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Assessing rice straw availability and associated carbon footprint for methanol production: A case study in India

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ABSTRACT

The necessity of transitioning to clean energy sources is driving a transformative shift towards the utilisation of biofuels as a promising pathway to achieve a future with net-zero emissions and robust energy security. This global imperative has intensified research into biofuels, with bio-methanol emerging as a highly promising candidate.

This study conclusively demonstrates the feasibility of producing bio-methanol from rice straw residues in rural India, focusing specifically on Assam. Utilising GIS technology, the research accurately mapped rice straw availability and designed an optimised supply network for efficient collection and transportation. The findings revealed substantial rice straw resources in the region, capable of yielding over 1200 tonnes of bio-methanol annually. Furthermore, the associated carbon footprint was significantly lower than that of conventional methanol production.

By evaluating 5480 ha of potential cropland for rice, the study estimated an annual generation of 4411 tonnes of rice straw, translating to an impressive bio-methanol production potential of over 1215 tonnes, or approximately 3.3 tonnes per day. The study calculated the overall carbon footprint to be 421.84 tonnes CO_2e per year, equating to just 0.096 kg CO_2e per kilogram of rice straw and 0.347 kg CO_2e per kilogram of biomethanol, remarkably lower than the footprint of traditional fossil methanol production. The results demonstrate the viability of bio-methanol from rice straw as a sustainable biofuel solution for rural India. Precise biomass assessment, optimised transport networks, and significantly reduced carbon footprint align perfectly with India's clean energy objectives. This robust framework provides policymakers with a powerful tool to harness rural bioenergy, revolutionising the energy landscape and driving sustainable development towards a cleaner future not only in India but in other developing countries as well.

This study provides a compelling foundation for further exploration, asserting that biomethanol when blended with fossil fuels, can enhance energy security, foster a circular bioeconomy, and contribute significantly to net-zero emissions targets.

Abbreviations

GIS	Geographic information system
CF	Carbon footprint
ROI	Region of interest
SRF	Surplus residue factor
RPR	Residue production ratio
SR	Surplus residue
MP	Methanol production
LP	Land preparation
FA	Fertiliser application
TP	Transplanting
I	Irrigation

(continued on next page)

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(*continued*)

PA	Pesticide application
H	Harvesting
TH	Threshing
TSD	Total shortest distance

1. Introduction

The climate emergency, coupled with the energy crisis, is driving a transformative shift towards cleaner energy sources [1]. This transition presents an exciting opportunity to achieve a future with net-zero emissions and robust energy security. By strategically developing a diverse portfolio of renewable energy sources, we can unlock a sustainable future [2]. While significant progress has been made with solar and wind power generation, the challenge of storing renewable energy remains a hurdle when compared to the inherent storage capacity of fossil fuels, given the progress of climate change and global warming effects on each renewable energy [3,4]. However, biofuels offer a promising solution for a smoother transition to a clean energy future [5]. Global collaboration for biofuel development and utilisation is gaining momentum, and India stands at the forefront of this exciting prospect.

India, with its vast agricultural resources across nearly all major states [6–8], presents a unique opportunity to unlock the potential of biofuels on a large scale. Utilising these renewable crop residues for fuel production is practical and crucial for addressing rural energy shortages in India [9]. However, it is unlikely that in each state/region, such vast quantities of crop residues will be available in one location for biomethanol production in real-time. Efficient utilisation of these crop residue resources can address rural energy issues, promote regional development, and decrease the energy gap between rural and urban areas [10,11]. Thus, while India possesses significant potential for crop residue biomass as a sustainable energy source, practical implementation requires effective rural/urban planning and localised resource assessment at a microscopic level. This approach of producing biomethanol on a local small scale is more advantageous, as it can enhance the socio-economic conditions in rural India by maximising the availability of crop residues in different cases [12]. Addressing rural energy demand and promoting sustainable transportation in India necessitates innovative solutions. The Indian government is increasingly advocating for biofuels on major international platforms and has pledged towards reducing its carbon footprint (CF) and achieving net-zero emissions by 2070 [13,14].

Moreover, India faces major environmental and health challenges from the annual burning of approximately 92 million metric tonnes of crop residues, contributing to air pollution and global warming [15,16]. The total CO_2 equivalent emissions from burning those 92 million metric tonnes of crop residues would be approximately 197.65 million metric tonnes CO_2e [17]. In this context, the strategic planning of biofuel production facilities based on sustainable crop residues across various regions of the country is crucial. Besides, the associated CF assessment is also necessary for quantifying the environmental impact of biofuel production from crop residues. Such initiatives will aid the government and policymakers in effectively reducing fossil fuel consumption and integrating more biofuels into India's energy mix, thus supporting the nation's environmental goals and energy independence with this circular bioeconomy approach [18–22].

Accurate assessment and planning of small-scale availability of crop residues are essential for sustainable biofuel production. As crop residues are dispersed both spatially and temporally, it is essential to identify areas of availability, quantify the residues, and optimise the collection and transportation network [23]. Geographic Information Systems (GIS) and remote sensing technologies are two powerful tools for this purpose. GIS analysis of recent satellite imagery can be performed to identify agricultural resources and quantify their availability over time. This spatial and temporal data helps in creating accurate biomass resource maps, facilitating integrated planning for energy production [24]. Several works of literature describe the use of GIS-based analysis for the successful identification of biomass resources and bioenergy planning by considering environmental factors and transportation costs [23,24]. Through GIS, decision-makers can develop comprehensive strategies for biomass resource utilisation, ensuring efficient and sustainable bioenergy production [25].

Assam, a major northeastern state of India, exemplifies the urgent need for decentralised renewable energy generation. Reliance on fossil fuels has resulted in a significant CF, making Assam highly vulnerable to climate change [26]. Despite claims of electrification, many areas still lack reliable electricity and rural transportation, highlighting the necessity for alternative energy solutions [27]. From 1535 MW during peak hours in 2016 to 1970 MW in 2023, there was an overall increase in the demand for power [28]. Recent reports indicate that Assam's electricity demand is expected to quadruple by 2030. To maintain energy security, about 3000 MW of renewable energy capacity will be needed by 2026–2027 and 5000 MW by 2031–2032 [29]. In response, the Government of Assam is committed to mitigating and adapting to climate change, working towards creating a low-carbon renewable energy growth strategy to meet the state's rising energy needs. The government's goal is to initiate, promote, support, and coordinate efforts related to non-traditional energy resources, including solar, wind, biomass, microhydel, and municipal solid waste. Additionally, the government aims to disseminate information about technical advancements and current technologies in non-conventional and renewable energy to various user groups, policymakers, financial institutions, consultants, and entrepreneurs [30]. While there are plans to invest in modern technologies like floating solar [31], the bioenergy potential from agricultural residues in the region cannot be overlooked.

By harnessing both advanced renewable technologies and the substantial bioenergy potential from agricultural residues, Assam can move towards a more sustainable and resilient energy future. Assam's diverse biomass resources, including crop residues, require careful planning for efficient utilisation [24]. Rice, the staple food for the local population, is also the most extensively farmed crop in Assam. The state's total geographic area is 78,438 square kilometres, and in 2020, rice production was recorded at 4.98 million tonnes [32,33]. Rice straw, a significant agricultural residue abundantly available in Assam, is often left unattended or burned in the fields after traditional uses. Rice straw is a kind of lignocellulosic biomass that contains 12 % lignin, 25 % hemicellulose, and 43 % cellulose [34–36]. While India has made significant strides in rice straw-based biofuel production in recent times, this sector requires further exploration regarding the availability and proper rice straw management for using the potential benefit of biofuel production [34–39]. Beyond assessing the potential for biofuel production, numerous studies have examined the CF associated with rice straw production and its conversion into biofuels [40–42]. However, rice straw has significant potential in terms of biomethanol production as well as CF reduction [6,42]. To support Govt. of Assam's objective for energy security, the development of bioenergy planning and management frameworks at a microscopic level in the rural Assam scenario is very much essential.

This research addresses a significant by focusing on rice straw as a biomass resource for methanol production in rural Assam, India, a region that has not been extensively explored for its bioenergy potential. The main objectives and novelty of this study for these aspects are outlined below-

a) To assess the spatial availability of potential cropland using classification algorithms in GIS for quantifying the rice straw residues and corresponding biomethanol production potential,
b) To develop a cost-effective supply network for the collection and transportation of rice straw feedstocks,

c) To evaluate the CF related to the production, collection, transportation of rice straw and the subsequent biomethanol production.

