DECENTRALISED RENEWABLE ENERGY GENERATION FROM RICE STRAW RESIDUE IN SONITPUR DISTRICT OF ASSAM, INDIA: A STUDY ON RESOURCE ASSESSMENT AND POTENTIAL GREENHOUSE GAS EMISSION

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE
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DECLERATION

I do hereby declare that the thesis entitled "**Decentralised renewable energy generation from rice straw residue in Sonitpur district of Assam, India: A study on resource assessment and potential greenhouse gas emission**", being submitted to the Department of Energy, Tezpur University, is a record of original research work carried out by me. All sources of assistance have been assigned due acknowledgement. I also declare that neither this work as a whole nor a part of it has been submitted to any other University or Institute for any other degree, diploma or award.

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The committee recommends for the award of the degree of Doctor of Philosophy.

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The fear of the LORD is the beginning of knowledge—Proverbs 1:7

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ABSTRACT

Energy is the prime requirement for the growth and development of human society. The intensity of energy use has determinant influence on development of a region. Until now, major share of global energy need is fulfilled through fossil energy resources and this could continue for some more time. However, the fossil energy resources are diminishing at an alarming rate and they are also the major cause of global climate change. Therefore, all nations of the world are giving substantial importance to renewable and clean sources of energy. India, a major global economy, is also facing serious energy crisis. To maintain India's economic growth rate and achieve energy needs of every citizen, energy security and energy sustainability are major concerns for India. Fossil energy sources of the country are inadequate to meet its domestic energy need and therefore the country fairly dependent on foreign energy imports. More than 80% of the oil demand of India is met through foreign imports. Realising the limitations of fossil energy in India, the Government of India has attempted to harness renewable energy resources by implementing various policies, schemes and projects.

Assam is one of the 29 states of India situated in the North-Eastern part. Like many parts of India, there is a serious imbalance of energy supply-demand in Assam. Chronically deficient electrical power supply is considered as one of the major bottlenecks for development in the state of Assam. With the limitations of the traditional sources of energy, it is imperative to promote appropriate sources of renewable energy. The state of Assam is an agriculturally dominating region where about 70% population relies on crop production. Further, rice based cropping system is followed in all the districts of this region. Thus, prospect of surplus rice residue as a source of decentralised renewable energy generation has been matter of investigation of the present investigation.

Biomass, solar, wind and small hydro are the major sources of renewable energy in India. Biomass resources are almost uniformly distributed all over India. Among the various sources of biomass resources, India generates a large amount of agricultural residue biomass. Uses of agricultural residues including rice straw for renewable heat and power generation have been reported from many parts of the world including India. Agricultural residue has prospect as a resource for decentralised power generation in

many power deficient regions including in Assam. Soundness of power generation technology, appropriateness of feedstock (crop residue characteristics), precise and reliable assessment of feedstock (supply ensured) and prediction of environmental consequences are some of the major pre-requisites for planning and promoting crop residue based power generation. Considering the rice residue based power generation, technological soundness and feedstock characterisation have already been almost resolved. However, the issues of assessment and prediction of GHG emission are found unattended and therefore considered for the present investigation as highlighted below.

Crop residues are distributed resource with spatio-temporal variation in its availability. Furthermore, its competing uses also vary geographically. Traditional methods of assessment using survey and secondary data are not adequate to precisely estimate agricultural residue of a region. This is one of the barriers in implementation of agricultural residue based renewable energy programme. The use of Remote sensing (RS) and Geographic Information System (GIS) based spatial technique in renewable energy assessment has been gaining popularity all over the world. RSGIS can provide precise information of biomass resource strength even at a very small scale. In addition, the generated information can be retrieved and updated at user will. There are many successful examples of RSGIS uses in the assessment of forest and agricultural residue biomass. Furthermore, RSGIS have been also used to design biomass power plant, select optimal power plant location and identify cost effective biomass transportation network.

Unsustainable exploitation of biomass resources may even release more GHG (greenhouse gas) than its fossil counterpart and jeopardise many ecosystem functions. For example, bioenergy feedstocks production from natural forests or grasslands may not be justified option because these are already natural CO_2 sink. Furthermore, carbon payback time of bioenergy feedstocks production on such lands could also be very long. There are many successful examples of power generation using straw which is a potential by-product of rice crop production system. Large amount of rice straw is available in Assam, indicating prospect for power generation. However, it is important to assess net GHG balance of such rice straw power generation from a life cycle prospective. Life cycle assessment (LCA) has been widely used to assess GHG balance of biomass power projects. But, in India, database regarding biomass energy LCA, particularly agricultural residue based biomass energy is very limited.

Considering (i) potential of rice straw as a distributed energy resource for decentralised power, (ii) usefulness of spatial tools in biomass resource assessment, and (iii) importance of assessing greenhouse gas emission from rice straw based biomass power, the present research is conducted in Sonitpur district of Assam, India with three specific objectives, *viz.*, (1) to develop a spatial tool for biomass resource assessment, (2) to assess rice straw residue biomass availability for decentralised energy generation, (3) to assess GHG emission performance of biomass energy generation from rice straw using life cycle assessment (LCA) technique. Standard procedures are followed to achieve the objectives as highlighted below.

A Remote sensing (RS) and Geographic Information System (GIS) based spatial model is developed to assess distribution and availability of crop residues in Sonitpur district. A variety of inputs (software, spatial and non-spatial data and mathematical model) are used to run and generate output from the spatial model. ERDAS Imagine 9.1 software is used for satellite image processing, georeferencing and accuracy assessment, while ArcGIS 9.2 software is used to map spatial distribution of rice cropland and subsequently crop residue in Sonitpur district. The spatial data includes (i) remote sensing data (satellite images of medium and high resolution), (ii) Global Positioning System (GPS) data, and (iii) geographical maps (topographical maps, administrative boundary maps, road network map). On the other hand, non-spatial data includes (i) agricultural data, and (ii) field survey and laboratory analysis data. The output of this modelling tool in the form of spatial maps and attribute tables are further used with mathematical models to quantify rice straw residue availability and subsequently biomass energy potential. This is done at three pre-set spatial levels, *viz.* (i) district (highest level of administrative unit within the province), (ii) development block (administrative units for decentralised governance) and (iii) village (smallest recognised administrative unit).

