit; (2) for use as a cooking fuel; (3) for electricity generation by the turbine to provide electricity to local households. The three elements are listed in order of decreasing priority. This means the analysis considers providing villagers with clean cooking fuel in the form of bio-oil as the first priority after providing electricity for the operation of the BioTRIG system itself. If bio-oil production exceeds the demand for cooking purposes the analysis considers the use of bio-oil for electricity generation by an engine. Energy demands for cooking were estimated based on literature values quoting a demand of one 15 kg cylinder of liquified petroleum gas (LPG) per household per 30 days (Ravindranath and Ramakrishna, 1997). As part of the survey, it was identified that while most households use a range of cooking fuels (e.g., wood and dung), gas was the most popular option, with 81 % of households using it for at least some of their cooking. If bio-oil is available for electricity generation, after satisfying its demand as a cooking fuel, the displacement of grid electricity is assumed. The model considers the direct application of biochar to local farmland leading to emissions due to the unstable fraction of carbon within the char. Stable carbon on the other hand acts as a carbon sink leading to GHG reduction. Furthermore, the application of biochar to farmland leads to the displacement of commercial fertilisers which are known to pollute waterbodies causing nutrient enrichment and habitat degradation (Bijay-Singh, 2021). Finally, the generated gas is assumed to be directly combusted for auxiliary needs, i.e., to heat the BioTRIG system.

As waste production is subject to significant variation, a stochastic method in the form of a Monte Carlo simulation was employed to account for its variability. Data representing 1200 households was used to fit the probability density distributions of waste production. An exponential fit was employed for all three types of waste. These probability density distributions were then used within the Monte Carlo simulation. The fitted distributions and statistics are discussed in Section 3.1.

2.3. Life cycle assessment

2.3.1. Goal and scope definition

LCA was used to evaluate the scheme's environmental performance. LCA allows the user to model a product, process, or system throughout its entire life cycle to evaluate resulting environmental impacts. For this work, MATLAB (overall environmental impact assessment and cost-benefit analysis modelling), Microsoft Excel (collating and analysing survey data), and the dedicated LCA software GaBi (extracting background data) were used to perform the analysis. The functional unit of LCA is the treatment of the waste generated per capita per annum. In addition to the pyrolysis processing of waste, the following processes were considered in the LCA: (i) Bio-oil combustion for cooking and electricity generation; (ii) Pyrolysis gas combustion to heat the pyrolysis process; (iii) Soil application of biochar to nearby fields. Furthermore, the following processes are displaced or avoided by introducing the new processes proposed in the scheme: (iv) Electricity from the Indian national grid; (v) Previous use of waste feedstocks (i.e., burning of dung and wood for cooking and the composting of agricultural waste); (vi) Commercial N, P, and K fertilisers. The displacement of existing practices is based on results obtained from the conducted survey. An illustration of the system boundary is shown in Fig. 2.

2.3.2. Life cycle inventory analysis

A description of each of these processes with the relevant assumptions made is given in the following sections:

(i) Bio-oil combustion for cooking and electricity generation

Bio-oil generation from different feedstocks is initially calculated from the waste availability and pyrolysis conversion efficiencies for the different feedstocks. The conversion efficiencies depend on the types of feedstocks. According to the three types of feedstocks (namely dung, wood waste, and agricultural waste) considered in this work, the conversion efficiencies for the production of biochar, bio-oil and gas range from 14.3 to 47.7 wt%, 31.3–72.4 wt%, and 11.5–19.0 wt% (Atienza-Martínez et al., 2020; Bridgwater and Peacocke, 2000). The thermal conversion efficiency of the cooking stove was assumed to be 50 % (Jugjai et al., 2001). The electricity conversion efficiency was assumed to be 40 % and 10 % of the generated electricity was supplied to meet the auxiliary demand (Gmünder et al., 2010; Shakti Sustainable Energy Foundation, ICF International, 2014). Full conversion of carbon to CO_2 is assumed during the combustion process to calculate CO_2-eq emissions due to bio-oil combustion (Gillenwater et al., 2005).

(ii) Pyrolysis gas combustion to heat the pyrolysis process

Pyrolysis gas combustion was modelled using the gas composition resulting from the pyrolysis of the respective waste feedstock and it was assumed that the pyrolysis process was sustained by the heat generated.

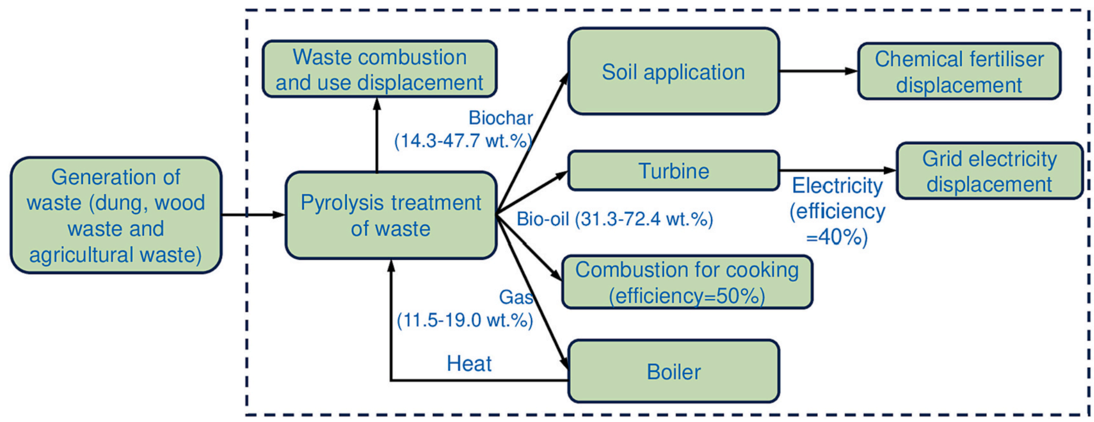


Fig. 2. Illustration of the system boundary.

Previous studies showed the heat generated by the combustion of pyrolysis gas was sufficient to sustain the pyrolysis process itself (Chhabra et al., 2021). For this complete combustion of CH_4 to CO_2 and H_2O was assumed. Furthermore, higher hydrocarbons in the gas were treated as CH_4 for this analysis as limited information was available on the exact nature of these.

The emissions and avoided emissions due to biochar application were modelled based on the resulting biochar composition for each waste type. Biochar from each waste has a certain fraction of stable/unstable carbon. Stable carbon acts as a carbon sink and results in −2.20 kg of CO_2-eq per kg of stable carbon applied. The unstable carbon fraction on the other hand is released as CO_2 and results in 1.41 kg of CO_2-eq per kg of unstable carbon applied (Mulabagal et al., 2016). Furthermore, there are emissions due to the N content in the biochar. An N to N_2O conversion factor of 0.015 was used, based on Møller et al. (2009), with the respective equivalency factor given in Table S1 to calculate the carbon equivalent emissions due to N in the biochar (Møller et al., 2009).

(iii) Electricity from the Indian national grid

The survey showed that >99 % of households were connected to the Indian national grid, with a small number of households not having an electricity supply. Hence the analysis assumes the displacement of electricity provided by the grid due to the introduction of pyrolysis-based electricity generation. This was modelled using GaBi software using the most recent electricity mix for the Indian grid.

As previously described in Section 2.1, bio-oil is only used for electricity generation if the local demand for bio-oil as a cooking fuel is satisfied. Furthermore, it is to be noted that auxiliary electricity demands to run the pyrolysis and engine unit do not lead to the displacement of grid electricity.

(iv) Previous use of waste feedstocks (i.e. burning of dung and wood for cooking and the composting of agricultural waste)

In the survey, it was found that dung and wood waste are currently most frequently used as cooking fuel. 66 % of households stated that dung is disposed of by burning it, while 49 % of households burn their wood waste. Hence the model assumes that the direct combustion of dung and wood waste are displaced by the proposed scheme.

Agricultural waste on the other hand is currently most frequently composted, with 87 % of households composting their waste according to the conducted survey. Avoided emissions are modelled using a method proposed by Sánchez et al. (2015). For this, it is estimated that 0.3 g of N_2O and 4 g of CH_4 are released per kg of agricultural waste. These are converted to carbon equivalent emissions by using the respective equivalency factors given in Table S1.

(v) Commercial N, P, and K fertilisers

As the model introduces biochar as a soil amendment the need for commercial fertilisers is reduced. Using the resulting biochar composition (from the three different waste feedstocks) in combination with the emissions related to the production of commercial N, P, and K fertiliser the avoided emissions due to the displacement of commercial fertiliser were calculated. Emission values of 8.90, 1.80, and 0.96 kg of CO_2-eq per kg of N, P, and K fertiliser respectively were used (Ascher et al., 2020). Additional life cycle inventory data is given in Table 1.

2.3.3. *Life cycle impact assessment*

The impact category considered in this work was the scheme's global warming potential (GWP) or in other words its carbon footprint. The impact category GWP uses the unit carbon dioxide equivalents (CO_2-eq) and was assessed using the impact assessment method CML 2001. The equivalency factors used to convert to CO_2-eq are shown in Table S1 (Supplementary Information).

2.3.4. *Data interpretation*

Checks were made to ensure the LCA was complete and self-consistent. To account for the variability in waste generation, a Monte Carlo simulation approach was incorporated into the LCA (Sun and Ertz, 2020). Exponential distributions were fitted to the waste production data (Fig. 3 shown below). Random samples, based on the defined distributions, were drawn at each Monte Carlo simulation instance. In turn, the drawn samples were used to calculate the GWP for the given simulation run. The simulation was completed for 1000 iterations.

2.4. *Cost-benefit analysis*

The economic analysis was conducted based on the calculation of the benefit-cost ratio (BCR) and NPV. Data on cost and benefit elements was primarily taken from existing literature, survey results, and local sources. The BCR is calculated using

$$\mathrm{BCR} = \frac{\sum \mathrm{PW(Benefit)}}{\sum \mathrm{PW(Cost)}} \tag{1}$$

where PW indicates the present worth of a benefit or cost element (Sullivan et al., 2019). A ratio of greater than one indicates that the benefits outweigh the costs, meaning that the project is economically feasible.

Annual worth (AW) elements were converted to PW using the following relationship

Table 1
Additional life cycle inventory data.