By employing GIS tools to precisely assess biomass availability and optimise transportation networks for feedstock collection, the study introduces a novel approach to improving the efficiency and sustainability of bioenergy production in rural areas. Moreover, integrating carbon footprint (CF) assessments with advanced technologies provides a comprehensive strategy to reduce environmental impact while supporting India's transition to a greener, more equitable energy future. The study's objectives distinguish it further by combining spatial analysis with environmental sustainability, addressing both practical and ecological challenges in bioenergy production. This approach not only enhances the sustainability of bioenergy but also underscores the critical role of rice straw in India's bioenergy landscape.

2. Methodology

This methodology describes the steps taken to develop the framework for assessing the availability of rice straw, corresponding biomethanol production potential, optimal collection and transportation network, and associated CF in a rural region in India. A combination of GIS and Excel-based assessments are used to analyse the spatial availability of potential croplands and identify and quantify areas where rice straw production would be abundant. Then biomethanol production potential of the region of interest (ROI) is estimated based on the rice straw production potential. After the classification of rice straw fields through spatial analysis, the road network is examined to evaluate the shortest routes for collection and cost-effective transportation. Finally, CF associated with rice straw management activities, including rice cropping, harvesting, threshing, collection, and transportation, are estimated. The procedures for these aspects are discussed in the following sections.

2.1. Study area and ROI

The study area considered in this investigation lies on the north bank of the Brahmaputra River, in the southeast corner of the Sonitpur district of Assam, India. Assam, with a total area of 78,438 sq. kms and 50 % of its land under cultivation, holds significant potential for bioenergy. The state has 24,179 sq. kms dedicated to cereal production, including rice, jowar, maise, wheat, ragi, and barley.

The Sonitpur district comes under the north bank plain agro-climatic zone of the state. The Kameng district of Arunachal Pradesh borders it to the north, the Brahmaputra River to the south, the Lakhimpur district to the east, and the Udalguri district to the west [43]. A brief district profile is highlighted in Table 1.

The region of interest (ROI) comprises 90 villages surrounding Tezpur University in Tezpur, Assam, which is identified as a promising location for establishing a small-scale biomethanol production plant in the near future. The river "Kameng" flows through the eastern part of the ROI. The geographic coordinates of the proposed biomethanol plant (Tezpur University) are 26°41′47.544″N 92°50′6.09″E. Tezpur University, a leading institution in energy research, has a strong record of developing and implementing renewable energy projects through its Department of Energy [44,45]. The university has actively engaged with the local community on various government-funded projects, contributing significantly to the region's socio-economic development. In recent years, Tezpur University has also established successful collaborations with academic and industrial partners [46]. Surrounded by paddy fields, this ROI offers a substantial potential for socio-economic growth through the establishment of a small-scale biomethanol production plant utilising rice straw.

Fig. 1 illustrates the ROI from a national, state, and district perspective with the depiction of the village boundaries. This proposed study aims to assist Tezpur University administration in planning and implementing a rural biofuel production project. Upon successful implementation, this small-scale biofuel project will contribute to the socio-economic development of the nearby region and support the Government of India's biofuel initiative to achieve net-zero emissions in the near future [47].

Table 1
District profile of Sonitpur, Assam [43].

Total Area	272,000 ha
Study area Location	26.28°–27.08° N 91.19°–93.47° E
No of development blocks	7
Agricultural subdivision	1 (Tezpur)
No of villages	910
No of Gaon-panchayat (Village Council)	82
Major crops	Rice (Staple food crop), Tea (Cash crop) [24]
Major industries	Tea Processing
Climate	Subtropical monsoon climate
Geography	Largely plain with some hills, with a number of rivers with Himalayan foothill origin flowing southwards merging with river Brahmaputra

2.2. Cropland availability and biomethanol potential assessment

2.2.1. Visualisation of the available cropland in the study area

Due to the significant spatial and temporal variations available in the study area for quantifying the rice straw potential, this research evaluated the potential cropland available within the ROI through GIS. Open source software QGIS 3.34 Prizren and Global Mapper are used to map the selected study area. Remotely sensed satellite images in different multi-spectral regions and temporally are collected for the ROI. The selection of satellite images is in reference to the end of the rice harvesting period in the region, based on Assam's crop calendar [48]. The source of the satellite images is the Sentinel 2 database, provided by collaborated efforts of ESA, EU and Copernicus Data Space Ecosystem [49]. For the whole assessment, EPSG:32646-WGS84/UTM zone 46N is used as CRS (coordinate reference system). The details of satellite imagery are listed in Table 2.

The SCP plugin in QGIS is used to preprocess the satellite images, creating a unified spatial base map that combines all images across different band wavelengths to enhance the display of brightness, contrast, and true colour composite images. Specific training samples are then implemented through the classification tool in the SCP plugin, allowing the entire region of interest (ROI) to be categorised into various classes, with the "Cropland" class being isolated. During the post-processing stage, the classified "Cropland" image is refined, segmented, and corrected using Google satellite imagery to align it with village boundaries, resulting in a more accurate assessment of available cropland in the ROI. The resultant "Cropland" classified map becomes useful for determining the cropland, biomethanol production potential and network analysis.

2.2.2. Feedstock availability & biomethanol potential assessment

Once the cropland area of the ROI is evaluated through GIS classification and postprocessing, the total potential rice crop production for each year can be calculated using Eq. (1) [6]. Subsequently, the rice straw assessment is conducted following the methodology outlined in Ref. [6], with the surplus residue estimation detailed in Eq. (2). The proposed plan involves producing syngas through the gasification of rice straw, followed by converting the syngas to methanol via the methanol synthesis reaction. For this conversion, we employ the same syngas-to-methanol conversion factor of 0.25, to quantify the biomethanol production potential. The syngas production potential and biomethanol production potential are then estimated using Eq. (3) [6].

$$P = Y \times A \quad (1)$$

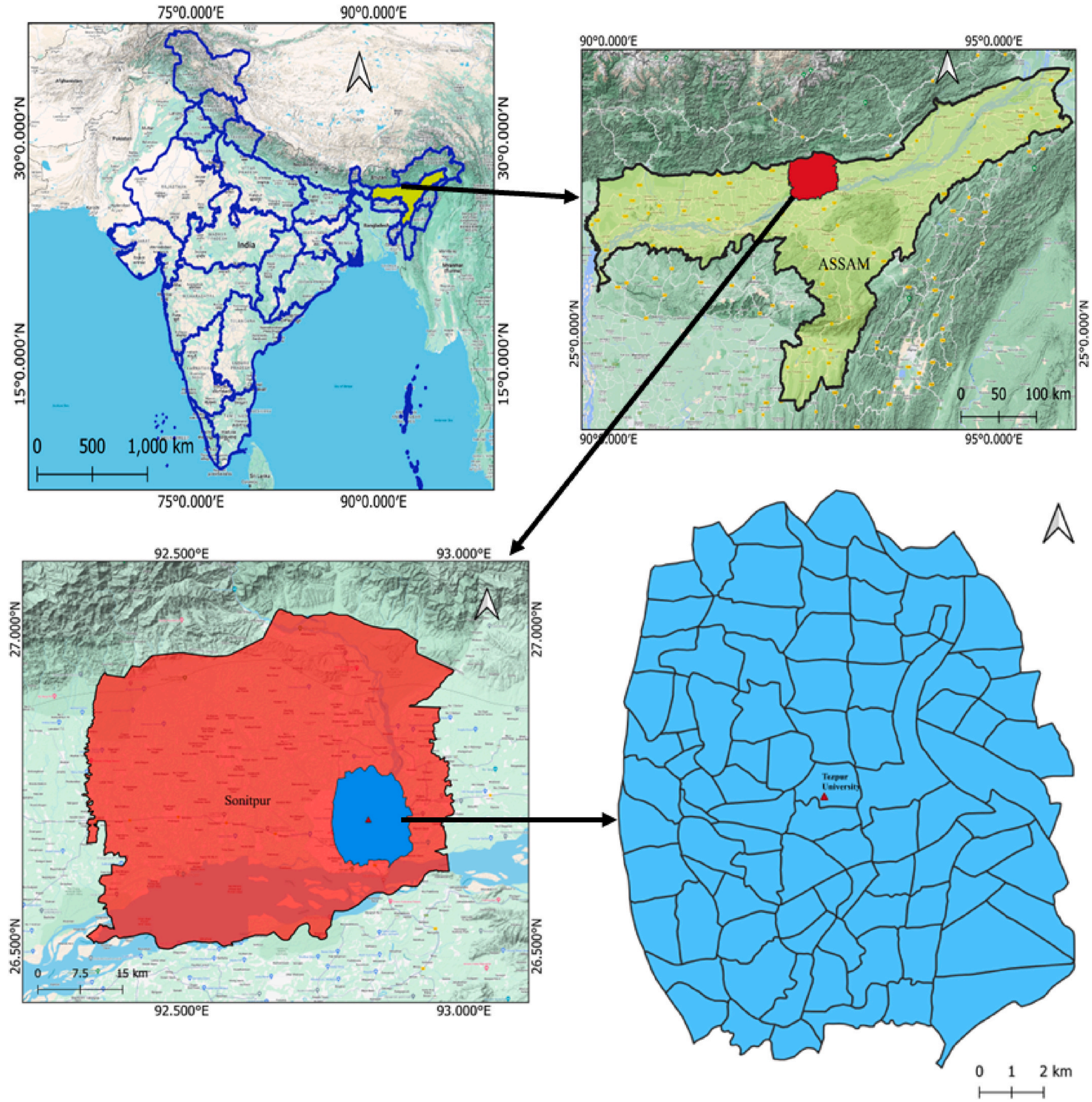

Fig. 1. Study area map and ROI with 90 villages around the proposed plant location (Tezpur University).