Greenhouse gas (GHG) emission performance of rice straw based biomass power is assessed from LCA prospective. Three major GHGs *viz.* CO_2, CH_4 and N_2O are considered while evaluating the emission performance. The GHG emission is estimated throughout the life cycle stages of rice straw based biomass power, *i.e.* (a) rice crop cultivation, (b) straw residue collection and transportation, and (c) straw residue conversion in biomass conversion plant to generate power. In the first phase (rice crop cultivation), emissions due to land preparation, transplanting, irrigation and harvesting are estimated. Various inputs required in this phase include human and animal work, farm machineries and diesel (to run farm machineries). Emissions due to rice straw residue collection and transportation are estimated in the second phase considering medium size tractor as a transporting unit. In the third phase, emissions due to rice straw conversion in power plant to generate power are estimated. For all the three phases, input specific emission co-efficient data are taken from standard sources. The GHG emission performance is also compared with an assumed coal fired power plant (having equivalent power generation capacity in comparison with rice straw based power plant). Spatial mathematical tools are proposed incorporating specific system parameters to estimate the emission from (i) crop residue based power generation and (ii) coal based power generation.

Considering the variation of rice crop cultivation practices prevailing in Sonitpur district of Assam, four different rice cultivation scenarios, *viz.* (i) scenario-I, (ii) scenario-II, (iii) scenario-III, and (iii) scenario-IV are designed for evaluation of GHG emission performance. While scenario-I is business as usual or traditional scenario, the other scenarios are mechanised scenarios with improved technological packages and with variations in mechanisation levels.

Spatial model developed for assessment of surplus crop residue at user-defined spatial levels are found useful for planning rice residue based electricity generation programme in Sonitpur district of Assam. Thus, the present research successfully demonstrated the applicability of the spatial tool for a representative agricultural rural region of India enabling to precisely estimate the resource as well as its equivalent power potential up to the smallest administrative unit (village).

Annual rice straw residue potential for renewable energy generation in Sonitpur district is 0.11 million tonne (1733948 GJ), equivalent to 11 MW continuous electrical power. Straw residue availability among the 14 development blocks varies from the lowest of 1591 tonne (equivalent to about 0.61 MW continuous electrical power in *Gabharu* development block) to the highest of 16468 tonne (equivalent to about 1.61 MW continuous electrical power in *Dekiajuli* development block). Among the 1615 villages of the district, 831 villages have net rice straw residue potential less than 100 tonnes per annum and the rest 380 villages have net straw residue potential higher than 100 tonne per annum. Rice straw residue alone can support more than 10 kW continuous electrical power generations in each of the 667 villages in the Sonitpur district. Further, 8 villages each are potential for more than 50 kW at individual village level, out of these 667 villages.

The lifecycle GHG emission for decentralised electrical power generation are successfully modelled in spatial scale and becomes useful for assessment for the case of Sonitpur district. Two options of fuel *viz.*, (i) distributed surplus rice straw and (ii) centralised coal, are compared for GHG emission performance using the developed model, *i.e.* GIS assisted LCA of rice straw biomass power.

The practices of rice crop production and level of mechanisation influence the GHG emission while considering the rice residue as potential feedstock. About 6% increase in CO_2 equivalent GHG emission is resulted from the rice straw considered in mechanised methods of rice cultivation (1.53 kg of CO_2 equivalent kWh^{-1}) compared with the traditional method (bullock and animal powered) of rice cultivation (1.44 kg of CO_2 equivalent kWh^{-1}).

Substantial amount of emission reduction (about 47%) is possible in rice residue based decentralised power generation (even with the highly mechanised crop cultivation) compared with conventional coal based centralised power generation (2.12 kg of CO_2 equivalent kWh^{-1}).

The spatial models (crop residue and GHG emission assessments) and outcomes of the present investigation would assist decision makers to plan decentralised crop residue based biomass power plant for power crisis driven rural India. Surplus rice straw residue is found as potential feedstock for decentralised power generation in Sonitpur district of Assam (India) from both abundance and GHG emission performance. The spatially distributed power generation potential from crop residue fuelled electricity along with potential GHG emission is assessed for 1615 villages of Sonitpur district of Assam (India). However, some related aspects *viz.*, (i) village level electricity demand assessment and (ii) agro-economic and social consideration pertaining to rice straw utilisation for power generation could not be considered in the present investigation and therefore suggested for future work.

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List of abbreviations

Abbreviations	Descriptions
AOI	Area Of Interest
BAU	Business As Usual
DSS	Decision Support System
FCC	False Colour Composite
GCP	Ground Control Points
GHG	Greenhouse Gas
GIS	Geographic Information System
GPS	Global Positioning System
IRS	Indian Remote sensing Satellite
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
LISS	Linear Imaging and Self Scanning Sensor
RPR	Residue Production Ratio
RS	Remote Sensing
RMS	Root Mean Square
UTM-WGS 84	Universal Transverse Mercator-World Geodetic System 84

List of symbols

Symbols	**Descriptions**
'	Minute
0	Degree
CH_4	Methane
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalent (is a measure to compare the emissions from different GHGs based on their global warming potential, *source: US Environmental Protection Agency*)
E_f	Emission factor
GCM	Giga cubic meters
GJ	Gigajoule
GW	Gigawatt
H	Hour
Kg	Kilogram
kW	Kilowatt
kWh	Kilowatt hour
LHV	Lower heating value
MJ	Megajoule
MT	Million tonne
Mtoe	Million tonnes oil equivalent
MW	Megawatt
N_2O	Nitrous oxide
TJ	Terajoule
TWh	Terawatt hour

CHAPTER 1

INTRODUCTION

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INTRODUCTION

1.1. World energy status

Adequate supply of energy is the prime requirement for growth and development of human society. There is clear evidence of the linkage between availability vis-a-vis consumption of energy and development. The developmental disparities amongst the regions are attributed to many factors including availability and affordability of energy. Energy poverty is a very serious issue for many Asian, African and Latin American countries and it has drawn global attention. Amongst the Asian countries, energy concerns of China and India are taking centre stage because of the existing status and future aspiration for development. Further, with the increase in population, rise in income and infrastructure developments, energy demands of the most of the affluent countries are rising continuously. Thus, it is imperative to generate and supply additional amount of energy to meet overall human development goal.