	Dung	Wood	Agricultural waste	References
Pyrolysis conversion efficiencies				
Biochar [wt%]	0.488	0.143	0.477	(Atienza-Martínez et al., 2020; Bridgwater and Peacocke, 2000)
Bio-oil [wt%]	0.362	0.724	0.313	(Atienza-Martínez et al., 2020; Bridgwater and Peacocke, 2000)
Pyrolysis gas [wt%]	0.190	0.133	0.115	(Atienza-Martínez et al., 2020; Bridgwater and Peacocke, 2000)
Biochar properties				
C [wt%]	0.396	0.750	0.450	(Atienza-Martínez et al., 2020; Phyllis, 2024a)
C fraction [wt%] – stable	0.402	0.721	0.610	(Bridgwater and Peacocke, 2000; Zhao et al., 2013)
C fraction [wt%] – unstable	0.598	0.279	0.390	calculated
N [wt%]	0.0184	0.015	0.015	(Atienza-Martínez et al., 2020; Phyllis, 2024a)
P [wt%]	0.0086	0.00041	0.0022	(Phyllis, 2024a; Phyllis, 2024b)
K [wt%]	0.008637	0.00256	0.0194	(Atienza-Martínez et al., 2020; Phyllis, 2024a)
Bio-oil properties				
C [wt%]	0.73	0.50	0.73	(Atienza-Martínez et al., 2020; Bridgwater and Peacocke, 2000)
LHV [MJ/kg] *	36.05*	19.00	30.70*	(Bridgwater and Peacocke, 2000; Xiu and Shahbazi, 2012)
Pyrolysis gas properties				
CO [vol%]	0.100	0.410	0.260	(Atienza-Martínez et al., 2020; Bridgwater and Peacocke, 2000)
CO_2 [vol%]	0.600	0.512	0.550	(Atienza-Martínez et al., 2020; Bridgwater and Peacocke, 2000)
CH_n [vol%]	0.100	0.055	0.130	(Atienza-Martínez et al., 2020; Bridgwater and Peacocke, 2000)
H_2 [vol%]	0.20	0.0018	0.03	(Atienza-Martínez et al., 2020; Bridgwater and Peacocke, 2000)
N_2 [vol%]	0	0	0.30	(Atienza-Martínez et al., 2020; Bridgwater and Peacocke, 2000)

	Dung	Wood	Agricultural waste	References
	General			
Energy conversion				
Auxiliary demands [%]	10			(Gmünder et al., 2010)
Electricity conversion efficiency of engine [%]	40			(Shakti Sustainable Energy Foundation, ICF International, 2014)
Reference processes				
Energy demand for cooking in the form of LPG [kWh/household/year]	2322			(Ravindranath and Ramakrishna, 1997), calculated
Equivalent emissions from Indian electricity grid [kg CO_2-eq/kWh]	1.16			GaBi - Indian Grid Mix
Avoided emissions due to the displacement of agricultural waste composting				
N2O emission due to composting [kg N_2O/kg waste]	0.0003			(Sánchez et al., 2015)
CH4 emissions due to composting [kg CH_4/kg waste]	0.004			(Sánchez et al., 2015)
Avoided emissions due to the displacement of wood burning in stoves				
Efficiency wood-fired stove [%]	0.15			(Chagunda et al., 2017)
Emissions due to firewood burning [kg CO_2-eq/GJ useful energy delivered to stove]	539			(Cashman et al., 2016)

* referred to as HHV.

$$PW = AW\left[\frac{i(1+i)^N}{i(1+i)^N - 1}\right]^{-1} \tag{2}$$

where i denotes the interest rate and N the study period in years (Sullivan et al., 2019). It is to be noted that the analysis assumes an interest rate of 12.76 % and a life cycle/study period of 20 years unless otherwise stated (Wright et al., 2010; Pradhan et al., 2016).

The project NPV is defined by the following equation

$$NPV = \sum PW(Benefit) - \sum PW(Cost) \tag{3}$$

where, as the name suggests, all financial cost and benefit elements are taken as their PW value.

2.4.1. Cost and benefit elements

The cash flows resulting in benefits or revenues for the project come from (i) the sale of produced electricity, (ii) the sale of generated biochar, and (iii) the sale of bio-oil to power cooking stoves. Costs occurred due to (iv) the required capital cost (CAPEX) for the pyrolysis unit and related operation and maintenance (O&M) costs, (v) CAPEX and O&M costs for the engine unit to generate electricity from bio-oil, and (vi) feedstock costs. Since onsite deployment of the system in each village served is considered, the cost of transportation of feedstocks is assumed to be minimal and is excluded in the analysis. Further explanation regarding all benefit and cost elements is given below:

(i) Benefits due to the sale of the generated electricity

Incomes due to the sale of electricity were calculated from the annual amount of bio-oil available for electricity production, an engine efficiency of 40 % (Shakti Sustainable Energy Foundation, ICF International, 2014), and an electricity sales rate of 6.00 ₹ kWh^{-1} based on current local electricity prices (the exchange rate between Indian Rupee and US dollar was 0.0142). From this, the PW equivalent was calculated using Eq. (2).

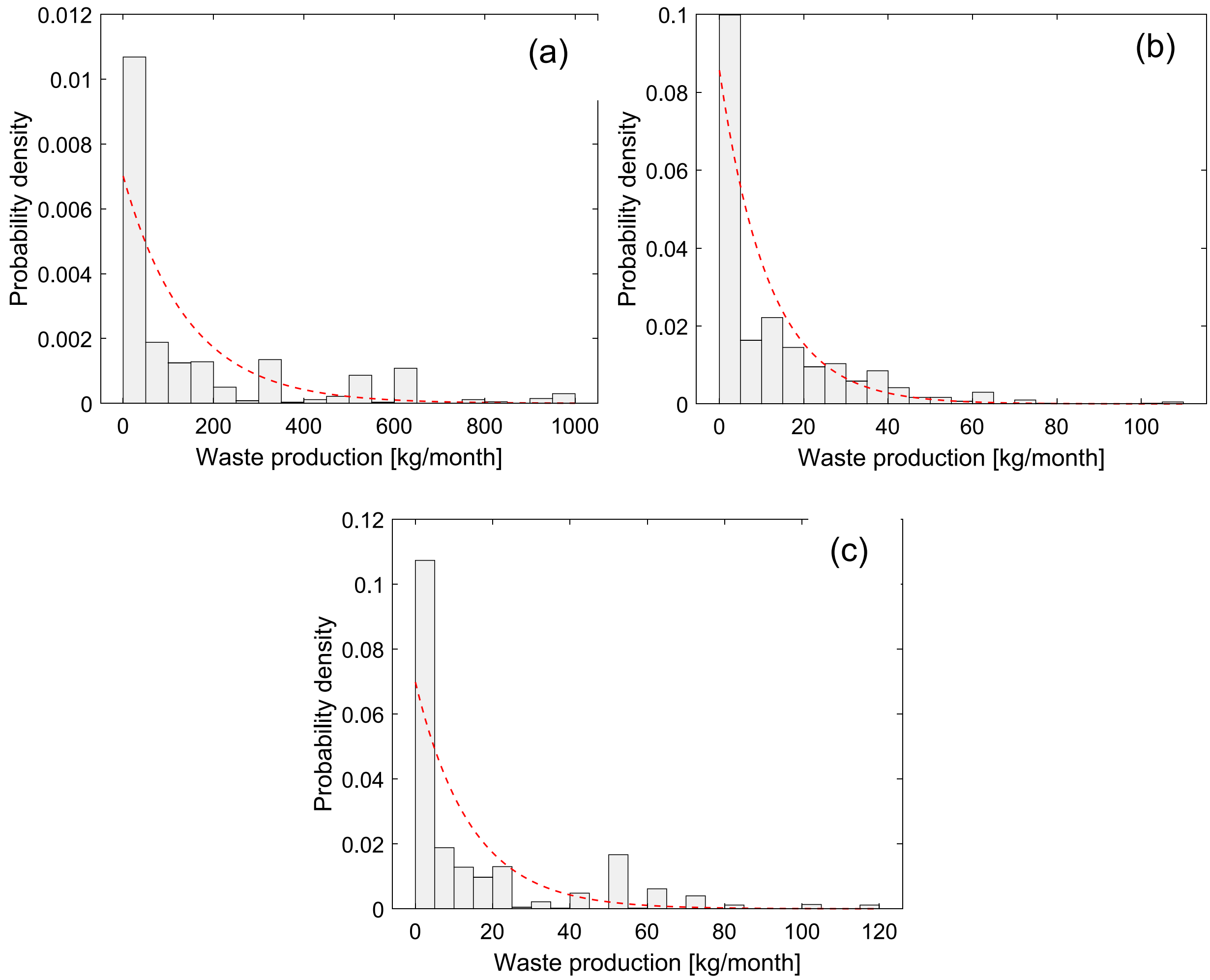


Fig. 3. Histograms and probability density distributions showing the production of (a) dung, (b) wood waste, and (c) agricultural waste.

(ii) Benefits due to the sale of the generated biochar

Initially, annual biochar production and typical N, P, and K contents from the three waste feedstocks considered were calculated. Local fertiliser prices were used to calculate the annual benefits resulting from the sale of biochar. The survey showed that most households (61 %) were willing to pay 80–100 % of current fertiliser prices for biochar. Hence, prices of 21.37, 56.85, and 48.38 ₹ kg^{-1} of N, P, and K fertiliser respectively were estimated based on the method outlined in Table S2 (Supplementary Information). Finally, benefits due to the sale of biochar were further converted to their PW equivalent using Eq. (2).

(iii) Benefits due to the sale of bio-oil to power cooking stoves

Firstly, the annual energy demand to power cooking stoves was found from Section 2.2. The survey showed that most households (68 %) were willing to pay 80–100 % of current cooking fuel prices for bio-oil. Hence, a bio-oil price of 4.33 ₹ kWh^{-1} is estimated based on local LPG prices. Annual incomes due to the sale of bio-oil for cooking purposes were calculated from this which have been further converted to their PW equivalent using Eq. (2).

(iv) Costs occurred due to CAPEX and O&M costs for the pyrolysis unit

The pyrolysis system was assumed to operate for 329 days each year for 16 h each day. The system's feedstock feed rate is calculated for each Monte Carlo run. This was used to relate the designed system to a reference system with a feed rate of 100.00 kg h^{-1} defined in a study by Islam and Ani (2000). Hence the system was scaled to the designed size by employing a power sizing technique to account for economies of scale. This is given by

$$\text{Cost}_k = \text{Cost}_i \left(\frac{S_k}{S_i}\right)^f \tag{4}$$

where S_k and S_i denote the designed facility capacity and base capacity respectively. The scaling factor f is taken as 0.7. This is the value generally employed in literature (You et al., 2016).