Table 2
Specifications of the remote sensing data collected for this study [49].

Satellite	Sentinel 2 (Twin satellite)
Sensor	L2A (MSI)- Bottom of atmosphere
Swath	290 km
Spatial resolution	10 m
Spectral bands (wavelengths)	B2-Blue (490 μm), B3-Green (0.560 μm), B4-Red (0.665 μm) and B8-NIR (0.842 μm)
Acquisition dates (Path, Row)	February 17, 2023
Cloud coverage	0 %

$$SR = P \times RPR \times SRF \quad (2)$$

$$MP = 0.25 \times SGY \times SR \quad (3)$$

Where, P is the overall rice crop production, Y is the rice crop yield, A is the area of cropland, SR is the surplus rice straw residue, RPR is the residue production ratio, SRF is the surplus residue factor, MP is the methanol production potential, and SGY is the syngas yield from rice straw gasification. Table 3 shows the rice yield, RPR, SRF and SGY used in this study.

Table 3
Factors used for estimation of rice straw and biomethanol potential.

Factors	Values	[Ref.]
Rice yield (Y) (in kg/ha)	2236	[50]
Residue production ratio (RPR)	1.5	[6]
Surplus residue factor (SRF)	0.24	[6]
Syngas yield (SGY) (in Nm^3/kg)	1.16	[6]

2.3. Network analysis for collection and transportation of rice straw

The success of any biofuel plant hinges on two critical factors: efficient collection and cost-effective transportation of its feedstock. Biomass, by its very nature, exhibits variations in availability across vast geographical regions. This inherent spatial variability makes collection and transportation a key cost driver for biofuel production. To minimise these costs, biofuel facilities require a well-designed network for optimal collection and transportation of feedstock [24].

This study focuses on identifying the most cost-effective road network for collecting all the rice straw available within the ROI. While the broader area encompasses a diverse range of roads, including highways, main service roads, rural roads, urban roads, and even cycle paths, our transportation modelling prioritises national highways, main roads, and rural roads – the infrastructure most suitable for large-scale feedstock movement. The foundation for our analysis is a base road network map acquired from the OpenStreetMap (OSM) database [51]. However, to ensure comprehensiveness and an up-to-date road network map for our analysis, many missing road segments within the ROI have been digitised over the base roadmap network using QGIS 3.34 Prizren and Google satellite imagery.

To streamline transportation and ensure a steady supply, it is proposed to collect and store the rice straw biomass at specific designated locations. The study area is organised into 9 clusters, each containing multiple villages. Using QGIS, specifically designated locations in the centroidal area of these clusters are chosen as collection sites, strategically selected away from residential areas to avoid causing inconvenience to local residents. This also helps in reducing the travel distances for farmers delivering their feedstock as it optimises collection efficiency and reduces transportation costs [24]. Then, using the QGIS's Network Analysis (Point to Layer) method over the designed road network, the shortest transportation distances were determined. This analysis covered two main aspects: the shortest distance from the biofuel plant located at Tezpur University to the collection points and the shortest distance between each village centroid and its respective cluster's collection point.

2.4. CF associated with rice straw-based biomethanol production

This study includes a modern local rice cropping scenario with the involvement of human labour and machinery work only, derived from discussions with farmers in the ROI. This local scenario has been designed based on different inputs associated with rice cropping and straw generation processes. The scenario is detailed in Table 4. The main operations involved in rice cropping and rice straw generation taken into consideration in this study are-land preparation (LP), fertilisers application (FA), transplanting (TP), irrigation (I), pesticide application (PA), harvesting (H), threshing (TH), collection and transportation (C&T). Tables 5 and 6 give insight into the CF coefficients and farm machinery details, respectively.

2.4.1. CF associated with rice straw production

To accurately assess the CF associated with the production process of rice straw, it is essential to consider the emissions from various operations involved in rice cultivation. However, it is clear that the primary goal of these operations is to maximise rice grain production. Consequently, an argument can prevail in terms of attributing the majority of the CF from these operations to the rice grain itself. In this study, the CF assessment has been conducted using a 60:40 attribution ratio for rice grain to rice straw [60]. This means that 60 % of the CF is allocated to rice grain production, while 40 % is attributed to rice straw. To maintain consistency, a CF attribution factor (CFF) of 0.4 has been uniformly applied to all inputs associated with rice straw production, including human labour, machinery work, diesel consumption, fertiliser and pesticide usage. The CFs associated with gross rice straw and surplus rice straw production are calculated using Eqs. (4a) and (4b).

Table 4
Input parameters for CF analysis for local rice production scenario.

Operations	Human-h/ha	Engine or thresher-h/ha*	Tractor-h/ha	Diesel, l/ha
Land preparation (LP)	30	0	30	37.5
Fertiliser application (FA)**	22	0	0	0
Transplanting (TP)	224	0	0	0
Irrigation (I)	20	20	0	25
Pesticide application (PA)**	9	0	0	0
Harvesting (H)	235	0	0	0
Threshing (TH)	13	4	0	5

*Engine work and thresher work are considered the same.
**CF associated with the consumed amount of fertilisers and pesticides is calculated directly based on area, coefficients for which are shown in Table 5.

Table 5
CF coefficients for different inputs.

CF inputs	CF coefficients for inputs	[Ref.]
Human-h engagement	0.009 kg CO_2/h	[52]
Farm machinery (Engine/Thresher/Tractor)-h engagement	12.8 kg CO_2e/kg farm machinery	[53]
Diesel consumption (Direct)	2.6595 kg CO_2/l	[54]
	0.0009 kg CO_2e CH_4/l	
	0.0191 kg CO_2e N_2O/l	
Diesel consumption (indirect)	0.5644 kg CO_2e/l	
Fertiliser	226.48 kg CO_2e N_2O/ha	[55]
Pesticide	3.6 kg CO_2e/ha	[56]

$$CF_{GR} = CFF \times \sum\nolimits_{j=1}^{n} \left(\sum\nolimits_{i=1}^{n} (CF_i \times I_i) \times A_j \right) \tag{4a}$$

$$CF_{SR} = CF_{GR} \times SRF \tag{4b}$$

Where, CF_{GR} is the CF associated with rice straw production from the jth cluster, measured in tonne CO_2e; CFF is the CF attributing factor for rice straw production; CF_i is the emission coefficient for the ith work-input, expressed in kg CO_2e per unit input, as detailed in Table 6; I_i is the quantity of ith input, unit/ha, as detailed in Table 4; A_j is the area under jth cluster.

2.4.2. CF associated with the collection and transportation of rice straw

In this study, the collection and transportation of rice straw were analysed with specific parameters. For each trip, it was assumed that four individuals would be engaged alongside a tractor capable of transporting a maximum load of 1000 kg (or 1 tonne) of rice straw. The

Table 6
Farm machinery details [57–61].

Machinery	Capacity	Weight	Useful life
Tractor	28 kW	1340 kg	10000 h
Ploughing attachment for Land preparation	4 disc	490 kg	10000 h
Tractor hydraulic trolley for transportation	3000 kg	900 kg	10000 h
Engine/thresher for Irrigation and Threshing	3.7 kW	140 kg	10000 h

time required only for the collection and loading of 1 tonne of rice straw was estimated to be 12 human hours (Human-h).

The transportation operation was divided into two distinct stages, Stage 1 and Stage 2. Stage 1 involves transporting the rice straw from the cropland to a collection centre, and Stage 2 involves moving the rice straw from the collection centre to a power plant. By delineating these stages, this study aims to provide a comprehensive understanding of the human and machinery resources required and associated CF for the efficient collection and transportation of rice straw from cropland to plant location. The collection and loading time has also been considered in Stage 2. The associated human-hours, tractor-hours and diesel consumption in rice straw collection, Stage 1 and Stage 2 transportation can be calculated using the formulae depicted in Table 7.

Where.