It is reported that world primary energy demand will rise by 35% between 2010 and 2035, or 1.2% average per year [1]. There have been many studies to predict the future demand. The predictions of such a study are presented in Table 1.1 [1]. According to the prediction, fossil fuels will continue to be the dominant source of global energy supply through 2035. In 2010, fossil fuels met 81% of world primary energy demand. However, it is also evident that the conventional fuels are going to be diminished very soon. Moreover, fossil fuel depletion time is reported to be around 35, 107 and 37 years for oil, coal and gas, respectively [2]. This means that by the beginning of mid 22nd century, only coal will be available as fossil energy. Besides such energy crisis, burning of fossil fuel is also responsible for increasing concentration of greenhouse gases in the atmosphere, thus resulting in global warming and associated adverse climatological impacts.

Table 1.1: World energy demand under three different scenarios (Mtoe) [1]

	Actual		**New policies[1]**		**Current policies[2]**		**450 scenarios[3]**	
Energy source	**2000**	**2010**	**2020**	**2035**	**2020**	**2035**	**2020**	**2035**
Coal	2378	3474	4082	4218	4417	5523	3569	2337
Oil	3659	4113	4457	4656	4542	5053	4282	3682
Gas	2073	2740	3266	4106	3341	4380	3078	3293
Nuclear	676	719	898	1138	886	1019	939	1556
Hydro	226	295	388	488	377	460	401	539
Bioenergy*	1027	1277	1532	1881	1504	1741	1568	2235
Other renewables	60	112	299	710	265	501	340	1151
Total	**10099**	**12730**	**14922**	**17197**	**15332**	**18677**	**14177**	**14793**

* includes both traditional and modern uses

[1] New policies: Existing policies are maintained and recently announced commitments and plans, including those yet to be formally adopted, are implemented in a cautious manner.

[2] Current policies: Government policies that had been enacted or adopted by mid-2012 continue unchanged.

[3] 450 scenarios: Policies are adopted that put the world on a pathway that is consistent with having around a 50% chance of limiting the global increase in average temperature to 2 °C in the long term, compared with pre-industrial levels.

Thus, rising energy demand, global energy crisis and climate change has compelled almost all the nations of the world to search for renewable sources of energy. As evident from Table 1, generation and demand for renewable energy including biomass energy will continue to rise.

1.2. World renewable energy status

Renewable energy can contribute to social and economic development, energy access, energy security, and reducing negative impacts on environment and health, besides having a large potential to mitigate climate change [3]. The Renewable Energy Policy Network for the 21st Century (REN21) reported that renewable energy supplied 19% of global final energy consumption in 2012, of which modern renewables provided about 10% and the remaining 9% by traditional biomass [4]. Furthermore, it is also projected that about 4.6 trillion kWh of renewable energy will be added to the grid by the end of 2035 [5]. Increasing shares of renewable energy in the national energy budget have also been observed for many countries. There are many such examples all over the World. In the European Union, 72% of new electricity generation capacity in 2013 comes from renewables (contrast to a decade earlier, when conventional fossil generation accounted for 80% of new capacity). Again, in China, new renewable power addition capacity surpassed new fossil fuel and nuclear power for the first time in 2013. Growing number of countries have aimed to phase-out use of fossil fuels in stipulated time and mandated use of renewable energy in its industrial sectors. As of 2013, Denmark banned the use of fossil fuel-fired boilers in new buildings and aims for 40% of total heat supply to be generated from renewables by 2020. About 20 million Germans are already living in so-called 100% renewable energy regions. Djibouti, Scotland, and the small-island state of Tuvalu aim to derive 100% of their electricity from renewable sources by 2020. In India also, the share of renewable power to its total installed capacity is 13% as of 2013 [6]. In terms of total biopower (biomass resource based power) capacity, USA, Germany, China, Brazil and India are the top five leading countries as of 2013.

The global market share of renewable energy has also been growing very fast. In 2005, solar, wind and biofuel together captured world renewable energy market worth of nearly $39 billion (bn), increases to $188 bn in 2010 and touches $249 bn in 2013 [7]. It is projected that by 2023, renewable energy business will be worth of $398 bn, of which $158 bn, $146 bn and $94 bn will be contributed by solar power, biofuels and wind power, respectively. In India also, investment and business opportunities in renewable energy sector reached $4 bn per year by 2013-2014 [8].

1.3. India's energy status

Improving living standard, economic and industrial expansions, population growth has possess serious constrains on India's energy sector. Although the country is recognised as one of the fastest growing economies of the World, however, basic energy need of thousands of millions of its citizens are yet to be fulfilled. As of 2014, India's total installed electricity generation capacity is 245 GW, of which 168 GW comes from thermal sources (coal) and approximately 5 GW, 41 GW and 32 GW comes from nuclear, hydro and renewable resources, respectively [8]. Taking a historical prospective, Kumar and Jain, 2010, reported that during 1970 to 2007, coal consumption in India has increased from 71.2 MT (million tonne) to 462.7 MT, crude-petroleum consumption gone up from 18.4 MT to 146.5 MT and the natural gas consumption rose from 0.64 giga cubic meters (GCM) to 31.36 GCM. Similarly, electricity consumption has also increased from a level of 43.7 TWh to 443.1 TWh during the same period [9]. However, power generation capacity of India shall be further increased to nearly 800 GW from the current capacity of 245 GW [10] so as to support the basic energy needs of its population.

Contrary to the demand, India's indigenous energy reserves are not adequate and therefore, the country is fairly dependent on foreign imports. For instance, against the consumption of 219.21 MT crude oil in 2012-13, indigenous production was only 37.86 MT [11]. India imports nearly 80% of crude oil. Although, India has a good reserve of coal, a portion of coal demand is also met through foreign import. In 2013-14, against the coal demand of 769.69 MT, indigenous production was 614.55 MT, thus the gap 155.14 MT was met through imports [12]. Furthermore, low quality (in terms of energy content) and high content of sulphur in Indian coal are also matters of concern. Major portion of coal produced in India is used for electricity generation (coal based power plants accounts for nearly 60% of the total installed electricity generation capacity). Other energy options like, large hydro and nuclear power projects are facing serious environmental criticisms and beleaguered with problems. Thus, there are serious supply-demand imbalances almost for all the forms of primary energy in the country. Demand for electricity has also exceeded supply with improving living standard. The electricity supply shortages have forced almost all the sectors -industrial, commercial, institutional or residential - to rely on diesel or furnace oil. Lack of adequate rural electricity supply has led to large scale use of kerosene. Many rural communities in India do not have adequate supply of electricity. As of 2008, about 125000 villages and hamlets are without access to electricity in India [13]. Even after a nationwide village electrification programme has been implemented by the Indian Government under the Rajiv Gandhi Grameen Vidyutikaran Yojana (RGGVY), more than 58,000 villages remain without electricity connection in 2010 [14]. It is also reported that about 78 million Indian mainly depend on kerosene for lighting [15]. Moreover, the quality of electricity in most of the connected rural areas is also not satisfactory as it is predominantly characterised by fluctuating voltage, unreliable supply and shortage of power [16]. Non-access to reliable electricity and rural poverty are reported to be closely related [17-20]. Poor electricity supply not only hampers essential activities of rural households, but also has negative impact on health, education, farming and related livelihood activities. Considering the existing state of affairs, additional generation of electricity is imperative to support sustainable rural development in India.