Further scaling was done by relating the system costs of the baseline year of the reference study to the current time. This was done using Chemical Engineering Plant Cost Index (CEPCI) values. Thus, the cost was scaled using the relationship

$$\text{Cost}_i = \text{Cost}_j \left(\frac{\text{CEPCI}_i}{\text{CEPCI}_j}\right) \tag{5}$$

where i and j represent the reference year (2020) and base year (2000) respectively. O&M costs were estimated by using a CAPEX to O&M costs ratio of 0.2.

(v) Costs occurred due to CAPEX and O&M costs for the power generation unit

A similar methodology as the one employed in (iv) was used to calculate the CAPEX of the power generation unit. A reference (Jugjai et al., 2001) kW engine with a CAPEX of 514,350 ₹ (5658 £) was used to estimate the cost of the designed engine by using Eqs. (4) and (5) (Nouni et al., 2007). The O&M cost was calculated using the methodology outlined in Nouni et al. (2007) where an annual O&M cost of 10 % of the engine's CAPEX was used to convert from AW to PW (Nouni et al., 2007).

(vi) Feedstock costs

In the conducted survey villagers have been asked how much they would have to be compensated for to part with each considered waste feedstock. The results are summarised in Table 2. This data has been used to fit triangular feedstock cost distributions to each feedstock type. For the distributions, the mean costs for dung waste, wood waste, and other agricultural waste were 73.03, 58.12, and 80.92 ₹ kg^{-1}, respectively, and the lower and upper bound values were 25 ₹ kg^{-1} and 200 ₹ kg^{-1}. Waste production was calculated based on the exponential probability density distributions fitted to the waste production data from the survey results. This is discussed in more detail in Section 3.1. Both the feedstock cost distribution and waste production distribution were applied in the cost-benefit analysis using a Monte Carlo simulation approach similar to that in LCA. Finally, the AW equivalent costs were calculated and converted to their PW equivalent by using Eq. (2).

2.5. Business model innovation

Based on the results of our economic profitability analysis, and the data collected through our survey, we hypothesise three different business models, to explore innovative configurations that would make our proposed bioenergy trigeneration scheme sustainable. We drew inspiration from Osterwalder and Pigneur's Business Model Canvas (Osterwalder and Pigneur, 2010), in a version that caters for social enterprises or not-for-profit ventures that have economic, environmental sustainability, and social innovation goals. A business model canvas sets out nine key building blocks, that, together, constitute the organisational architecture through which an economic entity unlocks and delivers value (Osterwalder and Pigneur, 2010; Sparviero, 2019; Evans et al., 2017; Magretta, 2002; Johnson et al., 2008).

Inspired by the seminal work on business models (Osterwalder and Pigneur, 2010), sustainable business models (Geissdoerfer et al., 2018) employ strategies including circular business model innovation (Bocken et al., 2016), social enterprises (Defourny and Nyssens, 2010), bottom-of-the-pyramid ventures (Prahalad, 2009) and product service systems (Tukker, 2004). Scholarly work in this area suggests there are nine sustainable generic business model strategies (Bocken et al., 2014), which include: (1) maximisation of material energy efficiency, (2) closure of resource loops, (3) renewable and natural process substitutes, (4) functionality over ownership, (5) stewardship role adoption, (6) sufficiency, (7) repurposing for environmental of societal benefit, (8) inclusive oriented value creation and (9) sustainable scale-up (Geissdoerfer et al., 2018). Such strategies support the innovation of the business model in four ways: the creation of sustainable start-ups, the transformation of business models that embed sustainability, business model diversification, and the acquisition and integration of sustainable business models.

In our scenario modelling, we also draw on scholarly work on the circular economy (Kirchherr et al., 2017), the term is frequently used to capture a combination of activities that include the reduction, reuse, recovery, and recycling of materials that enable not only economic gains to be established but also environmental and social gains. While there is much debate within the scholarly work on the circular economy as to whether it requires a system shift to be truly effective (Zhijun and Nailing, 2007; Davis and Hall, 2006), it is clear from the literature that the circular economy can also be enacted at a regional and individual consumer level (Li et al., 2010). Interestingly, business models have not been widely explored as enablers in this context, even though some scholars argue there is a key role for the business model in the development of the circular economy (Brennan et al., 2015; Lewandowski, 2016). Moreover, consumers are viewed within the literature to be a key enabler and stakeholder within a business model that supports the circular economy (Gallaud and Laperche, 2016). In our study, it is apparent that entire village communities have a pivotal role to play in enabling a business model that supports the establishment and maintenance of a circular economy for the proposed bio-energy scheme.

In our study, we adopted a modified version of the triple-layered business model canvas proposed by Joyce and Paquin (2016). Our version of this canvas builds on its economic basis to include environmental and social aspects and aligns with scholarly work, which argues that sustainable value in the business model context incorporates economic, social, and environmental benefits (Evans et al., 2017). Table 3 below represents a synthesised version of the triple layered business model canvas.

On top of the baseline scenario which considers feedstock prices based on survey results as described in Section 2.4.1 (demand-driven scenario), two alternative scenarios allow for a more economically feasible implementation of the proposed scheme are summarised in Table 4. Table 4 illustrates the expected economic, social, and environmental benefits to villagers of the scenarios. It focuses on the core business principles and the benefits derived. However, it is important here to highlight the rationale behind the scenarios includes economic, social and environmental benefits are not just for the villagers. There are inherent broader benefits derived across the key stakeholders including the corporate funder and the state government who benefit in different ways from engaging and supporting this venture. The corporate benefits from CSR activity, through enhanced reputation and the potential of consumer pull more broadly. The state government benefits from the societal and environmental benefits in their geographic area under their governance, not least the health benefits afforded from the population of villagers using cleaner fuel to cook and heat. Therefore, supporting a business model that is holistically sustainable and which creates and

Table 2
Instances of required compensation in ₹ kg^{-1} for dung waste, wood waste, and other agricultural waste as obtained from the survey.

Waste categories	<25	25–50	50–100	100–200	>200
Dung waste	311	202	84	173	68
Wood waste	590	303	53	115	101
Other agricultural waste	447	199	67	129	211

Table 3
Principles of the triple-layered business model canvas.

Layers	Economic	Social	Environmental
Dimensions/components of the business model architecture	Value proposition	Social value	Functional value
	Customer relations	Societal culture	End-of-life
	Channels	Scale of outreach	Distribution
	Customer segments	End-users	Use phase
	Activities	Governance	Production
	Resources	Employees	Materials
	Partners	Local communities	Supplies & outsourcing
	Costs	Social Impacts	Environmental impacts
	Revenues	Social benefits	Environmental benefits

Table 4
A summary of business model scenarios.

	Feedstock prices for dung, wood, and agricultural waste [₹ kg^{-1}]	CAPEX	Economic benefits to villagers	Social benefits to villagers	Environmental benefits to villagers
Demand-driven scenario	Triangular distribution based on survey (mean costs: 73.03, 58.12, and 80.92)	No reduction	Income from the sale of dung, wood, and, agricultural waste	Improvement of life conditions based on feedstock sale; empowerment of villagers/communities to manage the BioTRIG system; end-user-centric system	Reduction in farmland pollution; production of cleaner energy and biochar
Offer-driven scenario	3, 2, and 1.7 (Pradhan et al., 2016; Carus and Piotrowski, 2012; IndiaMART, n.d.)	100 % covered by private sector company	Income from the sale of dung, wood, and agricultural waste	Empowerment of villagers/communities to manage the BioTRIG system; diffusion of a culture of sharing; end-user centric system; aggregation	Reduction in farmland pollution; production of cleaner energy and biochar
Circular economy scenario	0, 0, and 0	100 % covered by private sector company	Income from the sale of dung, wood, and agricultural waste; Free biochar and bio-oil at 1/5 of the price of conventional LPG	Empowerment of villagers/communities to manage the BioTRIG system; diffusion of a superior culture of sharing (donation of feedstock); end-user centric system; aggregation	Reduction in farmland pollution; production of cleaner energy and biochar

captures value across the key stakeholders/partners is fundamental to its potential success and longevity. Importantly, the offer-driven scenario considers feedstock prices as per the literature. The circular economy scenario on the other hand proposes that villagers contribute their waste feedstocks for free, in exchange for free biochar and highly discounted bio-oil for cooking. The social and environmental layers of the offer-driven scenario and circular economy scenario were explained in Table S3 in the supplementary material. Detailed analysis of the business model innovation and associated results of economic analysis will be shown in Section 3.4.

3. Results and discussion

3.1. Survey results

Many survey results are quoted throughout Section 2, as they have been used to shape the economic and environmental model of the scheme. Some other key survey results are, for instance, that changing to healthier cooking practices was a top priority for many households. 81 % of households stated that they want to change their current practices 'very much' or 'as soon as possible'. In line with this, households were asked to rate the importance of having access to organic soil additives and clean cooking fuel on a scale from 1 to 10, where 10 indicates the highest importance. Both were found to be of great importance to households with averaged ratings of 9.81, and 9.84, respectively. Furthermore, households' willingness to sell their waste products was shown to be high, with 85 %, 99 %, and 90 % of households stating that they would be willing to sell their dung, wood, and agricultural waste, respectively. Finally, only 38 % of households stated that they are currently 'satisfied' or 'very satisfied' with their current electricity arrangement, indicating large room for improvement. It is interesting to notice that this result was under the condition that most households were connected to grid. Meanwhile, almost all households rated the highest importance of 10 for stable electricity supply, suggested that it is key to ensure stable electricity generation while exploring for measures to improve households' satisfaction to electricity supply. These results further support the business model innovation and new scenario designs in Section 2.5.

Histograms with fitted probability density distributions for the production of dung, wood waste, and agricultural waste are shown by Fig. 3. Initially, a range of different distribution fits were compared. By visual inspection, it was identified that exponential distributions of the form $p(x) = \frac{1}{\mu}e^{-\frac{x}{\mu}}$ were found to fit the waste production data best due to a significant proportion of survey respondents producing no waste of any given waste type. The exponential fits shown in Fig. 3 can be described by their mean values (μ). Values of $\mu = 142.63$, 11.68, and 13.32 describe the exponential distributions for the production of dung, wood waste, and agricultural waste, respectively. It is key to note that the shown distributions are specific to the region where the survey has been conducted. However, a similar methodology could be employed for other areas. Overall, the proposed BioTRIG scheme was found to be capable of providing local communities with a significant proportion of clean cooking fuel in the form of biomass (Supplementary information Fig. S1).