- N_j is the number of trips, which is calculated based on Eq. (5),
- AD is the average distance covered for transportation of rice straw from cropland to collection point (*Considered as 5 km in total),
- S is the average speed of the tractor considered (25 km/h),
- M is the mileage of the tractor (0.11 km/l),
- TSD_j is the total shortest distance for jth location acquired from network analysis data, A_j is the area under jth cluster.

$$\mathbf{Nj} = \frac{\text{Total Rice Straw in jthe Cluster}}{\text{Load capacity each trip}} \tag{5}$$

2.4.3. CF-associated biomethanol production

The CF associated with rice straw-based methanol production is calculated by considering not only the emissions from the rice cropping operations but also the operations involved in methanol production. The CF associated with processes, such as gasification of rice straw and syngas conditioning, is not considered here, as it is already accounted for in the carbon content of the biomass itself. Moreover, there is no CF associated with syngas cleaning, CO_2 removal and methanol synthesis process. Only the CF associated with rice straw processing, overall electricity consumption and ash handling operations are considered, CF coefficients for which are detailed in Table 8. The CF associated with rice straw-based methanol production (CF_{MP}) can be calculated using Eq. (6).

$$\mathbf{CF}_{MP} = \sum_{\mathbf{i=1}}^{\mathbf{n}} (\mathbf{CF_m})_{\mathbf{i}} \times \mathbf{MP} \tag{6}$$

2.4.4. Overall CF-associated rice straw-based biomethanol production in the ROI

The overall CF (CF_{total}) associated with rice straw-based methanol production, encompassing the stages of rice straw production, collection, transportation, and subsequent methanol production, can be calculated using Eq. (7).

$$CF_{total} = CF_{RS} + CF_{C\&T} + CF_{MP} \tag{7}$$

Where, CF_{RS} is the total CF associated with rice straw production, $CF_{C\&T}$ is the total CF associated with the collection and transportation, and CF_{MP} is the total CF associated with methanol production.

Table 8
CF associated with methanol production [42].

CF input operations	CF coefficient $(CF_{MP})_i$
Rice straw processing	6.27×10^{-02} kg CO_2e/kg methanol
Electricity consumption	2.31×10^{-2} kg CO_2e/kg methanol
Ash handling	8.04×10^{-4} kg CO_2e/kg methanol
Total CF_m	8.66×10^{-2} kg CO_2e/kg methanol

2.5. Assumptions and considerations

There are certain assumptions taken into account for this case study, in the case of both GIS and CF analysis, as mentioned below-

a) To maximise the availability of feedstock (rice straw), a farming framework is proposed within the Region of Interest (ROI), encouraging farmers to adopt practices that enhance rice straw production.
b) The study recommends an annual rice cropping cycle to maximise rice straw production, with crop rotation advised to minimise fertiliser use.
c) Consistent values for Rice Production Rate (RPR), Straw Recovery Factor (SRF), and rice yield are assumed across all villages within the ROI, acknowledging potential variations in reality.
d) An average distance of 5 km for collection and transportation in the initial stage is considered, although this may vary depending on factors such as paddy field size and cluster configuration.
e) The bailing process is omitted from the CF analysis, assuming minimal rice straw residue is left in the cropland during harvesting.
f) Rice straw collection is planned to commence concurrently with threshing.
g) Machinery CF inputs for gasification and methanol synthesis are not included due to data unavailability.
h) Plant operation is assumed to be continuous for 365 days when calculating biomethanol production.
i) Tractor attachment weights (e.g., ploughing attachment, trolley) are factored into CF calculations for respective operations.

3. Results and discussion

3.1. Cropland visualisation

Fig. 2 shows the true colour composite basemap after preprocessing the Sentinel multispectral satellite images. The Kameng River is visible, flowing through the eastern part of the region. The proposed biomethanol plant, located at Tezpur University, is situated near the centre of the ROI, approximately 2 km from the Kameng River. To the northwest of Tezpur University, the runway of Tezpur-Salonibari Airport (TEZ), one of the six airports in Assam, is clearly visible.

Fig. 3 shows the available cropland in the region, highlighted in green patches. This "Cropland" classified image is derived from the image in Fig. 2 using the QGIS SCP plugin, followed by postprocessing, cleaning, and modification steps. Based on this final image, nine clusters have been created to quantify the available rice straw in different parts of ROI for easy collection and transportation.

Table 7
Time inputs for rice straw collection and transportation.

Operation	Human-h/ha	Tractor-h/ha	Diesel, l/ha
Collection and loading (Stage 1 & Stage 2)	$2 \times 12 \times \frac{Nj}{Aj}$	0	0
Stage 1- Transportation (From cropland to collection point)*	$4 \times \frac{AD \times Nj}{S \times Aj}$	$\frac{AD \times Nj}{S \times Aj}$	$\frac{AD \times Nj}{M \times Aj}$
Stage 2- Transportation (From collection point to power plant)	$4 \times \frac{TSDj \times Nj}{S \times Aj}$	$\frac{TSDj \times Nj}{S \times Aj}$	$\frac{TSDj \times Nj}{M \times Aj}$

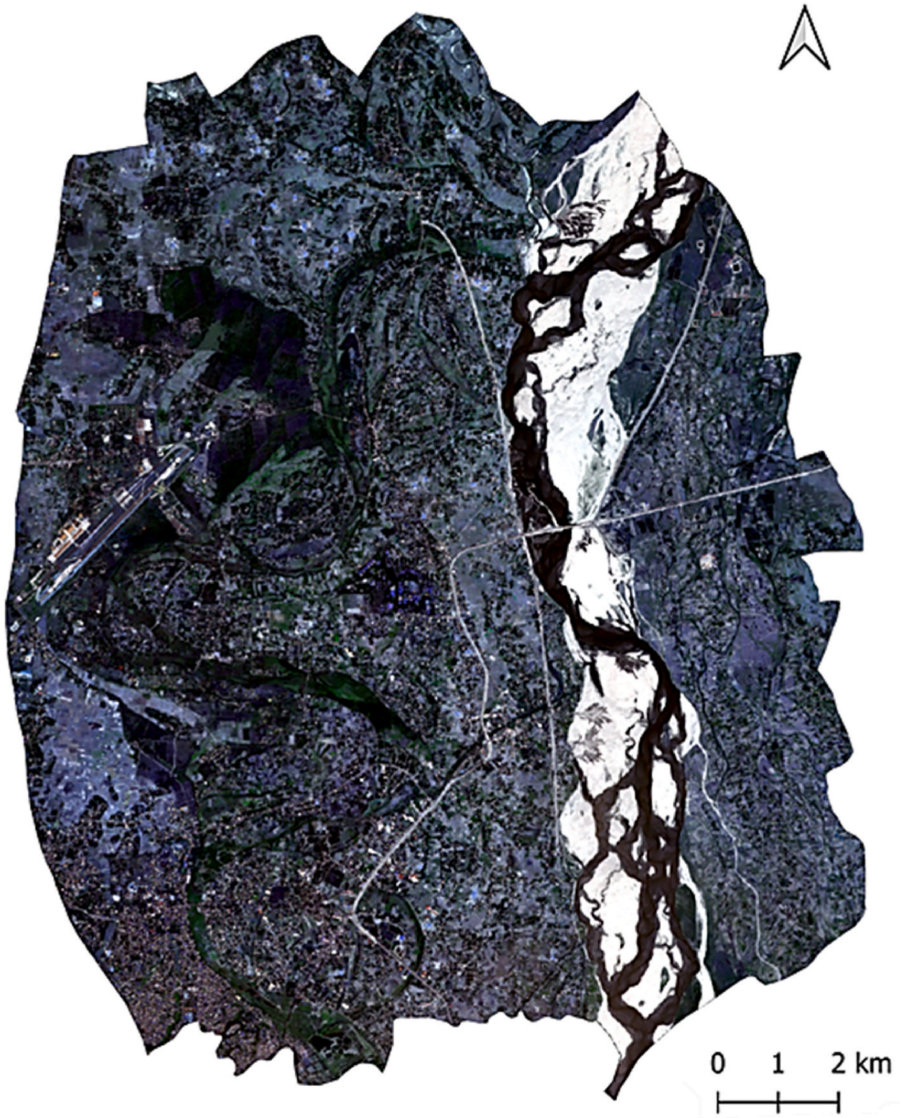

Fig. 2. True colour composite basemap of the ROI after preprocessing. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

3.2. Rice straw and biomethanol potential assessment

Table 9 presents the estimated cropland availability, rice straw yield, and biomethanol production potential for each cluster. Of the 90 villages within the ROI, 8 are excluded due to minimal or zero cropland, as they fall within riverbeds, airport zones, or inaccessible wetlands. The remaining 82 villages are divided into 9 clusters, as detailed in the previous section.