Thus, for a country like India, where energy demand is projected to be increased many folds in near future, additional renewable based generation is drawing attention.

1.4. India's renewable energy status

Besides the effort of increasing centralised generation capacity with conventional sources, decentralised generation based on renewable sources has also received serious attention in India in recent times. Two obvious reasons for such initiatives are (i) inherent limitations of conventional fossil fuel sources, and (ii) access of electricity to remotely located population. The Government of India has also made it mandatory for State Electricity Boards with favourable policy incentives to supplement installed capacity through renewable energy sources. Solar, wind, biomass and small hydro are some technologically feasible renewable energy options for decentralised power generation in India. Each of these options has its merits and demerits primarily due to location specific resource availability.

Over the past five years, renewable energy has witnessed over 20% growth, from an installed capacity of 14.4 GW in 2009 to 31.7 GW in 2014 [8]. Today renewable energy provides about 13% of the total national installed electric capacity. Renewable resource wise installed power generation capacities in India are 21, 4, 3.8 and 2.6 GW for wind power, biomass power, small hydro power and solar power, respectively. In fact, India is the fifth largest wind power producing country in the World. Status of deployment of various renewable energy systems/devices in India (as of 2014) is presented in Table 2 [8].

Table 1.2: Sector wise deployment of renewable energy systems/devices in India [8]

Sector	**Achievement (as of March, 2014)**
(i) Grid interactive power, MW	
Wind power	21131.83
Small hydro power	3803.70
Biomass power and gasification	1365.20
Bagasse cogeneration	2648.40
Waste to power	106.60
Solar power	2647.00
Total	**31702.73**
(ii) Off-grid/captive power (MW eq.)	
Waste to energy	132.70
Biomass (non-bagasse) cogeneration	531.80
Biomass gasifiers	164.70
Aero-generators/hybrid systems	2.30
SPV systems	174.40
Water mills/micro hydel	13.21
Biogas based energy systems	3.77
Total	**1089.40**
(iii) Other renewable energy systems	
Family biogas plants (numbers in millions)	4.74
Solar water heating-collection areas (million m^2)	8.10

To bolster the growth of renewable energy in India, the Government of India has initiated several policies, action plans and promotional schemes. A separate ministry, *i.e.* the Ministry of New and Renewable Energy (MNRE) is created for all matters related to new and renewable energy. Furthermore, renewable energy is one of the central themes of India's National Action Plan on Climate Change. Under the Jawaharlal Nehru National Solar Mission (JNNSM), it is targeted to generate 20000 MW grid connected solar power by 2022. Similarly, Renewable Energy Certificate (REC) mechanism is launched to promote pan-India renewable energy market. As mentioned earlier, in India, investment and business opportunities in renewable energy sector reached $4 bn per year by 2013-2014 [8].

Being a biologically resourceful and agriculturally dominant country, India has huge potential for biomass resource based renewable energy generation. As per the MNRE, biomass energy potential of the country is estimated to be about 22000 MW. Realising the potential of biomass for energy generation in India, the MNRE has targeted harnessing it with encouraging degree of success.

1.4.1. India's biomass energy status

Biomass resources are generally divided into four primary classes *viz.*, (i) wood and woody materials, (ii) herbaceous and other annual growth materials such as straw, grasses, leaves, (iii) agricultural by-products and residues including shells, hulls, pits, and animal manure, and (iv) refuse-derived fuels [21].

As mentioned earlier, the estimated biomass power potential in India is about 22 GW, of which agricultural residue and agro-industrial residues contributes 17 GW and bagasse cogeneration contributes rest 5 GW. As of 2014, biomass power and cogeneration projects aggregating to 4 GW have been installed in the country for feeding power to the grid in different states as presented in Table 1.3 [8].

The common biomass feedstock for power generation in India includes sugarcane bagasse, rice husk, rice straw, cotton stalk, coconut shells, soya husk, coffee waste, jute wastes, groundnut shells and forest based biomass including saw dust. A variety of biomasses including woody biomass [22] and loose biomass such as rice husk [23], cashew nut shell [24], areca nut [25], sugarcane residue [26] have been tested for bioenergy generation in India. Village level decentralised biomass power generation of kilowatt scale has also been commissioned in the country. Dasappa et al., 2011 [27] reported the successful deployment of six biomass gasifier based power plants with total installed capacity of 0.88 MW in Tumkur district of Karnataka.

Table 1.3: State wise commissioned biomass power/cogeneration projects in India

State	**Cumulative capacity, MW**
Andhra Pradesh	380.75
Bihar	43.42
Chhattisgarh	264.90
Gujarat	43.90
Haryana	45.30
Karnataka	603.28
Madhya Pradesh	26.00
Maharashtra	940.40
Odisha	20.00
Punjab	140.50
Rajasthan	101.30
Tamil Nadu	571.30
Uttarakhand	30.00
Uttar Pradesh	776.50
West Bengal	26.00
Total	**4013.55**

In general, the utilisation of biomass for energy generation can be viewed as (i) traditional where low energy conversion devices are associated, and (ii) modern where higher efficiency conversion devices are associated. Some specific issues of utilisations of biomasses as sources of energy as (i) traditional and (ii) modern ways in Indian context are highlighted below.

Although accesses to electricity and LPG have been improved in India compared to the last few decades, consumption of biomass as traditional fuel also increases in parallel and it dominates the fuel mix of rural households. Bhattacharya, [28] reported that majority of rural households in India rely on firewood, crop residue or animal wastes for cooking. Further, in the urban sector also, many households rely on traditional energy for cooking. On a comparative study of household energy uses pattern in India and China, Pachauri and Jiang [29] reported that at an aggregate level, solid fuels (traditional biomass and coal) comprise major share of total residential energy use in both the countries. Large scale use of firewood as cooking fuel is reported in India. Annually about 220 MT of firewood is utilised for cooking in the rural sectors of India [30]. Firewood contributes the major portion of final energy consumption depending on income level of households [31]. Apart from household uses, biomass is also extensively used in various traditional and rural enterprises such as brick making, rice par-boiling, hotel, restaurants, bakeries, potteries and charcoal making [30].