3.2. Environmental impacts

The scheme's environmental impact for 1000 Monte Carlo runs is shown by Fig. 4 (a). Approximately, 80 % of all runs result in the avoidance of CO_2-eq emissions. An avoidance in the range of 0 to – 200 kg CO_2-eq per capita per annum was found to be the most likely scenario with more than one quarter of all simulation runs producing results in that range. Overall, the scheme resulted in a mean avoidance of 350 kg of CO_2-eq per capita per annum with a standard deviation of 438 kg of CO_2-eq per capita per annum. The high standard deviation highlights the importance of understanding the variation in waste production, as results may greatly differ depending on a village's production. The analysis estimates an average rural household size of 5.4 (Gov.in, 2001). Considering Odisha's average per capita footprint of 2350 kg of CO_2-eq per capita per annum the scheme, on average, results in a 14.89 % emission reduction per capita compared to the rest of the state (Department of Forest and Energy-Government of Odisha, 2015).

Fig. 4 (b) shows the breakdown of the scheme's mean LCA results. Bio-oil combustion is the main process contributing to the scheme's GWP at 270 kg of CO_2-eq per capita per annum. The combustion of pyrolysis gas contributes to a lesser degree of less than one-third of bio-oil combustion. This is mostly because fewer pyrolysis gas is produced in comparison to bio-oil as shown in Fig. 1 and Section 2.3.2.

The displacement of grid electricity, the displacement of previous waste utilisation methods, fertiliser displacement, and biochar use all resulted in the avoidance of CO_2-eq emissions. The displacement of grid electricity and previous waste utilisation methods, as described in Section 2.3, resulted in an avoidance of 377 and 292 kg of CO_2-eq per capita per annum, respectively. Fertiliser displacement contributed to a lesser degree at 30 kg of CO_2-eq per capita per annum. Biochar application resulted in negligible emissions as the carbon storage benefits, due to the stable carbon in the char, were cancelled out by emissions resulting from the conversion of the unstable carbon fraction to CO_2, highlighting the importance of further assessing the stability of the produced biochar.

The average total waste production of 2.02×10^5 kg of waste per village per year corresponds to a mean avoidance of 603 kg CO_2-eq per

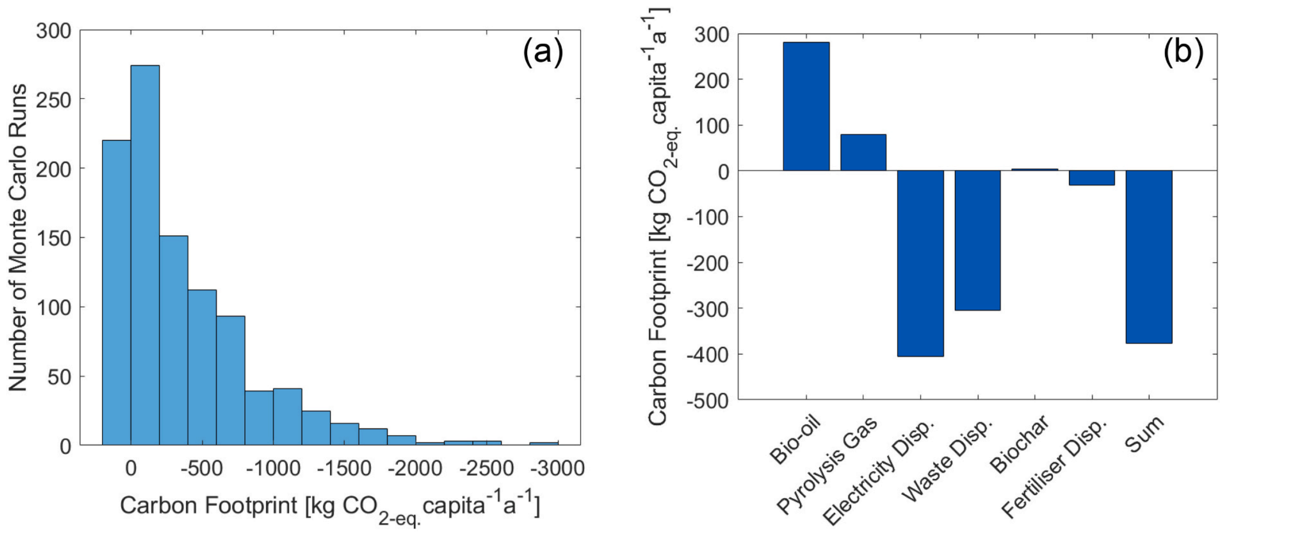


Fig. 4. Life cycle assessment results: (a) Distribution of life cycle assessment results for 1000 Monte Carlo simulation runs; (b) Mean life cycle assessment results by processes.

tonne of waste treated. Cheng et al. (2020) considered the slow pyrolysis of crop residues and woody wastes as a negative emission technology (Cheng et al., 2020). In their study avoided emissions ranging from 770 to 1050 kg CO_2-eq t^{-1} were calculated. These findings agree well with the results obtained in this study. The large range in values highlights the potential of survey results to minimise uncertainty. The pyrolysis of crop straw in the Shandong province of China has been shown to result in a GWP of −620 kg CO_2-eq t^{-1}, which is comparable to the findings of this study (Yang et al., 2020). Other researchers considered the pyrolysis of plastic waste. It has been found that chemical recycling of plastic waste via pyrolysis has a significantly lower carbon footprint (739 kg CO_2-eq t^{-1}) than waste incineration (1919 kg CO_2-eq t^{-1}) (Jeswani et al., 2021).

On a larger scale, Yang et al. (2021) considered biomass intermediate pyrolysis poly-generation (BIPP) as a readier to implement negative carbon technology than bioenergy with carbon capture and storage (BECCS) in the Chinese context (Yang et al., 2021). It was found that BIPP can result in emission reductions of 136.45 g CO_2-eq. MJ^{-1}, by applying biochar to soil, substituting pyrolysis gas for coke oven gas and conventional electricity production, and substituting bio-oil for coal tar in the production of chemical raw materials. In general, significantly larger GHG emission reductions are achievable by applying biochar to soil, as compared to substituting it for coal in power plants (Yang et al., 2021; Roberts et al., 2010; Peters et al., 2015).

3.3. *Economics*

The economic results obtained by CBA for 1000 Monte Carlo simulation runs are illustrated by Fig. 5 (a). A BCR of >1 generally indicates economic feasibility as all cash flows resulting in revenues outweigh cash flows resulting in costs. It is clear that the baseline system is not economically feasible as its costs heavily outweigh its benefits with the BCR not exceeding 0.27.

When considering average cash flows for the different processes it becomes clear that feedstock costs heavily dominate the analysis. Fig. 5 (b) shows that average feedstock costs are 19 times larger than the next biggest cost element (O&M costs) over the scheme's entire lifetime. Upon consulting literature values for the three considered feedstock types a significant mismatch between villager's expectations and feedstock prices considered in the literature can be identified. The current analysis considers mean feedstock costs (which have been informed by the survey data) of 73.03, 58.12, and 80.92 ₹ kg^{-1} for dung waste, wood

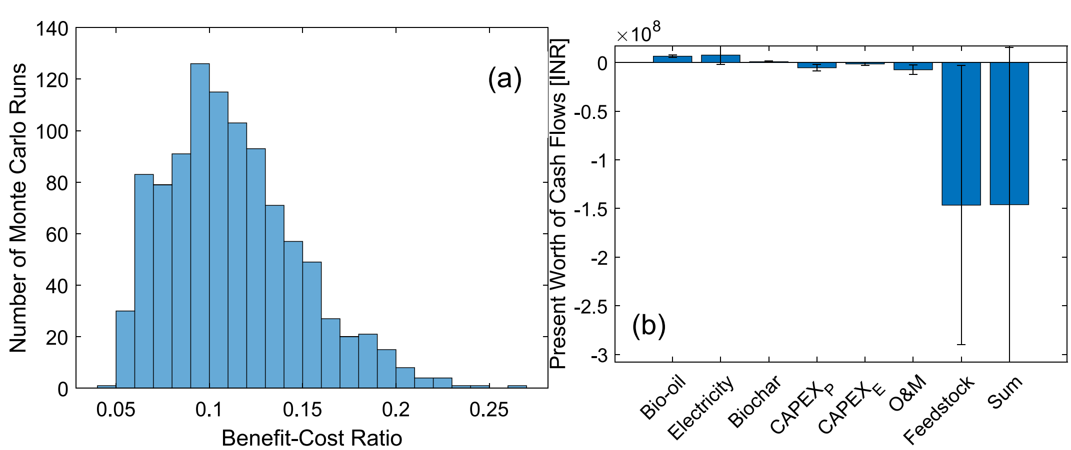


Fig. 5. (a) The benefit-cost ratio distribution for 1000 Monte Carlo simulation runs; (b) The average PWs of the scheme's cash flows resulting in benefits or costs. Error bars indicate +/− one standard deviation.

Table 5
Offer-driven scenario: details of the proposed business model canvas (economic layer).

Value proposition (vp)	An innovative system that utilises local waste as a feedstock to produce cleaner electricity, biochar for soil fertilisation, and cleaner bio-oil for cooking purposes.
Revenues	Initial investment by a private sector company, as corporate social responsibility (CSR) activity and in exchange for reputation, brand promotion, and consumer pull etc.; sale of electricity; sale of fertiliser; sale of bio-oil for cooking; government and third sector funding/grants.
Costs	Pyrolysis system (installation and operations); feedstock purchase; staff (for the deployment and initial running/maintenance of the pyrolysis plant); training of selected villagers for the running of the plant and the sale of its by-products (see Partners).
Customer segments	Villagers (purchasing electricity, biochar, and bio-oil; from villages included in the sample and surrounding areas); other companies interested in the by-products of the pyrolysis plant (e.g. Indian electricity authority; local stores of agricultural products; providers of fuels and cooking fuels); governmental and international grants.
Customer relationships	Point of sale for biochar and bio-oil located at the pyrolysis plant; sale of electricity via Indian electricity grid.
Channels	Mainly physical; promotional campaigns funded by the private sector company sponsoring the deployment of the pyrolysis plants.
Partners	Main partner: a private sector company willing to invest in the areas for CSR purposes. After initial deployment and setup, selected villagers are allocated the responsibility of running the pyrolysis system. In exchange, they obtain the pyrolysis by-products (electricity, biochar, and bio-oil) for free. Other villagers sell their feedstock at the pyrolysis plant. Money exchange is initially managed by dedicated staff, and, after a training period, by selected villagers.
Activities	Purchase/construction and deployment of the pyrolysis plants; setup of the plants; initial running of the plants; training selected villagers to run the plants and sell the by-products; CSR campaigns.
Resources	Pyrolysis plants; brand and reputation (private sector company); CSR-related reputation.