The villages belong to two different sub-districts—Tezpur Circle and Chariduar Circle, but they are unevenly distributed within the clusters. Cluster 4, which includes 8 villages, has the highest cropland area, totalling approximately 913.5 ha. This cluster has the potential to produce around 735.32 tonnes of surplus rice straw and 202.58 tonnes of biomethanol in FY-2023. In contrast, Cluster 8, with the fewest villages at 6, possesses the smallest cropland area, approximately 450.6 ha. It has the potential to produce 362.69 tonnes of surplus rice straw and 99.92 tonnes of biomethanol in FY-2023. The total cropland area available in the ROI is approximately 5480.535 ha, with a potential rice straw production of 4411.612 tonnes. The estimated biomethanol production potential is about 1215.4 tonnes per year, equivalent to roughly 3.33 tonnes per day, assuming year-round plant operation. This production capacity in the small ROI of 90 villages represents about 0.67 % of the output of a 500 tonnes per day natural gas-based methanol production plant at Namrup, Assam, which was recently commissioned in April 2023 under the flagship of the Government of Assam and Oil India [62]. Moreover, a yield of 0.275 kg methanol per kg of rice straw was observed, aligning with data reported in other literature sources [42,63,64]. This showcases the potential of small-scale biofuel plants to aid India's efforts towards a global biofuel alliance and net-zero emissions in the near future.

3.3. Collection and transport network analysis

Fig. 4 displays the road network for the ROI, modified over the OpenStreetMap (OSM) base map. Collection points have been established in each village cluster to facilitate the collection and transportation of rice straw. To meet the biofuel production target of 3.33 tonnes per day, a total of 4411.612 tonnes of surplus rice straw must be collected and transported from all available croplands. Fig. 5 presents the results of the network analysis (point to layer) performed on the designed road network. The shortest distances required to collect the rice straw residues are summarised in Table 10.

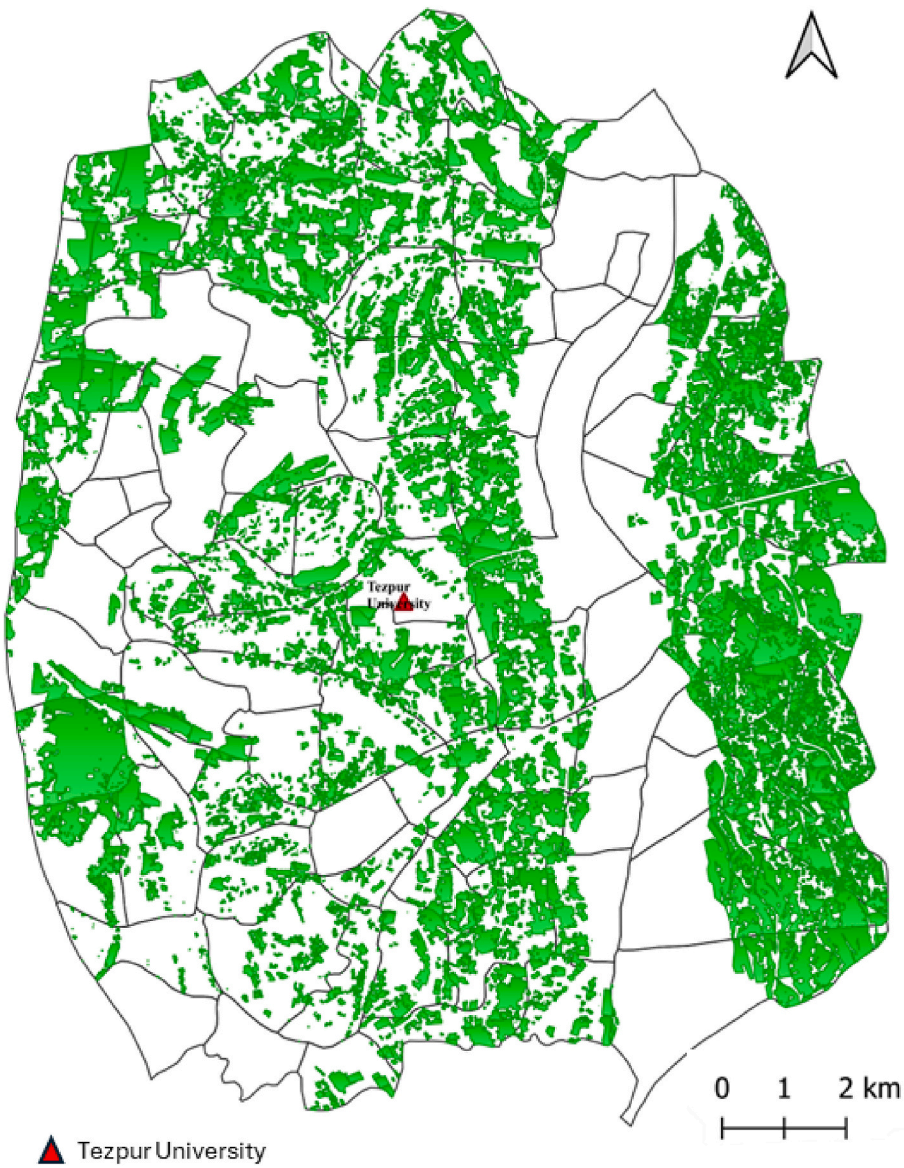

Fig. 3. "Cropland" (in green colour) classified map of the ROI after classification and postprocessing. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 9
Cluster-wise availability of cropland, rice straw and biomethanol potential in FY-2023.

Clusters	No of villages	Sub-district (Villages)	Potential cropland area (A) (in ha)	Surplus rice straw potential (SR) (in tonne)	Biomethanol production potential (MP) (in tonne)
Cluster 1	10	Tezpur Circle (10)	478.729	385.358	106.166
Cluster 2	10	Tezpur Circle (10)	532.067	428.293	117.995
Cluster 3	10	Tezpur Circle (9), Chariduar Circle (1)	497.905	400.794	110.419
Cluster 4	8	Tezpur Circle (7), Chariduar Circle (1)	913.484	735.318	202.580
Cluster 5	8	Chariduar Circle (8)	765.704	616.361	169.807
Cluster 6	12	Tezpur Circle (8), Chariduar Circle (4)	565.274	455.023	125.359
Cluster 7	9	Tezpur Circle (2), Chariduar Circle (7)	573.359	461.531	127.152
Cluster 8	6	Chariduar Circle (6)	450.568	362.689	99.921
Cluster 9	9	Chariduar Circle (9)	703.444	566.244	156.000
Zero Cropland Area	8	Tezpur Circle (5), Chariduar Circle (3)	0	0	0
Total			5480.535	4411.612	1215.399