The modern uses of biomass take the advantages of modern biomass conversion technologies such as combustion, pyrolysis, gasification, fermentation, anaerobic digestion for production of heat and electricity, liquid and gaseous transportation fuel, biogas for cooking. There is a huge potential for modern uses of biomass energy in rural India, especially in the cooking and lighting sectors. Balachandra, 2011 [32] advocated adopting modern biomass energy in India because of some distinct advantages. Suitable biomass resources are distributed nearby users' location. Moreover, modern technologies of conversion are also almost matured and available in India. For example, India has local expertise in developing and deploying biomass gasifier technologies for power generation and bio-methanation technologies for biogas production. The huge potential of greenhouse gas emission reduction is also indicated through the use of biomass fuel substituting traditional fossil fuel. The possibility of employment and income generation through decentralised biomass based renewable energy generation has also been seen considered as a contributor for rural development.

There has been some recent addition of biomass power projects in India probably stimulated by the factors mentioned in the above paragraph. For examples, the Punjab Energy Development Agency (PEDA) in the state of Punjab (India) has commissioned numbers of biomass power projects aggregating to a total capacity of 62.5 MW [33]. Similarly, a 10 MW biomass based (mostly rice husk) power plant in Gadchiroli district of Maharashtra is installed by A A Energy Limited [34]. It is also reported that a numbers of biomass gasifier projects have been installed in different parts of India with power output capacity ranging from 1 kWe to 1500 kWe [35]. The availability and suitability of feedstocks have been prime considerations for biomass power generation. Crop residues have been identified as one of the most versatile sources of biomass feedstock. There are certain issues concerning the application of crop residue biomass have been discussed below.

1.5. Crop residue based biomass energy

Being an agriculturally dominant nation, the strength of India's bioenergy programmes mostly lies in the agricultural sector. Agriculture is regarded as the backbone of India's economy. Agriculture contributes 17% to India's GDP and it is the source of livelihood for nearly 60% of India's population. About 60% of land area of the country is under various agricultural practices [36]. The arable land in the country is 159 million hectare (Mha), 11.2% of global share. Globally India ranks first in the production of jute and second in rice, wheat, sugarcane, cotton and ground nut. Due to the strength of agricultural activities in India, crop residues production in the country is also very large. However, due to the diversity in cropping practices and agro-climatic conditions across the India, distribution and availability of residues is highly spatio-temporal in nature. Although national level estimate of crop residue biomass potential in India is available, state level database is limited, except for a few states [37-40]. Since biomass energy projects are generally of small scale and targeted mainly for decentralised utilization to meet local energy demand, therefore, national estimates may not be adequate for state or local bioenergy planning.

As per the MNRE, India has potential to generate about 22000 MW power from agricultural and agro-industrial residues [8]. It is also reported that, on annual basis, about 74 million tonne (0.15 million tonne national per capita) of residue biomass generated from various agricultural crops could be utilised for energy generation in India [41]. Considering rice straw alone, the surplus availability is more than 22 million tonne per year [42]. Given the large regional differences in the type of crop residues, however, a region-specific analysis of residues, their competitive uses, and thus, the net availability for power generation is very important for successful implementation of sustainable rural energy programmes.

There are many examples of utilisation of agricultural residues such as rice straw for power and heat generation all over the world [43-44]. Denmark is one of the pioneer countries in developing and deploying straw based biomass energy technologies for heat and power generation. Biomass contributes nearly 70% of renewable-energy consumption in Denmark, mostly in the form of straw, wood and renewable wastes. It is also projected that consumption of biomass continues to rise as a source of energy for the supply of heat in district-heating plants and in smaller installations for households, enterprises and institutions in Denmark [45].

The characteristics of straw and its chemical composition have been found to influence the operation and maintenance of straw-fired power plants [46-47]. Slagging, fouling and sintering are some of the operational difficulties of biomass fired power plants, including straw fired power plants. It is claimed that the mechanisms as well as chemistry of these phenomena are well understood and accordingly specific mitigation strategies have also been proposed [48-50]. The success of such mitigation plans will depend on the maturity of the technologies with relevant R&D support. Moreover, adequacy of straw resources availability also has to be ensured for successful implementation of such biomass based power plants.

Rice straw is a by-product of rice farming and has variety of traditional applications with region specific distinction. For example, uses of rice straw as feedstock and as bedding material for livestock are common. Moreover, in some cases it is also used as domestic fuel and building materials in rural areas [51]. In some special cases compost making to support soil fertility and papermaking are also practiced [52]. Even within India, varied uses of rice straw are observed. In some parts of the country a large portion of rice straw is used as animal feed, whereas states like Punjab, Andhra Pradesh and Haryana, rice straw is not used as animal feed [53]. The availability of other suitable feed for animal could be the reason of not considering rice straw as animal feed in these regions.

Rice is a major crop in the state of Assam, India and thus generates large amount of residues, primarily straw. It is reported that the gross rice residues (straw and husk) availability in Assam is about 7.04 million tonne (straw 6.29 million tonne, husk 0.75 million tonne), out of which about 53% (*i.e.*, 3.75 million tonne comprising 3.15 million tonne from straw and 0.6 million tonne from husk) available as surplus (*i.e.*, amount of residue left unused) for energy generation purpose [37]. Farmers of Assam use parts of rice straw, which are harvested and taken along with grain (about one third of total plant height), as feed for livestock. In some cases, a small fraction is also used as domestic fuel. But such uses are location specific. The remaining portion of straw is left uncollected or burnt in the field. Leaving straw unused and field burning has negative impact on environment such as (i) methane emissions due to anaerobic decomposition of straw [54, 55] and (ii) emission of atmospheric pollutants due to burning [56]. Thus, except for the harvested portion (about 47% of gross residue availability), major portion of straw has no meaningful use in Assam. This unutilised fraction of residue could be used for energy generation. Recycling of the residue (produced after burning of rice straw for power generation) to crop field would ensure nutrient recycling.