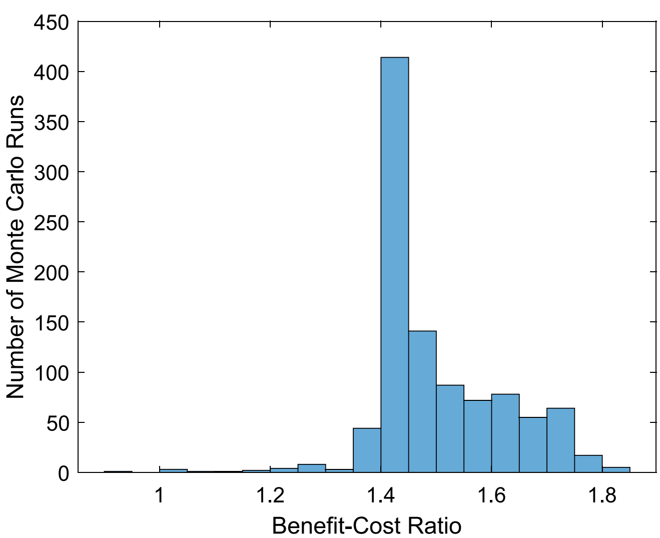


Fig. 6. Benefit-cost ratio distribution of the offer-driven scenario for 1000 Monte Carlo simulation runs under the assumption that the scheme's CAPEX is covered by a private sector company for CSR purposes.

waste, and other agricultural waste, respectively. Significantly lower values of 3.00 and 2.00 ₹ kg^{-1} for dung waste and wood waste have been obtained from local vendors in India (IndiaMART, n.d.). Similarly, a significantly lower cost of 1.50–1.70 ₹ kg^{-1} has previously been quoted in the literature for rice straw, a common type of agricultural waste in India (Pradhan et al., 2016; Carus and Piotrowski, 2012). As a result, alternative business models are proposed in Section 3.4 to encourage the uptake of the proposed scheme.

3.4. New business models

Based on the results of the economic analysis, we elaborated two versions of the triple layered business model canvas (Joyce and Paquin, 2016), based on the price paid to the villagers for contributing their feedstock to the system. In the first case, the price is set to values found in the literature, in particular, 3.00, 2.00, and 1.70 ₹ kg^{-1} respectively per dung, wood waste, and agricultural waste (offer-driven scenario). In the second case, the value is set to zero (circular economy scenario). We did not consider the prices requested by the villagers obtained using the survey (demand-driven scenario), as these were economically unrealistic (20–40 times higher than those reported in the literature).

3.4.1. Offer-driven scenario: feedstock price as per literature (3.00, 2.00, and 1.70 ₹ kg^{-1} respectively per dung, wood waste, and agricultural waste)

(1) Economic layer of the business model

In this scenario, the pyrolysis system is deployed under the aegis of a private sector company as a CSR activity and managed by the villagers. The 13 villages are grouped in 6 + 1 pairs, as illustrated by Fig. S2 (Supplementary Information), based on geographical proximity and one pyrolysis system is deployed per pair, to reduce CAPEX. The distance between the villages of Dasarathapur and Bindana, for example, is around a 3-h walk (or 29 min in a vehicle). The village of Balarampur has its own pyrolysis system, as a shared arrangement is not convenient due to the distance to the other villages. It is worth noting that the model takes into account only the villages included in this study, but nothing prevents other villages from joining, and reducing the geographical distances, possibly having more than two villages sharing the same system. The details of the resulting business model canvas are shown in Table 5 (economic layer).

In this scenario, the villagers contribute the feedstock necessary to feed the pyrolysis system in exchange for money. Further, they receive the benefits associated with the system itself: the displacement of grid electricity, the displacement of previous waste utilisation methods, and the displacement of previously utilised fertiliser. In this scenario, the larger investment is the pyrolysis plant, whose purchase and installation is funded by the intervention of a private sector company via CSR. Examples of CSR-related investments by large incumbents in different sectors in rural areas of developing countries are numerous and offer inspiration to find the right investor (Siemens, n.d.). Moreover, our survey offers several insights of the lives of villagers, which could inspire and attract the right company to fund the deployment of the pyrolysis system. For example, from our survey, almost all interviewed households have fans, a TV, and a mobile phone charger as commonly used appliances. Companies in these three industries may be a candidate to fund the deployment of the trigeneration technology in exchange for CSR-related reputation, but also for commercial purposes. In some villages, the received pyrolysis products exceeded their demands due to the large amount of feedstock available. This means the excess products can be sold to neighboring villages. The "bottom of the pyramid" model (Kolk et al., 2014) offers interesting suggestions for large incumbents to operate in this portion of the market.

Based on the results of our economic analysis, in particular, looking at the present value of cash flow analysis for the "Feedstock price as per literature" scenario, the sustainability of the BioTRIG system cannot be ensured without (i) the initial funding of a private sector organisation; (ii) ongoing funding that can be sought from national and international grants. This emphasises the development of a partnership approach to ensuring the sustainability of the business model.

The CBA results of the updated scheme are shown by Fig. 6. For the analysis it was assumed that the scheme's CAPEX is covered by a private sector company for CSR purposes. Furthermore, reduced feedstock prices based on literature values of 3.00, 2.00, and 1.70 ₹ kg^{-1} respectively for dung, wood waste, and agricultural waste have been used in the analysis. It was clearly illustrated that the system can operate economically with over 90 % of all simulation runs resulting in a BCR of 1.35–1.75.

(2) Social and Environmental layers of the business model:

We refer to the supplementary materials for the complete Social and Environmental layers of the business model canvas (Supplementary Information Table S3) (Joyce and Paquin, 2016). Here, it is worth emphasizing the following considerations:

(i) Social:

The *Social value* of our system largely consists of the empowerment of local communities constituted by 6 + 1 pairs of villages for the running and maintenance of the pyrolysis plant, as initially instructed, and trained for, by the private partner company involved in the deployment of the technology.

The role of *Local communities* is essential in our scheme. These constituencies (composed of 6 + 1 pairs of villages in adjacent locations) are the governance cornerstone of the scheme, as they are mainly in charge of running its operations, from the acquisition of the inputs (purchase of feedstock from villagers) to the sale of the products (cleaner electricity through the national grid, biochar, and bio-oil).

The *Social benefits* of our system are numerous and include the education of villagers towards cleaner household practices and household accountability, and the education and training of villagers towards running and maintaining the pyrolysis plants. It is shown that over 99 % of surveyed households were not aware of any adverse impacts of their current cooking practices on their health. A culture of shared technology (the plants among several villages) also facilitates community building within and across the geographic environment that is mutually beneficial. It enables the village communities to adopt a stewardship role of sustainable practices relative to their renewable energy consumption, agricultural productivity, and their health and well-being. This benefit aligns with the work of scholars on sustainable business model strategies (Geissdoerfer et al., 2018). It is also worth considering the social benefits deriving from our scheme for the partner private company, in terms of improved CSR reputation.

(ii) Environmental:

Functional value: An emphasis on the environmental value of the pyrolysis plants is in-designed in our scheme, which originated specifically to reduce the pollution deriving from agricultural waste disposal and other practices in villages in rural India.

Environmental benefits of our system have been largely discussed in the previous sections of this paper and include: the reduction of waste, production of cleaner electricity, etc.

End-of-life considerations around our project include the necessity to plan for the decommissioning of the pyrolysis plants once operations are to be ceased or at their end of life (lifetime of the system = 20 years). The presence of a reputable private sector company as the initial investor in the pyrolysis plants is, in our opinion, a guarantee that end-of-life dismantlement of the plants will be performed following the appropriate procedures, to avoid environmental damage.

3.4.2. Circular economy scenario: feedstock price at zero

(1) Economic layer of the business model

In the circular economy scenario, feedstock prices are zero. This means that villagers contribute their feedstock (dung, wood waste, and other agricultural waste) for free to feed the pyrolysis plants. Overall, the resulting economic business model is very similar to the offer-driven scenario (Table 5), but with some adjustments: the savings realised from the free feedstock will likely need to be shared with the villagers willing to give their feedstock for free. Villagers need to be compensated somehow for their contribution of feedstock. The most intuitive approach to do so is to offer them either free or discounted electricity, biochar, and/or bio-oil. To make the system more economically sustainable, considering the results from our present worth of cash flows analysis for the circular economy scenario (Feedstock price at zero), we can hypothesise villagers contributing feedstock to be remunerated with free biochar (the smallest source of profit in our model) and discounted/free bio-oil. The discount can be calculated as a percentage proportional to the amount of feedstock contributed. Further incentives can be offered for villagers to deliver their feedstock to the pyrolysis plant. A real-world example can be found in Wecycle, a Nigerian start-up that offers rewards for "wecyclers" willing to bike around and collect recyclable materials to feed a recycling plant (Matheson, 2015). Since being founded in 2012, the company has gone on to scale its activity via franchising across Nigeria, which demonstrates both a sustainable and a scale-able business model (Wecyclers, n.d.). Our survey has indicated that most respondents own a mobile phone, but very few have an internet connection at home. Therefore, another incentive could be offering villagers who are willing to deliver their feedstock for the pyrolysis plant the opportunity to connect to the internet for free through an internet access point deployed at the plant itself. This solution may be attractive to a private sector company in the telecommunications industry as the funder of the pyrolysis plants. In addition to the social benefits identified for the offer-driven scenario, this scenario can benefit villagers by reducing energy costs (villagers indicated this was a top-priority in our survey) and by providing the villagers with access to the internet, which can open up the world wide web to them and support shared value creation across all stakeholders.

The CBA results of the circular economy scenario are shown for two sub scenarios by Fig. 7. Like the offer-driven scenario, both sub-scenarios assume the scheme's CAPEX is covered by a private sector company for CSR purposes. Furthermore, villagers receive free biochar and cooking oil at 1/5 of the price of conventional LPG for cooking as compensation for providing feedstock for free (Fig. 7 (a)). Alternatively, the other sub scenario shown by Fig. 7 (b) further assumes that cooking oil is also provided for free. Electricity is sold at the same price as grid electricity for both sub-scenarios. 55 % and 41 % of all Monte Carlo simulation runs resulted in a BCR > 1 for the results shown in Fig. 7 (a) and (b) respectively.