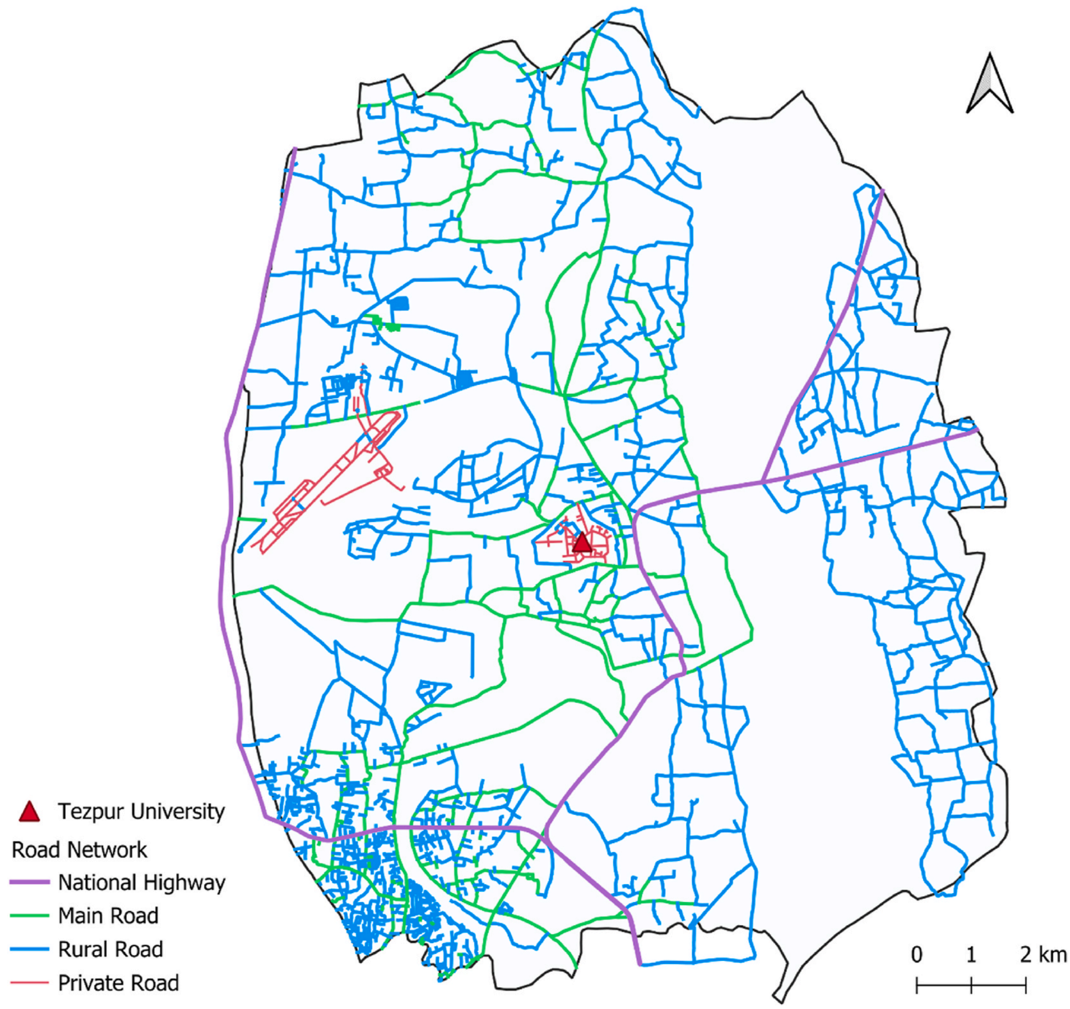

Fig. 4. Modified OSM-based roadmap network of the ROI.

It is observed that Cluster 4, despite having the highest rice straw residue potential, is also the farthest, requiring a total distance of 25.5 kms for collection and return. The two nearest collection points from the proposed plant location are for Cluster 6 and Cluster 3, with overall commutable distances for collection and transportation of 7.3 and 7.5 kms, respectively. The average total distance to cover for all clusters is found to be 15.68 km.

3.4. CF assessment of the rice straw-based biomethanol production

3.4.1. CF associated with rice cropping and rice straw generation

Table S1 and Fig. 7 show the comparison of CF associated with different operations and inputs in rice cropping. The total potential CF associated with rice cropping is found to be 528.59 kg CO_2e/ha. Consequently, the total potential CF associated with the gross rice straw production is estimated to be 211.44 kg CO_2e/ha. The CF associated with surplus rice straw production is found to be 50.74 kg CO_2e/ha, with a total yearly CF of 278.11 tonnes CO_2e for the whole ROI. In terms of rice cropping operations, the highest CF of 226.48 kg CO_2e/ha is attributed to fertiliser consumption, followed by land preparation (192.19 kg CO_2e/ha) and irrigation (84.86 kg CO_2e/ha). Fig. 6 shows the whole process of CF assessment for rice straw-based biomethanol production.

3.4.2. CF associated with the collection and transportation of rice straw

The CF associated with rice straw collection and transportation is detailed in Table 11. The total CF associated with rice straw collection for both stage 1 and stage 2 transportation is found to be 0.17 kg CO_2e/ha. However, the CFs for stage 1 and stage 2 transportation are found to be 1.67 and 5.18 kg CO_2e/ha. The total amount of CF associated with collection and transportation is estimated to be 7.02 kg CO_2e/ha, with a yearly amount of 38.47 tonnes CO_2e for the whole ROI.

3.4.3. CF associated with biomethanol production

The CF associated with the production of potential biomethanol has been depicted in Table S2. It can be seen that rice straw processing is the major source of CF for biomethanol production. The total CF associated with the biomethanol production process in the proposed ROI in a year would be 105.26 tonnes CO_2e, with 72.4 % associated with rice straw processing, 26.67 % associated with electricity consumption and the rest for ash handling.

3.4.4. Overall CF associated with rice straw based-biomethanol production

As shown in Table S3, Fig. 8 and using Eq. (7), the total CF_{total} associated with rice straw-based biomethanol production is estimated to be 421.840 tonnes CO_2e/year for the ROI. The breakdown of this CF is as follows.

- Rice straw production: This accounts for 65.93 % of the total CF associated with rice straw-based biomethanol production, with 0.063 kg CO_2e/kg rice straw.
- Rice straw collection and transportation: These activities contribute 9.12 % of the total CF for biomethanol production in the ROI per year, equating to 0.009 kg CO_2e per kg of rice straw.

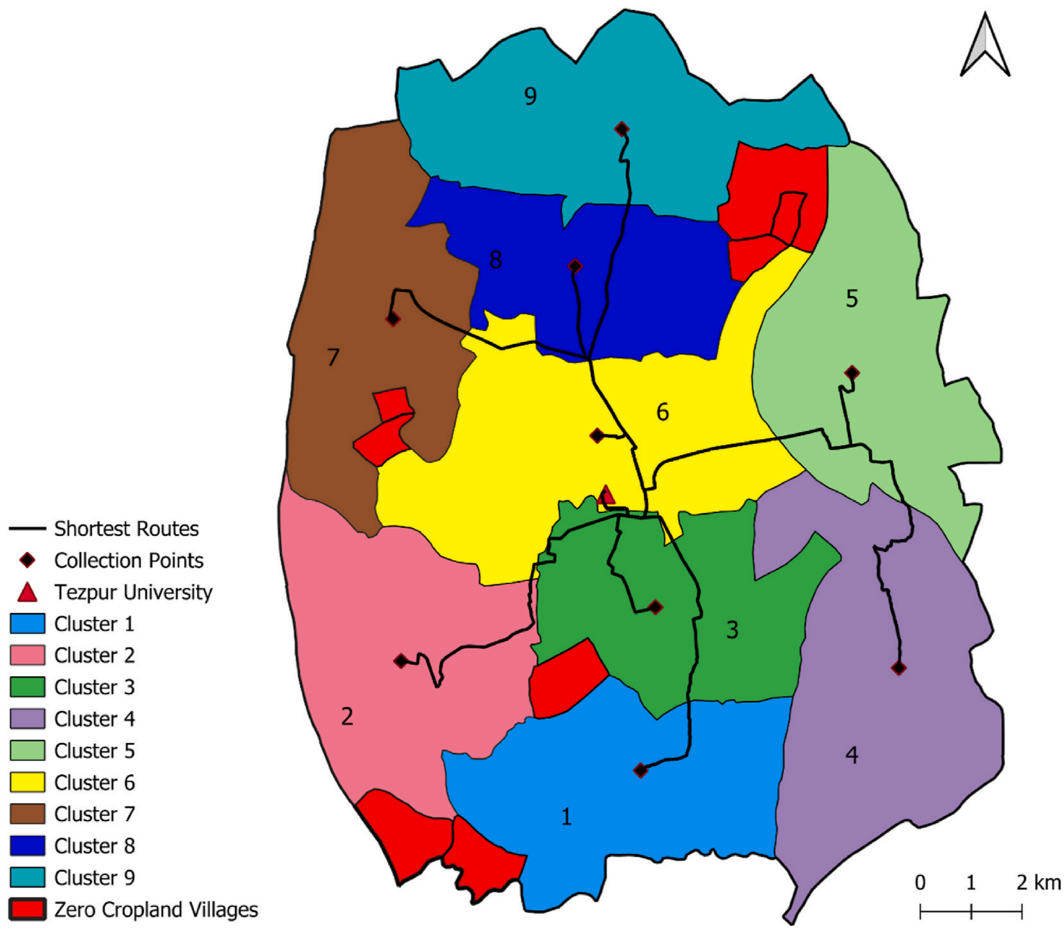

Fig. 5. A network analysis of collection points and shortest travel routes of different village clusters.

Table 10
Details of shortest distance routes for each cluster.

Cluster	Start location	End location	Shortest route distance in one direction (in m)	Total shortest distance to cover in both directions (TSD) (in km)	Number of trips required (N)
Cluster 1	Tezpur University	Collection point 1	7590.78	15.2	385
Cluster 2	Tezpur University	Collection point 2	8646.50	17.3	428
Cluster 3	Tezpur University	Collection point 3	3742.85	7.5	401
Cluster 4	Tezpur University	Collection point 4	12738.18	25.5	735
Cluster 5	Tezpur University	Collection point 5	8427.82	16.9	616
Cluster 6	Tezpur University	Collection point 6	3639.08	7.3	455
Cluster 7	Tezpur University	Collection point 7	9541.86	19.1	462
Cluster 8	Tezpur University	Collection point 8	6620.15	13.2	363
Cluster 9	Tezpur University	Collection point 9	9552.88	19.1	566

- Biomethanol production process: The process of producing biomethanol itself is responsible for 24.95 % of the total CF for the ROI per year.
- The net CF of 0.347 kg CO_2e/kg methanol was found, which was much lower than other studies, as well as fossil-based methanol [42, 65].