Assam is one of the 29 states of India situated in the North-Eastern part. There is a serious imbalance of energy supply-demand in Assam. Inadequate supply of energy has hampered the overall development of almost all sectors (domestic, industrial, service, commercial) of the state. With the limitations of the traditional sources of energy, it is imperative to promote appropriate sources of renewable energy. The state of Assam is an agriculturally dominating region where about 70% population relies of agriculture. Further, rice based cropping system is followed in all the districts. Thus, prospect of rice residue as a source of renewable energy is a matter of investigation in Assam.

Precise assessment of resource availability is one of the considerations for successful implementation of rice residue based biomass energy programmes in Assam. Remote sensing (RS) and GIS has been regarded as a handy tool for precise assessment of biomass resources including agro-crop residues.

1.6. Application of remote sensing (RS) and GIS in biomass resource assessment

The applications of RSGIS in biodiversity assessment, land use land cover mapping, hazard mapping, pollution monitoring and renewable energy resources assessment have been gaining popularity all over the world. The shift, from field based methods (survey, secondary data collection *etc.*) to geo-spatial technology is mainly attributed by three major advantages of RSGIS over traditional methods *viz.* (i) precise and timely information, (ii) local level to global scale coverage, and (iii) retrieve and reiterative capacity as per user convenience. Successful application of RSGIS in renewable energy assessment has been reported for hydro energy [57], wind energy [58], solar energy [59], geothermal energy [60] and biomass energy [61] are some examples of such successful uses. It is observed that broad application of spatial technique is particularly common in biomass resources studies, as reported for forest biomass [62, 63], agricultural biomass [52, 64], and energy plant for biodiesel [65]. Considering the crisis with conventional fossil based energy system, growth oriented planning of renewable energy system is becoming very crucial. Therefore, remote sensing and GIS could play a significant role in renewable energy planning in near future. One added advantage of GIS tools and technologies is its ability to integrate several required features (such as road network, demand site map *etc.*) in planning of renewable energy programmes.

GIS have been successfully applied in biomass resource assessment in India also. Ramachandra and his co-workers extensively used GIS for assessment of biomass, solar and hydro-power in Karnataka state of India. In a study, the authors used GIS for *taluk* wise assessment of agricultural residue, forest, horticulture, plantation and livestock biomass resources in Karnataka [66]. Ramachandra, 2009 also proposed a regional integrated energy plan (RIEP) based on spatial decision support system (DSS) for Uttara Kananda district of Karnataka. The DSS focuses on renewable resources including biomass resources that could be harnessed for energy, land use database, sector wise energy demand database and optimal allocation of energy resources for various tasks, and then explore the energy use consequences of alternative scenarios, such as, base case scenarios, high-energy intensity and improved end use efficiency options [67]. Singh et al, 2008 integrated GIS, agricultural statistics and mathematical model to assess agricultural biomass potential for bioenergy in Punjab state [38].

The environmental consideration has drawn serious attention for any developmental project including power generation project all over. There are different issues for assessing the possible environmental impact of biomass power plant. Comparative emission (greenhouse gas) performance in relation to conventional power plant is one such issue for consideration. Life Cycle Assessment (LCA) tool is now available to estimate GHG and hence to compare the possible impact of new power generation plant.

1.7. Life Cycle Assessment (LCA) of biomass energy

Unsustainable utilisation of biomass resources for bioenergy generation may even exacerbate global greenhouse gas emission and jeopardise many critical ecosystem services including impacts on soil, water, biodiversity and human health [68-73]. Furthermore, large scale cultivation of bioenergy crops may lead to food *vs.* fuel debate. Change in land use pattern to produce biofuels may create biofuel carbon debt by releasing more CO_2 than its counterpart fossil fuels [68]. Thus, it is critically important to evaluate the impacts of bioenergy from a life cycle prospective. Life cycle assessment (LCA) is an internationally recognized methodology for evaluating the global environmental performance of a product, process or pathway along its partial or whole life cycle, considering the impacts generated from ''*cradle to grave*'' [74]. Standard guidelines are available to conduct bioenergy LCA [75]. Generally, energy and GHG balances of bioenergy systems are compared with fossil reference systems [76]. Successful application of LCA in bioenergy has been reported in many countries [77-80]. However, In India, studies related to bioenergy LCA are very limited. Only a few studies have reported life cycle impact of bioenergy (biodiesel) production in India. Furthermore, no environmental impact assessment method specific to conditions in India currently exists [81, 82]. Thus, there is a need to conduct more biomass energy LCA researches pertaining to Indian conditions.

Spatial LCA is the use of spatial tools and techniques such as remote sensing and GIS in LCA study. Use of spatial tools is helpful in LCA based study of geographically distributed biomass resources. Certain impacts categories such as impact of land use change, impact on biodiversity could be better understood if spatial LCA is applied. However, spatial LCA is a new field of research and hence existing literatures are limited [83-85].

From the above discussions, it is seen that development disparity has occurred due to non-uniform availability and hence un-equal consumption of energy amongst the regions. This has to be addressed appropriately, by additional energy generation capacity, in order to achieve millennium development goal. However, conventional source based capacity addition has major limitations. Worldwide new and renewable energy resources are becoming more reliable and viewed as a promising alternative to fossil fuels. In Indian context, there are many alternative sources of energy available and promising growth of renewable energy has been seen in recent years. Further addition of renewable energy is required for rural centric decentralised power generation.

1.8. Objectives of the research

Considering (i) potential of rice straw as a distributed energy resource for decentralised power, (ii) usefulness of spatial tools in biomass resource assessment, and (iii) importance of assessing greenhouse gas emission from rice straw based biomass power, the present research is conducted in Sonitpur district of Assam, India with the following objectives.

[1] To develop a spatial tool for biomass resource assessment

[2] To assess rice straw residue biomass availability for decentralised energy generation

[3] To assess GHG emission performance of bioenergy generation from rice straw using life cycle assessment (LCA) technique

1.9. Organisation of the thesis

The text of the thesis is organised as below.

Chapter 1: Introduction

In this current Chapter, World and India's energy status including renewable energy is discussed. Potential of agricultural residue based biomass energy generation for decentralised application in rural India is highlighted by citing successful utilisation of agricultural residue including rice straw for heat and power generation. Need and usefulness of spatial tools in agricultural residue biomass assessment is also presented. Furthermore, need for estimation of greenhouse gas emission from biomass energy generation from life cycle prospective is discussed. Justification for selecting Sonitpur district of Assam, India as a study site for this research work is also given. Thus, discussion on (i) rice straw as a prospective resource for decentralised renewable energy, and (ii) importance of (a) spatial tool in rice straw residue assessment, (b) estimation of greenhouse gas emission from rice straw biomass power, and (iii) need of this research work for Sonitpur district leads to statement of the problem and objectives of the research work undertaken.