(2) Social and Environmental layers of the business model

In terms of social and environmental layers, the circular economy scenario presents similar features to the offer-driven one. We highlight here the main differences we envisage:

(i) Social:

In terms of *governance*, the circular economy scenario likely entails the need for increased intervention by local government authorities in the form of grants and other support to compensate for the potential (economic) imbalances created through the donation of feedstock by the

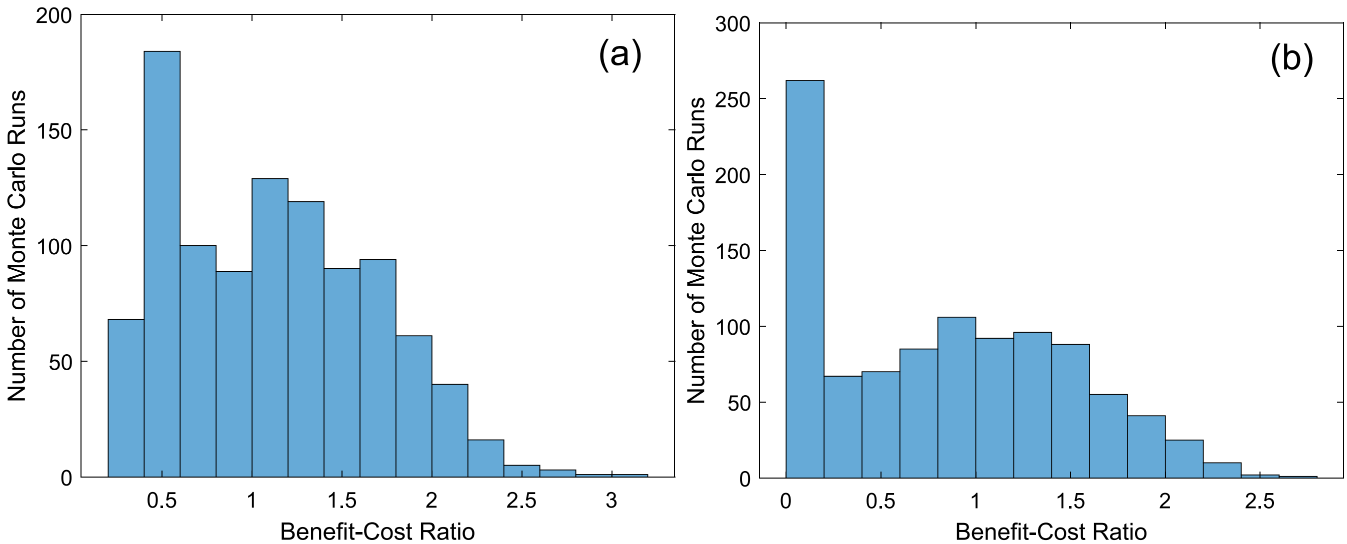


Fig. 7. Benefit-cost ratio distribution of the circular economy scenario for 1000 Monte Carlo simulation runs. (a) Shows the results for a bio-oil price of 1/5 of the price of conventional LPG; (b) assumes the free provision of bio-oil.

villagers; *Social benefits* include an enhanced education for the villagers towards a full circular economy model.

(ii) Environmental:

Use-phase: the circular economy scenario requires a very accurate distribution of the produced cleaner energy, biochar, and bio-oil, proportional to the donation of feedstock by villagers.

As the two scenario driven business models have been set out above it is useful now to briefly capture the distinct benefits and differences of each model. Regards the offer driven scenario, villagers are renumerated for supplying the feedstock to the pyrolysis plant, this is distinct from the circular economy model where villagers give their food stock waste for free. The opportunity to earn money for villagers is advantageous given the context of poverty. In this model the villagers also gain skills and training to run the pyrolysis plant, thus empowering their role within the community and the sustainability of the plant. The overriding benefit is holistic, households are educated on cleaner energy practices and accountability within the community. In the circular economy scenario, as well as contributing their feedstock for free to the plant, there is the opportunity to incentivize the free input of materials via discounted electricity, free biochar or free internet at plant location. Moreover, villagers could receive the equivalent amount of output from the plant as to what they put in. A key distinguishing feature is the level of governance required in this scenario, which would be a higher level of input from the local government. It would also require a greater level of education to ensure that the output provided to villagers is accurate to their input.

4. Conclusions

In this study, three major challenges for rural communities in India, which align with the United Nations' Sustainable Development Goals, are addressed by the proposed BioTRIG scheme. By incorporating results obtained by a survey, local conditions have been more accurately portrayed and uncertainties in the scheme's environmental impacts and economic feasibility have been addressed. Some of the survey's most notable findings are that changing to healthier cooking practices was a top priority for many households, with 81 % of households stating that they wanted to change their current practices 'very much' or 'as soon as possible'.

Most Monte Carlo simulation runs (78.3 %) were found to cover all of the local villagers' energy requirements for cooking purposes. This means, excess bio-oil may be used for local electricity generation, which may significantly aid with climate change mitigation efforts. The scheme's environmental performance was found to be good with a mean avoidance of 350 kg of CO_2-eq per capita per annum. Bio-oil combustion was found to be the largest emitter at 270 kg of CO_2-eq per capita per annum. The displacement of grid electricity and existing waste utilisation practices were found to be the two main factors leading to the avoidance of CO_2-eq emissions.

The survey also identified a significant mismatch between feedstock prices considered in the literature and prices asked for by the surveyed villagers. Feedstock prices asked for by villagers were found to be an order of magnitude of 20–40 times higher than those found in the literature. This led to an economically non-feasible scheme with its BCR not exceeding 0.27. The costs were heavily dominated by the feedstock costs and CAPEX. This issue was addressed by drawing inspiration from Osterwalder and Pigneur's Business Model Canvas and proposing two alternative business models. Most notably, our models propose the deployment of the BioTRIG system under the aegis of a private sector company, while being managed by 2/3 geographically proximate villages. The Monte Carlo simulation for the offer-driven scenario illustrated that the system could operate economically with over 90 % of all simulation runs resulting in a BCR of 1.35–1.75. Alternatively, the circular economy scenario resulted in a minimum of 41 % of all Monte Carlo simulation runs resulting in a BCR $>$ 1. The Business Model Canvasses proposed in this study demonstrated the following social and environmental benefits: empowerment of communities and villagers in the management of the BioTRIG system; diffusion of a culture of sharing; end-user centricity of the system; improvement of life conditions from sale or donation of feedstock (social); reduction in farmland pollution; production of cleaner energy and biochar (environmental).

Based on the results of this study, several recommendations for potential future studies are described below:

- In this study, GWP was considered as the mid-point environmental category in the LCA, but other impact categories might also be relevant and can be incorporated in future LCA studies such as particulate matter formation, land use, human toxicity, etc. Such studies will provide additional evidence to justify the environmental value of such developments.

- It is possible to improve the economic feasibility of the trigeneration development by continuous process efficiency enhancements and a better match between the trigeneration production and actual rural demands, which warrants better process and operation control and operation. The analysis of this work did not account for the influences of feedstock and process conditions on pyrolysis production, and it only applied the existing typical/average process data reported in the literature. Accurate process models should be developed, e.g., based on machine learning methods, which can be combined the LCA and economic analysis for dynamic evaluation and system designing (Ascher et al., 2022).

The challenges, namely, limited electrification, household air pollution, and farmland degradation and contamination are also faced by the rural households of some other developing countries which may have different socio-economic and environmental conditions (e.g., feedstock generation, energy price, energy demand, etc.) compared to those in India. For example, the yields and types of feedstocks might be different across different regions or countries. The differences imply that different pyrolysis process conditions may need to be in place to achieve the same level of production, while the level of production is further subject to actual energy and resource demand which can vary across different regions or countries. The applicability of the BioTRIG system as well as country-specific business model for the other countries is worth exploration.

CRediT authorship contribution statement

Simon Ascher: Writing – original draft, Formal analysis. **Jillian Gordon:** Writing – original draft, Supervision, Formal analysis. **Ivano Bongiovanni:** Writing – original draft, Supervision, Formal analysis. **Ian Watson:** Writing – review & editing, Supervision, Methodology. **Kristinn Hermannsson:** Writing – review & editing, Supervision, Methodology. **Steven Gillespie:** Writing – review & editing, Supervision, Methodology. **Supravat Sarangi:** Writing – review & editing, Methodology. **Bauyrzhan Biakhmetov:** Writing – review & editing, Formal analysis. **Preeti Chaturvedi Bhargava:** Writing – review & editing, Methodology. **Thallada Bhaskar:** Writing – review & editing, Methodology. **Bhavya B. Krishna:** Data curation. **Ashok Pandey:** Writing – review & editing, Supervision, Methodology. **Siming You:** Writing – original draft, Supervision, Project administration, Funding acquisition, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

All data supporting this study are provided in full in the paper.

Acknowledgement

The authors would like to acknowledge the financial support from the University of Glasgow & Scottish Funding Council Global Challenges Research Fund (SFC/AN/14/2019). Siming You also acknowledges the financial support from the Engineering and Physical Sciences Research Council (EPSRC) Programme Grant (EP/V030515/1). The authors also appreciate Mr. Leiyu Tian's help in developing the Graphical Abstract.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2024.170718.

References

Arranz-Piera, P., Kemausuor, F., Darkwah, L., Edjekumhene, I., Cortés, J., Velo, E., 2018. Mini-grid electricity service based on local agricultural residues: feasibility study in rural Ghana. Energy 153, 443–454. https://doi.org/10.1016/j.energy.2018.04.058.

Arriaga, P., Paolo, J.I.M., 2022. Electricity Distribution Concessions in Odisha.

Ascher, S., Li, W., You, S., 2020. Life cycle assessment and net present worth analysis of a community-based food waste treatment system. Bioresour. Technol. 305, 123076 https://doi.org/10.1016/j.biortech.2020.123076.

Ascher, S., Watson, I., You, S., 2022. Machine learning methods for modelling the gasification and pyrolysis of biomass and waste. Renew. Sust. Energ. Rev. 155, 111902 https://doi.org/10.1016/J.RSER.2021.111902.

Atienza-Martínez, M., Ábrego, J., Gea, G., Marías, F., 2020. Pyrolysis of dairy cattle manure: evolution of char characteristics. J. Anal. Appl. Pyrolysis 145, 104724. https://doi.org/10.1016/j.jaap.2019.104724.

Baldassarre, B., Calabretta, G., Bocken, N.M.P., Jaskiewicz, T., 2017. Bridging sustainable busi- ness model innovation and user-driven innovation: a process for sustainable value proposition design. J. Clean. Prod. 147, 175–186. https://doi.org/10.1016/J.JCLEPRO.2017.01.081.

Bhattacharyya, P., Bhaduri, D., Adak, T., Munda, S., Satapathy, B.S., Dash, P.K., et al., 2020. Characterization of rice straw from major cultivars for best alternative industrial uses to cutoff the menace of straw burning. Ind. Crop. Prod. 143, 111919 https://doi.org/10.1016/j.indcrop.2019.111919.