4. Overall framework potential

4.1. Limitation of this study

This study presents a robust framework for assessing biomethanol production from rice straw, but several limitations should be acknowledged. The model assumes uniform residue production and recovery rates across the study area, though these can vary due to factors like crop variety, farming practices, and climatic conditions. Additionally, preprocessing methods (e.g., baling) and long-term storage factors, including their associated carbon footprint and costs, were not considered, yet they are crucial in large-scale biomass harvesting and transportation. The study also lacks data on the emissions from gasification and syngas production, which could impact the overall environmental footprint. Furthermore, the research is focused on Assam, India, and its unique agricultural, infrastructure, and socio-economic context, which may limit the generalisation of the findings to other regions with different crop patterns, climates, or infrastructure.

4.2. Research generalisation

The utilisation of GIS technology and satellite imagery provides a

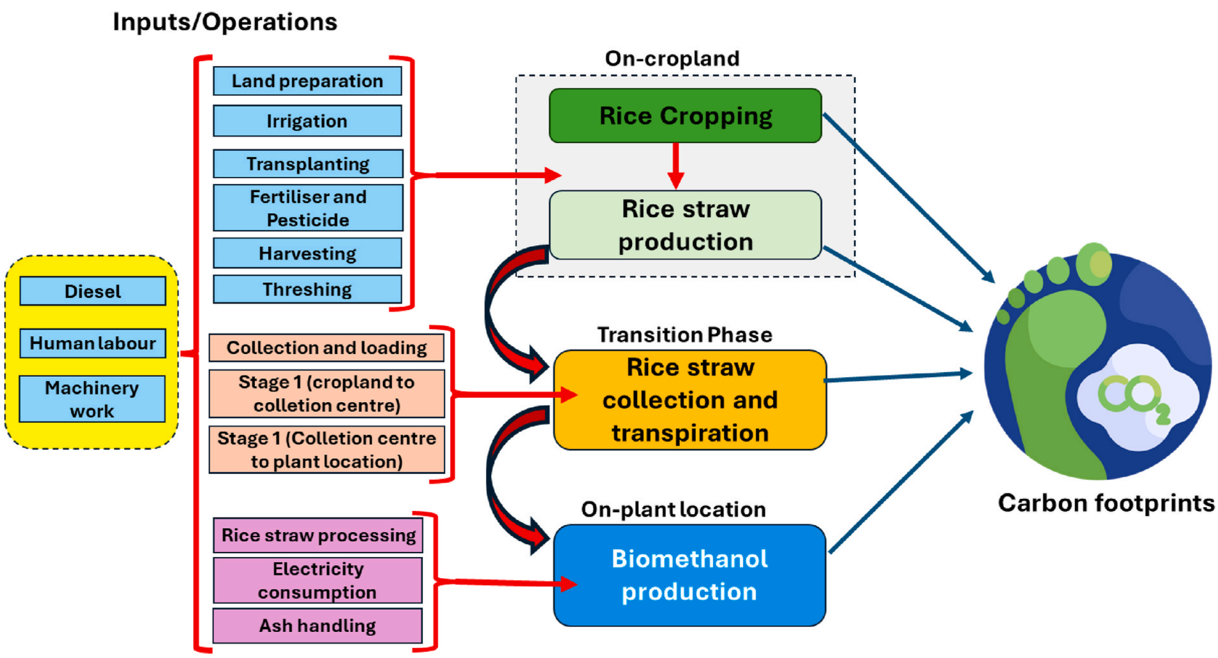

Fig. 6. Input and operations associated with rice straw-based methanol production.

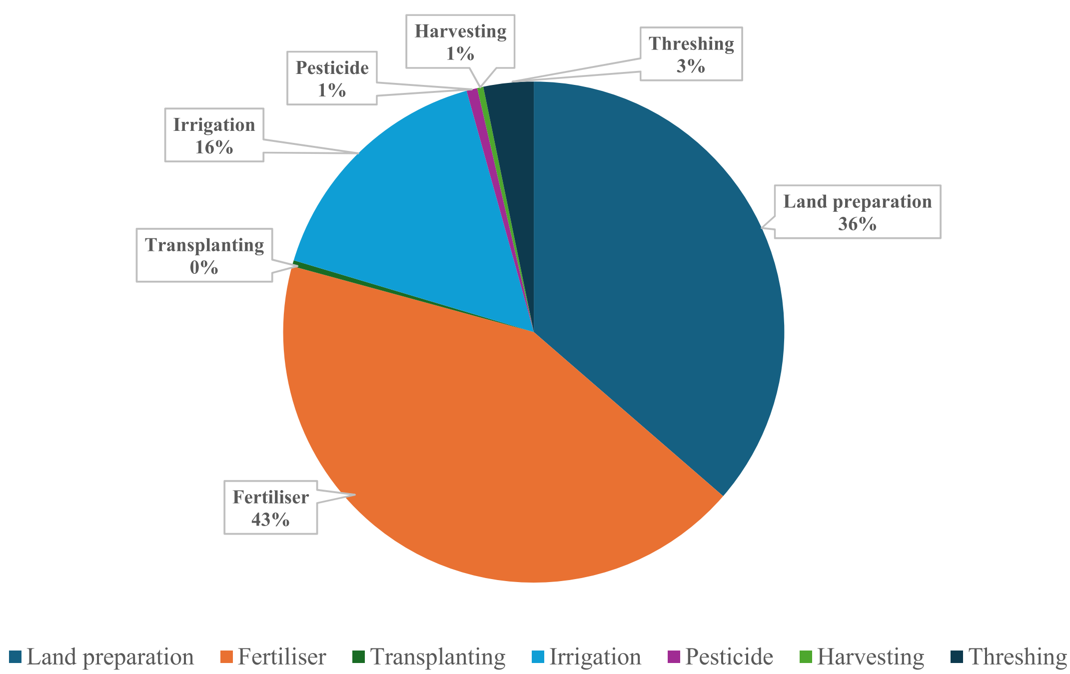

Fig. 7. Carbon footprint assessment outputs associated with rice cropping.

Table 11
Total CF associated with rice straw collection and transportation.

Operations	Inputs			CF of inputs (kg CO_2e/ha)			Operation wise CF/ha (kg CO_2e/ha)
	Human-h/ha	Tractor-h/ha	Diesel, l/ha	Human	Tractor	Diesel	
Collection and loading	19.32	0.00	0.00	0.17	0.00	0.00	0.17
Stage 1- Transportation	0.64	0.17	0.37	0.01	0.46	1.19	1.65
Stage 2- Transportation	2.02	0.50	1.15	0.02	1.45	3.72	5.19
Total	21.98	0.67	1.51	0.20	1.91	4.91	7.02
Total CF associated with rice straw collection and transportation (in kg CO_2e/ha)							7.02
Total CF associated for rice straw collection and transportation in the ROI/year (in tonne CO_2e)							38.473

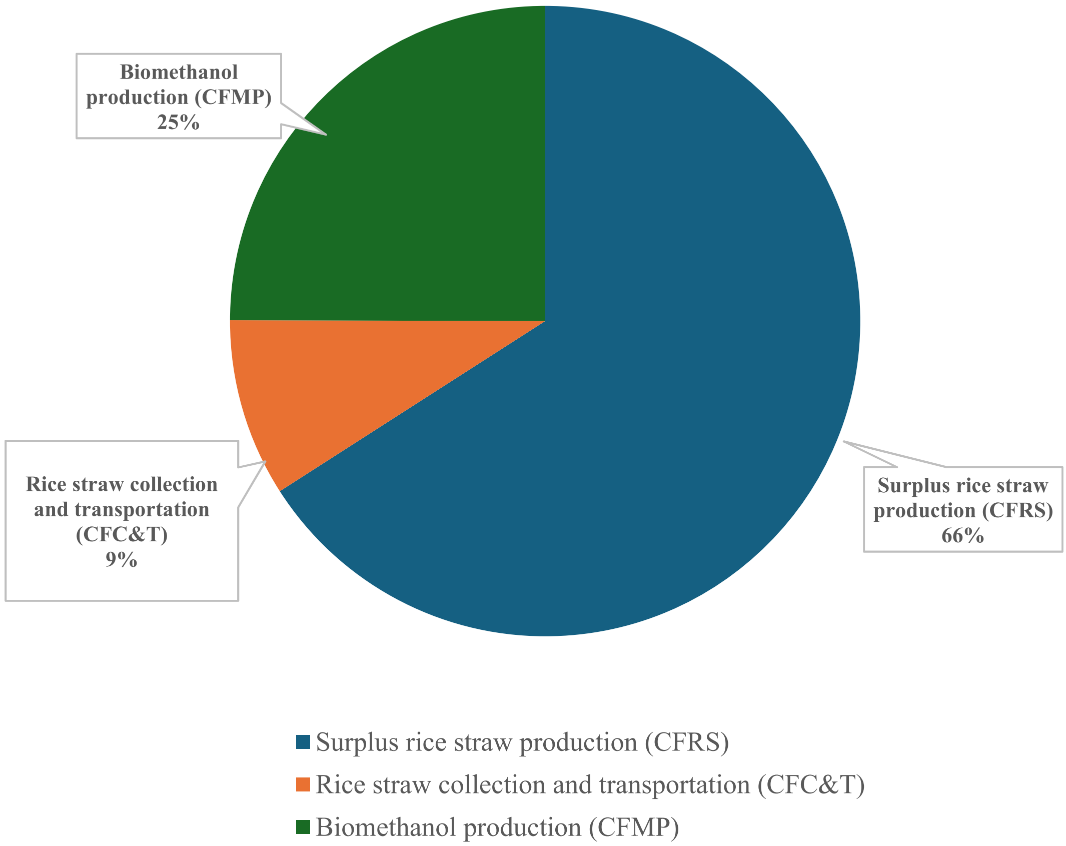

Fig. 8. Carbon footprint associated with rice straw-based methanol production stages.