Chapter 2: Literature review

Literature pertaining to use of biomass resource including rice straw for generation of renewable energy, application of remote sensing and GIS in biomass resource mapping and assessment of environmental performance of biomass energy using Life Cycle Assessment (LCA) methodology is presented in Chapter 2.

Chapter 3: Spatial tool for crop residue biomass resource assessment

In this Chapter, the detail procedure for development of the spatial tool to assess available rice straw residue biomass and subsequently biomass power generation are presented.

Chapter 4: Spatial assessment of rice straw residue

Details descriptions of study area along with justification for selection are presented in this Chapter. Spatial assessment of rice straw residue biomass availability and subsequently, biomass power generation in the study area at district, development block and village level is also presented and discussed in Chapter 4.

Chapter 5: Greenhouse gas emission from rice straw biomass power

In Chapter 5, potential greenhouse gas emission (CO_2, CH_4 and N_2O) due to power generation utilising rice straw residue available in the study area is presented from a life cycle prospective.

Chapter 6: Summary and conclusions

This Chapter enlists the summary of the results obtained to achieve the objectives of the research work. It also discusses limitations and future scope of the present research work.

The thesis ends with list of publications.

REFERENCES

[1] International Energy Agency. *World Energy Outlook 2012*, International Energy Agency, France, 2012.

[2] Shafiee, S., & Topal, E. When will fossil fuel reserves be diminished? *Energy Policy* **37**, 181--189, 2009.

[3] Intergovernmental Panel on Climate Change. *IPCC special report on renewable energy sources and climate change mitigation*, Cambridge University Press, Cambridge, UK and New York, USA, 2011.

[4] REN21-Renewable Energy Policy Network for the 21st Century. *Renewables 2014 Global Status Report*, 2014. http://www.ren21.net/Portals/0/documents/Resources/GSR/2014/GSR2014_full%20report_low%20res.pdf. (accessed 13/08/2014).

[5] US Energy Information Administration. *International Energy Outlook 2011*, 2011. http://www.eia.gov/forecasts/archive/ieo11/pdf/0484(2011).pdf.

[6] Ministry of New and Renewable Energy, Govt. of India. Annual Report 2012-2013. http://mnre.gov.in/file-manager/annual-report/2012-2013/EN/index.html.

[7] Pernick, R., et al. Clean Energy Trends 2014. Clean Edge Inc. http://www.cleanedge.com. (accessed 13/08/2014).

[8] Ministry of New and Renewable Energy, Govt. of India. Annual Report 2013-2014. http://mnre.gov.in/file-manager/annual-report/2013-2014/EN/index.html.

[9] Kumar, U., & Jain, V.K. Time series models (Grey-Markov, Grey Model with rolling mechanism and singular spectrum analysis) to forecast energy consumption in India, *Energy* **35**, 1709--1716, 2010.

[10] The World Bank. *India: Biomass for Sustainable Development-Lessons for Decentralised Energy Delivery Village Energy Security Programme*. World Bank, 2011. http:// http://www.mnre.gov.in/pdf/VESP-Final-Report-July%202011.pdf.

[11] Ministry of Petroleum & Natural Gas, Government of India. *Indian Petroleum & Natural Gas Statistics, 2013-14.* http://petroleum.nic.in/docs/pngstat.pdf (accessed 11/11/ 2014).

[12] Ministry of Coal, Govt. of India. Annual report 2013-2014. http://www.coal.nic.in/annrep1314.pdf. (accessed 11/11/2014).

[13] Central Electricity Authority, Govt. of India. *Annual Report 2008.* http://www.cea.nic.in/ (accessed 19/05/2011).

[14] Ministry of Power, Govt. of India. *DMU report: Un-electrified villages; 2010.* http://www.powermin.nic.in/bharatnirman/pdf/Unelectrified_Villages.pdf (accessed 28/11/2010).

[15] Ailawadi, V.S., & Bhattacharyya, S.C. Access to energy services by the poor in India: Current situation and need for alternative strategies, *Nat Resour Forum* **30**, 2--14, 2006.

[16] Ravindranath, N.H., et al. Sustainable biomass power for rural India: case study of biomass gasifier for village electrification, *Curr Sci* **87**, 932--941, 2004.

[17] Chaurey, A., et al. Electricity access for geographically disadvantaged rural communities—technology and policy insights. *Energy Policy* **32**, 1693--1705, 2004.

[18] Kemmler, A. Factors influencing household access to electricity in India. *Energy Sustain Dev* **11**, 13--20, 2007.

[19] Lhendup, T. Rural electrification in Bhutan and a methodology for evaluation of distributed generation system as an alternative option for rural electrification. *Energy Sustain Dev* **12**, 13--24, 2008.

[20] Kooijman-van Dijk, A.L., & Clancy, J. Impacts of electricity access to rural enterprises in Bolivia, Tanzania and Vietnam, *Energy Sustain Dev* **14**, 14--21, 2010.

[21] Jenkins, B.M., et al. Combustion properties of biomass, *Fuel Process Technol* **54**, 17--46, 1998.

[22] Patel, S.R., et al. Field-testing of SPRERI's open core gasifier for thermal application, *Biomass Bioenerg* **30**, 580--583, 2006.

[23] Kapur, T., et al. Electricity generation from rice husk in Indian rice mills: potential and financial viability, *Biomass Bioenerg* **14**, 573--583, 1998.

[24] Singh, R.N., et al. Feasibility study of cashew nut shells as an open core gasifier feedstock, *Renew Energ* **31**, 481--487, 2006.

[25] Palit, D., & Mande, S. Biomass gasifier systems for thermal applications in rural areas, *Boiling Point* **53**, 17--19, 2007.

[26] Jorapur, R., & Rajvanshi, A.K. Sugarcane leaf bagasse gasifiers for industrial heating applications, *Biomass Bioenerg* **8**, 91--98, 1995.

[27] Dasappa, S., et al. Operational experience on a grid connected 100 kWe biomass gasification power plant in Karnataka, India, *Energy Sustain Dev* **15**, 231--239, 2011.