Bijay-Singh, Craswell E., 2021. Fertilizers and nitrate pollution of surface and ground water: an increasingly pervasive global problem. SN Appl. Sci. 3, 1–24. https://doi.org/10.1007/S42452-021-04521-8, 2021 34.

Bocken, N.M.P., Short, S.W., Rana, P., Evans, S., 2014. A literature and practice review to develop sustainable business model archetypes. J. Clean. Prod. 65, 42–56. https://doi.org/10.1016/j.jclepro.2013.11.039.

Bocken, N.M.P., de Pauw, I., Bakker, C., van der Grinten, B., 2016. Product design and business model strategies for a circular economy. J. Ind. Prod. Eng. 33, 308–320. https://doi.org/10.1080/21681015.2016.1172124.

Bosch, R., Van De Pol, M., Philp, J., 2015. Policy: define biomass sustainability. Nature 523, 526–527. https://doi.org/10.1038/523526a.

Brennan, G., Tennant, M., Blomsma, F., 2015. Business and production solutions : closing loops & the circular economy. In: Kopnina, H., Shoreman-Ouimet, E. (Eds.), Sustain. - Key Issues. Routledge, pp. 219–239.

Bridgwater, A.V., Peacocke, G.V.C., 2000. Fast pyrolysis processes for biomass. Renew. Sust. Energ. Rev. 4, 1–73. https://doi.org/10.1016/S1364-0321(99)00007-6.

Buffi, M., Cappelletti, A., Rizzo, A.M., Martelli, F., Chiaramonti, D., 2018. Combustion of fast pyrolysis bio-oil and blends in a micro gas turbine. Biomass Bioenergy 115, 174–185. https://doi.org/10.1016/j.biombioe.2018.04.020.

Cantrell, K.B., Hunt, P.G., Uchimiya, M., Novak, J.M., Ro, K.S., 2012. Impact of pyrolysis temperature and manure source on physicochemical characteristics of biochar. Bioresour. Technol. 107, 419–428. https://doi.org/10.1016/j.biortech.2011.11.084.

Carus, M., Piotrowski, S., 2012. Deliverable D1.2: Assessment of Procurement Costs for the Preferred Feedstocks.

Cashman, S., Rodgers, M., Huff, M., Feraldi, R., Morelli, B., 2016. Life Cycle Assessment of Cookstove Fuels in India and China.

Chagunda, M.F., Kamunda, C., Mlatho, J., Mikeka, C., Palamuleni, L., 2017. Performance assessment of an improved cook stove (Esperanza) in a typical domestic setting: implications for energy saving. Energy Sustain. Soc. 7, 1–9. https://doi.org/10.1186/s13705-017-0124-1.

Cheng, F., Luo, H., Colosi, L.M., 2020. Slow pyrolysis as a platform for negative emissions technology: an integration of machine learning models, life cycle assessment, and economic analysis. Energy Convers. Manag. 223, 113258 https://doi.org/10.1016/j.encon-man.2020.113258.

Chhabra, V., Parashar, A., Shastri, Y., Bhattacharya, S., 2021. Techno-economic and life cycle assessment of pyrolysis of unsegregated urban municipal solid waste in India. Ind. Eng. Chem. Res. 60, 1473–1482. https://doi.org/10.1021/acs.iecr.0c04746.

Davis, G., Hall, J., 2006. Circular Economy Legislation: The International Experience.

Defourny, J., Nyssens, M., 2010. Conceptions of social enterprise and social entrepreneurship in Europe and the United States: convergences and divergences. J. Soc. Entrep. 1, 32–53. https://doi.org/10.1080/19420670903442053.

Department of Forest and Energy-Government of Odisha, 2015. Estimation of Odisha's Carbon Footprint.

Dias, G.M., Ayer, N.W., Kariyapperuma, K., Thevathasan, N., Gordon, A., Sidders, D., et al., 2017. Life cycle assessment of thermal energy production from short-rotation willow biomass in Southern Ontario, Canada. Appl. Energy 204, 343–352. https://doi.org/10.1016/j.apenergy.2017.07.051.

El-Chichakli, B., Von Braun, J., Lang, C., Barben, D., Philp, J., 2016. Policy: five cornerstones of a global bioeconomy. Nature 535, 221–223. https://doi.org/10.1038/535221a.

Evans, S., Vladimirova, D., Holgado, M., Van Fossen, K., Yang, M., Silva, E.A., et al., 2017. Business model innovation for sustainability: towards a unified perspective for creation of sustainable business models. Bus. Strateg. Environ. 26, 597–608. https://doi.org/10.1002/bse.1939.

Gadde, B., Menke, C., Wassmann, R., 2009. Rice straw as a renewable energy source in India, Thailand, and the Philippines: overall potential and limitations for energy contribution and greenhouse gas mitigation. Biomass Bioenergy 33, 1532–1546. https://doi.org/10.1016/j.biombioe.2009.07.018.

Gallaud, D., Laperche, B., 2016. Circular Economy, Industrial Ecology and Short Supply Chain, vol. 4. Wiley Blackwell, London.

Geissdoerfer, M., Vladimirova, D., Evans, S., 2018. Sustainable business model innovation: a review. J. Clean. Prod. 198, 401–416. https://doi.org/10.1016/j.jclepro.2018.06.240.

Gillenwater, M., Woodfield, M., Simmons, T., McCormick, M., Camobreco, V., Hockstad, L., et al., 2005. Calculation Tool for Direct Emissions From Stationary Combustion. Washington DC.

Gmünder, S.M., Zah, R., Bhatacharjee, S., Classen, M., Mukherjee, P., Widmer, R., 2010. Life cycle assessment of village electrification based on straight jatropha oil in Chhattisgarh, India. Biomass Bioenergy 34, 347–355. https://doi.org/10.1016/j.biombioe.2009.11.006.

Gon Chaudhuri, S.P., Krishnan, R., 2018. Planning to Mainstream Distributed Electricity Generation From Renewables. In: Green Energy Technol. Springer Verlag, pp. 335–348. https://doi.org/10.1007/978-981-10-8393-8_14.

Gov.in, 2001. Indian Census Data Highlights. http://censusindia.gov.in/Data_Products/Data_Highlights/Data_Highlights_link/data_highlights_hh1_2_3.pdf. (Accessed 30 March 2020).

Hiloidhari, M., Vijay, V., Banerjee, R., Baruah, D.C., Rao, A.B., 2021. Energy-carbon-water footprint of sugarcane bioenergy: a district-level life cycle assessment in the state of Maharashtra, India. Renew. Sust. Energ. Rev. 151, 111583 https://doi.org/10.1016/j.rser.2021.111583.

Holguín, E.S., Flores Chacón, R., Gamarra, P.S., 2019. Sustainable and Renewable Business Model to Achieve 100% Rural Electrification in Perú by 2021. In: 2019 IEEE PES Conf. Innov. Smart Grid Technol. ISGT Lat. Am. 2019. https://doi.org/10.1109/ISGT-LA.2019.8895439.

IndiaMART. IndiaMART n.d. https://www.indiamart.com/ (accessed June 3, 2021).

Islam, M.N., Ani, F.N., 2000. Techno-economics of rice husk pyrolysis, conversion with catalytic treatment to produce liquid fuel. Bioresour. Technol. 73, 67–75. https://doi.org/10.1016/S0960-8524(99)00085-1.

Jeswani, H., Krüger, C., Russ, M., Horlacher, M., Antony, F., Hann, S., et al., 2021. Life cycle environmental impacts of chemical recycling via pyrolysis of mixed plastic waste in comparison with mechanical recycling and energy recovery. Sci. Total Environ. 769, 144483 https://doi.org/10.1016/j.scitotenv.2020.144483.

Johnson, M.W., Christensen, C.M., Kagermann, H., 2008. Reinventing your business model. Harv. Bus. Rev. https://hbr.org/2008/12/reinventing-your-business-model. (Accessed 1 September 2023).

Joyce, A., Paquin, R.L., 2016. The triple layered business model canvas: a tool to design more sustainable business models. J. Clean. Prod. 135, 1474–1486. https://doi.org/10.1016/j.jclepro.2016.06.067.

Jugjai, S., Tia, S., Trewetasksorn, W., 2001. Thermal efficiency improvement of an LPG gas cooker by a swirling central flame. Int. J. Energy Res. 25, 657–674. https://doi.org/10.1002/er.708.

Kalargaris, I., Tian, G., Gu, S., 2017. Combustion, performance and emission analysis of a DI diesel engine using plastic pyrolysis oil. Fuel Process. Technol. 157, 108–115. https://doi.org/10.1016/j.fuproc.2016.11.016.

Kirchherr, J., Reike, D., Hekkert, M., 2017. Conceptualizing the circular economy: an analysis of 114 definitions. Resour. Conserv. Recycl. 127, 221–232. https://doi.org/10.1016/J.RESCON- REC.2017.09.005.

Kolk, A., Rivera-Santos, M., Rufín, C., 2014. Reviewing a decade of research on the "base/bottom of the pyramid" (BOP) concept. Bus. Soc. 53, 338–377. https://doi.org/10.1177/0007650312474928.

Kothari, R., Vashishtha, A., Singh, H.M., Pathak, V.V., Tyagi, V.V., Yadav, B.C., et al., 2020. Assessment of Indian bioenergy policy for sustainable environment and its impact for rural India: strategic implementation and challenges. Environ. Technol. Innov. 20, 101078 https://doi.org/10.1016/j.eti.2020.101078.

Lehto, J., Oasmaa, A., Solantausta, Y., Kytö, M., Chiaramonti, D., 2014. Review of fuel oil quality and combustion of fast pyrolysis bio-oils from lignocellulosic biomass. Appl. Energy 116, 178–190. https://doi.org/10.1016/j.apenergy.2013.11.040.

Lewandowski, M., 2016. Designing the business models for circular economy-towards the conceptual framework. Sustain 8, 1–28. https://doi.org/10.3390/SU8010043.

Li, C., Shen, B., 2019. Accelerating renewable energy electrification and rural economic development with an innovative business model: a case study in China. Energy Policy 127, 280–286. https://doi.org/10.1016/j.enpol.2018.12.009.

Li, H., Bao, W., Xiu, C., Zhang, Y., Xu, H., 2010. Energy conservation and circular economy in China's process industries. Energy 35, 4273–4281. https://doi.org/10.1016/J.ENERGY.2009.04.021.