universally applicable method for identifying cropland availability and quantifying residue production, allowing for precise localisation of biomass resources. Adjustments to regional cropping cycles, residue recovery rates, and local agricultural practices ensure the accuracy of the data. Residue production ratios (RPR) and surplus residue factors (SRF), derived from farming practices, can be replaced with region-specific parameters to assess biomass potential. Supply chain optimisation strategies, including collection and transportation, can be tailored to regional road networks for cost-effective logistics. Similarly, carbon footprint coefficients and economic assessments can be adjusted to reflect local energy mixes, emission factors, and machinery specifications, ensuring relevance across diverse socio-economic contexts. The framework is scalable to larger or smaller agricultural footprints, aligning with clean energy initiatives globally. Its modular design supports integration with other crop residues, such as wheat straw, maise stover, or sugarcane bagasse, making it adaptable to various agricultural systems, particularly in developing economies. This versatility positions the framework as a valuable tool for advancing bioenergy development while contributing to global net-zero emission goals.

4.3. Policy implications for emerging economies

This framework supports the transition to sustainable energy systems, particularly in countries like India. By demonstrating the feasibility of decentralised biomethanol plants it encourages localised energy production, reducing reliance on centralised fossil fuel systems and improving rural energy security. Policies offering subsidies or tax benefits can further drive economic growth in underserved areas. Additionally, the model promotes a circular bioeconomy by converting agricultural residues like rice straw into biofuels, supported by measures such as minimum support prices (MSP) or carbon credit incentives. It provides an alternative to residue burning, aligning with climate goals while improving public health. The framework also integrates into national energy objectives like India's Net-Zero targets for 2070, creating jobs in biomass collection, transport, and plant operations, thus fostering rural development.

The model can be scaled across India by adapting parameters for regional residues like wheat straw or sugarcane bagasse, enabling tailored biofuel policies. Globally, it is applicable in emerging economies with similar challenges, such as Southeast Asia or Africa, where it can be adapted to local crops and conditions. Multi-feedstock systems combining residues with municipal waste or animal manure enhance scalability. The framework also provides a basis for international biofuel collaboration, fostering knowledge exchange and joint ventures.

4.4. Transporation and collection challenges

While this study focuses on an optimised framework for rice straw collection and transportation, there are numerous potential implementation challenges. Seasonal road closures due to monsoons in Assam can disrupt transportation; this could be mitigated by mapping alternative routes and incorporating seasonal road usability data. Labour shortages from socio-economic factors or competing demands may be addressed through community engagement, policy incentives, or mechanised collection, though the latter requires investment and training. Transportation delays, caused by bottlenecks or vehicle breakdowns, can be minimised through cluster-based collection points, dynamic scheduling, and contingency planning. Collaboration with policymakers for infrastructure improvements is also essential. Future iterations of the framework could integrate probabilistic models for uncertainty management, real-time GIS updates for adaptive planning, and partnerships with stakeholders to address these challenges, enhancing scalability and practical applicability in diverse scenarios.

4.5. Supply chain complexity factors

Several complexity factors, as mentioned below, need to be addressed to make the framework robust and scalable for larger or international applications. This will enable policymakers to tackle real-world challenges effectively while ensuring that biomethanol production remains feasible [66–68].

a) Multi-tier supplier networks

Scaling the framework to larger operations introduces multi-tier supplier networks, adding variability in pricing, quality, and delivery timelines. This can be addressed through supplier contracts to standardise residue quality, digital platforms for tracking residue availability and payments, and cluster coordinators or cooperatives to streamline supplier interactions and operations.

b) Cross-border supply chains

Cross-border operations bring challenges like regulatory requirements, tariffs, and logistical complexities. These can be addressed by aligning bioenergy trade policies with neighbouring countries through policy harmonisation, planning for transportation infrastructure and customs processes, and leveraging free trade agreements and partnerships to mitigate risks and ensure smooth operations.

c) Supply chain disruptions

Disruptions such as natural disasters, strikes, or fuel shortages can significantly affect biomass availability. To mitigate these risks, it is essential to implement strategies like redundancy and diversification, which involve developing alternative supply sources and routes to minimise reliance on single clusters. Additionally, dynamic modelling that incorporates real-time monitoring can help adapt routes and schedules as needed. Inventory buffers, such as short-term storage at collection centres, can also ensure a steady supply during delays.

d) Future Adaptation of the Framework

To tackle these complexities, advanced tools can significantly improve the framework. Agent-Based Modelling (ABM) can simulate interactions between suppliers and networks to optimise operations. Scenario analysis allows the evaluation of potential disruptions, such as road closures or labour shortages, helping to develop effective contingency plans. Blockchain technology can enhance transparency and traceability across supply chains, especially in multi-tier and cross-border networks, ensuring reliability and accountability.

5. Conclusion and future prospects

This study demonstrates the potential for biomethanol production from rice straw biomass in rural Assam, India, by emphasising accurate biomass assessment and optimised transport networks for efficient bioenergy production. By considering feedstock availability, its associated CF, and the integration of advanced technologies, this research supports India's transition to a sustainable energy future. GIS was applied to accurately determine the spatial availability of rice straw in Assam. This technology was crucial in analysing the biomass at appropriate spatial scales, confirming that significant quantities of rice straw are available for effective biomethanol production.

Designing cost-effective supply networks for the collection and transportation of rice straw was a critical component of the study. Optimised networks ensure economical and efficient biomass transport, minimising logistic costs and enhancing the feasibility of bioenergy projects. The region of interest (ROI) for this case study includes 90 villages around the proposed plant location. The overall potential cropland for rice cropping in the ROI is estimated to be approximately 5480.535 ha, with a rice straw production capacity of 4411.612 tonnes per year. Consequently, the rice straw-based biomethanol production potential is estimated to be around 1215.399 tonnes per year, equivalent to approximately 3.3 tonnes per day. An assessment of the CF associated with the production, collection, and transportation of rice straw and the subsequent biomethanol production within the ROI revealed emissions of 421.840 tonnes of CO_2e per year. This translates to 0.096 kg CO_2e per kilogram of rice straw and 0.347 kg CO_2e per kilogram of biomethanol, lower than the CF of traditional fossil-based methanol.

This case study has bright future potential, especially in terms of boosting energy security. The key to this is concentrating on the useful use of the methanol generated as a substitute fuel. A techno-economic analysis (TEA) will ascertain the economic feasibility and identify any technical problems, while a thorough life cycle inventory analysis (LCIA) will evaluate the environmental implications across all phases of production. One important tactic is to successfully combine methanol with fossil fuels that are widely used, such as diesel. By utilising current infrastructure and progressively switching to more sustainable energy sources, this blending can gradually reduce diesel consumption and can pave a path for alternative fuel implementation. As such, biomethanol has the potential to play a key role in resolving concerns related to energy security, encouraging a circular bioeconomy, and aiding in the achievement of net-zero emissions targets.

CRediT authorship contribution statement

Tanmay J. Deka: Writing – review & editing, Writing – original draft, Investigation, Formal analysis, Data curation, Conceptualization. **Bakul Budhiraja:** Writing – original draft, Software, Formal analysis, Data curation. **Ahmed I. Osman:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Debendra C. Baruah:** Writing – review & editing, Writing – original draft, Visualization, Validation, Project administration, Conceptualization. **David W. Rooney:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Project administration, Funding acquisition, Conceptualization.

Declaration of interest statement

The authors state that they have no known competing financial interests or personal ties that could appear to have influenced the work described in this study.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.biombioe.2024.107580.

Data availability

Data will be made available on request.

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