Liu, T., Huffman, T., Kulshreshtha, S., McConkey, B., Du, Y., Green, M., et al., 2017. Bioenergy production on marginal land in Canada: potential, economic feasibility, and greenhouse gas emissions impacts. Appl. Energy 205, 477–485. https://doi.org/10.1016/j.apenergy.2017.07.126.

Magretta, J., 2002. Why business models matter. Harv. Bus. Rev. https://hbr.org/2002/05/why-business-models-matter. (Accessed 1 September 2023).

Matheson, R., 2015. Bringing "Everyone Wins" Recycling to Nigeria | MIT News | Massachusetts Institute of Technology. https://news.mit.edu/2015/wecyclers-cargo-bike-recycling-nigeria-0305. (Accessed 2 June 2021).

McCallum, C.S., Kumar, N., Curry, R., McBride, K., Doran, J., 2021. Renewable electricity generation for off grid remote communities; life cycle assessment study in Alaska, USA. Appl. Energy 299, 117325. https://doi.org/10.1016/j.apenergy.2021.117325.

Ministry of Petroleum, Natural Gas, 2022. Cabinet approves Amendments to the National Policy on Biofuels -2018. pib.gov.in/PressReleaseIframePage.aspx?PRID=1826266. (Accessed 12 February 2024).

Møller, J., Boldrin, A., Christensen, T.H., 2009. Anaerobic digestion and digestate use: accoun- ting of greenhouse gases and global warming contribution. Waste Manag. Res. 27, 813–824. https://doi.org/10.1177/0734242X09344876.

Mulabagal, V., Baah, D., Egiebor, N., Chen, W., 2016. Handbook of Climate Change Mitigation and Adaptation. In: Handb. Clim. Chang. Mitig. Adapt. https://doi.org/10.1007/978-1-4614-6431-0.

Mythili, G., Goedecke, J., 2015. Economics of land degradation in India. In: Econ. L. Degrad. Improv. - A Glob. Assess. Sustain. Dev. Springer International Publishing, pp. 431–469. https://doi.org/10.1007/978-3-319-19168-3_15.

Niu, S., Dai, R., Zhong, S., Wang, Y., Qiang, W., Dang, L., 2021. Multiple benefit assessment and suitable operation mechanism of medium- and large-scale biogas projects for cooking fuel in rural Gansu, China. Sustain. Energy Technol. Assess. 46, 101285 https://doi.org/10.1016/j.seta.2021.101285.

Nouni, M.R., Mullick, S.C., Kandpal, T.C., 2007. Biomass gasifier projects for decentralized power supply in India: a financial evaluation. Energy Policy 35, 1373–1385. https://doi.org/10.1016/j.enpol.2006.03.016.

Oasmaa, A., Kytö, M., Sipilä, K., 2008. Pyrolysis oil combustion tests in an industrial boiler. Prog. Thermochem. Biomass Convers. 1468–1481. https://doi.org/10.1002/9780470694954.ch121.

Osterwalder, A., Pigneur, Y., 2010. Business Model Generation: A Handbook for Visionaries, Game Changers, and Challengers. Wiley.

Pandey, P., 2020. Transitioning to a bio-economy: Indian initiatives in the bioenergy domain. SSRN Electron. J. https://doi.org/10.2139/ssrn.3625392.

Patnaik, S., Tripathi, S., Dethier, S., Jain, A., 2017. Access to Clean Cooking Energy in India: Beyond Connections, Towards Sustained Use.

Peters, J.F., Iribarren, D., Dufour, J., 2015. Biomass pyrolysis for biochar or energy applications? A life cycle assessment. Environ. Sci. Technol. 49, 5195–5202. https://doi.org/10.1021/es5060786.

Phyllis, 2024a. Phyllis#2714. https://phyllis.nl/Browse/Standard/ECN-Phyllis#2714. (Accessed 4 January 2024).

Phyllis, 2024b. Phyllis#1528. https://phyllis.nl/Browse/Standard/ECN-Phyllis#1528. (Accessed 1 April 2024).

Pradhan, S.G.B., Singhal, S.A.K., Bakshi, S.A.S., Iyer, S.M.K., 2016. Central Electricity Regulatory Commission New Delhi. Petition No. SM/03/2016 (Suo-Motu).

Prahalad, C., 2009. The Fortune at the Bottom of the Pyramid, 5th ed. Prentice Hall, Upper Saddle River.

Ravindranath, N.H., Ramakrishna, J., 1997. Energy options for cooking in India. Energy Policy 25, 63–75. https://doi.org/10.1016/S0301-4215(96)00105-X.

Ro, K.S., Cantrell, K.B., Hunt, P.G., 2010. High-temperature pyrolysis of blended animal manures for producing renewable energy and value-added biochar. Ind. Eng. Chem. Res. 49, 10125–10131. https://doi.org/10.1021/ie101155m.

Roberts, K.G., Gloy, B.A., Joseph, S., Scott, N.R., Lehmann, J., 2010. Life cycle assessment of biochar systems: estimating the energetic, economic, and climate change potential. Environ. Sci. Technol. 44, 827–833. https://doi.org/10.1021/es902266r.

Rödl & Partner. Market overview: bioenergy in India 2020. https://www.roedl.com/insights/renewable-energy/2020-02/market-overview-bioenergy-india. (Accessed 14 June 2021).

Sánchez, A., Artola, A., Font, X., Gea, T., Barrena, R., Gabriel, D., et al., 2015. Greenhouse gas emissions from organic waste composting. Environ. Chem. Lett. 13, 223–238. https://doi.org/10.1007/s10311-015-0507-5.

Shackley, S., Carter, S., Knowles, T., Middelink, E., Haefele, S., Sohi, S., et al., 2012. Sustainable gasification-biochar systems? A case-study of rice-husk gasification in Cambodia, part I: context, chemical properties, environmental and health and safety issues. Energy Policy 42, 49–58. https://doi.org/10.1016/j.enpol.2011.11.026.

Shakti Sustainable Energy Foundation, ICF International, 2014. Diesel Generators: Impro- ving Efficiency and Emission Performance in India.

Siemens. Siemens India CSR Initiative n.d. https://www.youtube.com/watch?v=dis9v-OCMeM (accessed June 2, 2021).

Soam, S., Borjesson, P., Sharma, P.K., Gupta, R.P., Tuli, D.K., Kumar, R., 2017. Life cycle assessment of rice straw utilization practices in India. Bioresour. Technol. 228, 89–98. https://doi.org/10.1016/j.biortech.2016.12.082.

Sparviero, S., 2019. The case for a socially oriented business model canvas: the social enterprise model canvas. J. Soc. Entrep. 10, 232–251. https://doi.org/10.1080/19420676.2018.1541011.

Sullivan, W.G., Wicks, E.M., Koelling, C.P., 2019. Engineering Economy, 17th ed. Pearson Education, Limited.

Sun, S., Ertz, M., 2020. Life cycle assessment and Monte Carlo simulation to evaluate the environmental impact of promoting LNG vehicles. MethodsX 7, 101046. https://doi.org/10.1016/j.mex.2020.101046.

The World Bank, 2017. Climate Investment Funds, Program ESMA. Mini Grids in Uttar Pradesh, a Case Study of a Success Story.

Tukker, A., 2004. Eight types of product-service system: eight ways to sustainability? Experiences from suspronet. Bus. Strateg. Environ. 13, 246–260. https://doi.org/10.1002/bse.414.

United Nations, 2021. Sustainable Development Goals. https://sdgs.un.org/goals. (Accessed 17 March 2021).

Wecyclers. Our Story - Wecyclers n.d. https://www.wecyclers.com/about/ (accessed June 2, 2021).

Wright, M.M., Daugaard, D.E., Satrio, J.A., Brown, R.C., 2010. Techno-economic analysis of biomass fast pyrolysis to transportation fuels. Fuel 89, S2–10. https://doi.org/10.1016/j.fuel.2010.07.029.

Xiu, S., Shahbazi, A., 2012. Bio-oil production and upgrading research: a review. Renew. Sust. Energ. Rev. 16, 4406–4414. https://doi.org/10.1016/j.rser.2012.04.028.

Yang, Q., Zhou, H., Bartocci, P., Fantozzi, F., Mašek, O., Agblevor, F.A., et al., 2021. Prospective contributions of biomass pyrolysis to China's 2050 carbon reduction and renewable energy goals. Nat. Commun. 21. https://doi.org/10.1038/s41467-021-21868-z.

Yang, X., Han, D., Zhao, Y., Li, R., Wu, Y., 2020. Environmental evaluation of a distributed-centralized biomass pyrolysis system: a case study in Shandong, China. Sci. Total Environ. 716, 136915 https://doi.org/10.1016/j.scitotenv.2020.136915.

Yang, Y., Liang, S., Yang, Y., Xie, G.H., Zhao, W., 2022. Spatial disparity of life-cycle greenhouse gas emissions from corn straw-based bioenergy production in China. Appl. Energy 305, 117854. https://doi.org/10.1016/j.apenergy.2021.117854.

Yao, Z., You, S., Dai, Y., Wang, C.H., 2018. Particulate emission from the gasification and pyrolysis of biomass: concentration, size distributions, respiratory deposition-based control measure evaluation. Environ. Pollut. 242, 1108–1118. https://doi.org/10.1016/J.ENVPOL.2018.07.126.

You, S., Wang, W., Dai, Y., Tong, Y.W., Wang, C.H., 2016. Comparison of the co-gasification of sewage sludge and food wastes and cost-benefit analysis of gasification- and incineration-based waste treatment schemes. Bioresour. Technol. 218, 595–605. https://doi.org/10.1016/j.biortech.2016.07.017.

You, S., Tong, H., Armin-Hoiland, J., Tong, Y.W., Wang, C.H., 2017. Techno-economic and greenhouse gas savings assessment of decentralized biomass gasification for electrifying the rural areas of Indonesia. Appl. Energy 208, 495–510. https://doi.org/10.1016/j.apenergy.2017.10.001.

You, S., Li, W., Zhang, W., Lim, H., Kua, H.W., Park, Y.K., et al., 2020. Energy, economic, and environmental impacts of sustainable biochar systems in rural China. Crit. Rev. Environ. Sci. Technol. 1–29. https://doi.org/10.1080/10643389.2020.1848170.

Zhao, L., Cao, X., Mašek, O., Zimmerman, A., 2013. Heterogeneity of biochar properties as a function of feedstock sources and production temperatures. J. Hazard. Mater. 256–257, 1–9. https://doi.org/10.1016/j.jhazmat.2013.04.015.

Zhijun, F., Nailing, Y., 2007. Putting a circular economy into practice in China. Sustain. Sci. 2, 95–101. https://doi.org/10.1007/S11625-006-0018-1, 2007 21.