[28] Bhattacharyya, S.C. Energy access problem of the poor in India: Is rural electrification a remedy? *Energy Policy* **34**, 3387--3397, 2006.

[29] Pachauri, S., & Jiang, L. The household energy transition in India and China, *Energy Policy* **36**, 4022--4035, 2008.

[30] Kishore, V.V.N., et al. Biomass energy technologies for rural infrastructure and village power–opportunities and challenges in the context of global climate change concerns, *Energy Policy* **32**, 801--810, 2004.

[31] Ekholm, T., et al. Determinants of household energy consumption in India, *Energy Policy* **38**, 5696--5707, 2010.

[32] Balachandra, P. Modern energy access to all in rural India: An integrated implementation strategy, *Energy Policy* **39**, 7803--7814, 2011.

[33] Punjab Energy Development Agency. http://peda.gov.in/Bio-massPower.html. (accessed 14/11/2014).

[34] A A Energy Limited. http://www.aaenergyltd.com/. (accessed 14/11/2014).

[35] Combustion, Gasification and Propulsion Laboratory (CGPL), Indian Institute of Science. http://cgpl.iisc.ernet.in/site/Installations/Gasifierindia3/tabid/185/Default.aspx. /. (accessed 14/11/2014).

[36] The World Bank. *Data*, http://data.worldbank.org/indicator/AG.LND.AGRI.ZS (accessed 01/11/2013).

[37] Baruah, D.C., & Hiloidhari, M. Adequacy of crop residue biomass as renewable energy for tea drying in Assam: A spatial assessment, *J Agricultural Engineering* **46**, 43--50, 2009.

[38] Singh, J., et al. Energy potential through agricultural biomass using geographical information system-A case study of Punjab, *Biomass Bioenerg* **32**, 301--307, 2008.

[39] Das, S., & Jash, T. District-level biomass resource assessment: A case study of an Indian State West Bengal, *Biomass Bioenerg* **33**, 137--143, 2009.

[40] Chauhan, S. Biomass resources assessment for power generation: A case study from Haryana state, India, *Biomass Bioenerg* **34**, 1300--1308, 2010.

[41] Purohit, P. Economic potential of biomass gasification projects under clean development mechanism in India, *J Cleaner Prod* **17**, 181--193, 2009.

[42] Gadde, B., et al. 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 Bioenerg* **33**, 1532--1546, 2009.

[43] Nikolaisen, L., et al. *Straw for Energy Production: Technology–Environment–Economy* (2nd ed), The Centre for Biomass Technology, Netherlands, 1998.

[44] Matsumura, Y., et al. Amount, availability, and potential use of rice straw (agricultural residue) biomass as an energy resource in Japan, *Biomass Bioenerg* **29**, 347--354, 2005.

[45] Danish Energy Agency. http://www.ens.dk/en/supply/renewable-energy/biomass-danish-energy-sector. (accessed 19/10/2014).

[46] Khan, A.A., et al. Biomass combustion in fluidized bed boilers: Potential problems and remedies, *Fuel Process Technol* **90**, 21--50, 2009.

[47] Niu, Y., et al. Study on fusion characteristics of biomass ash, *Bioresour Technol* **101**, 9373--9381, 2010.

[48] Allica, J.H., et al. Straw quality for its combustion in a straw-fired power plant, *Biomass Bioenerg* **21**, 249--258, 2001.

[49] Davidsson, K.O., et al. Counter measures against alkali-related problems during combustion of biomass in a circulating fluidized bed boiler, *Chem Eng Sci* **63**, 5314--5329, 2008.

[50] Xiong, S.J., et al. Slagging characteristics during combustion of corn stovers with and without kaolin and calcite, *Energy Fuels* **22**, 3465--3470, 2008.

[51] Smil, V. Crop residues: Agriculture's largest harvest, *Bioscience* **49**, 299--308, 1999.

[52] Elmore, A.J., et al. Spatial distribution of agricultural residue from paddy for potential biofuel production in China, *Biomass Bioenerg* **32**, 22--27, 2008.

[53] Devendra, C., & Thomas, D. Crop–animal interactions in mixed farming systems in Asia, *Agri Syst* **71**, 27--40, 2002.

[54] Sass, R.L., et al. Methane emission from rice fields as influenced by solar radiation, temperature, and straw incorporation, *Global Biochem Cycles* **5**, 335--350, 1991.

[55] Schütz, H., et al. A 3-year continuous record on the influence of daytime, season, and fertilizer treatment on methane emission rates from an Italian rice paddy, *J Geophys Res* **94**, 405--416, 1989.

[56] Crutzen, P.J., & Andreae, M.O. Biomass Burning in the Tropics: Impact on Atmospheric Chemistry and Biogeochemical Cycles, *Science* **250**, 1669--1678, 1990.

[57] Kusre, B.C., et al. Assessment of hydropower potential using GIS and hydrological modeling technique in Kapili river basin in Assam (India), *Appl Energy* **87**, 298--309, 2010.

[58] Mari, R., et al. A GIS-based interactive web decision support system for planning wind farms in Tuscany (Italy), *Renew Energ* **36**, 754--763, 2011.

[59] Gastli, A., & Charabi, Y. Solar electricity prospects in Oman using GIS-based solar radiation maps, *Renew Sust Energ Rev* **14**, 790--797, 2010.

[60] Noorollahi, Y., et al. Geothermal energy resources and development in Iran, *Renew Sust Energ Rev* **13**, 1127--1132, 2009.

[61] Lasserre, B., et al. Assessment of potential bioenergy from coppice forests trough the integration of remote sensing and field surveys, *Biomass Bioenerg* **35**, 716--724, 2011.

[62] Ramachandra, T.V. Mapping of fuelwood trees using geoinformatics, *Renew Sust Energ Rev* **14**, 642--654, 2010.

[63] Kinoshita, T., et al. A spatial evaluation of forest biomass usage using GIS, *Appl Energy* **86**, 1--8, 2009.

[64] Hoskinson, R.L., et al. Using a decision support system to optimize production of agricultural crop residue biofeedstock, *Biomass Bioenerg* **31**, 186--194, 2007.

[65] Zhuang, D., et al. Assessment of bioenergy potential on marginal land in China, *Renew Sust Energ Rev* **15**, 1050--1056, 2011.

[66] Ramachandra, T.V., & Shruthi, B.V. Spatial mapping of renewable energy potential, *Renew Sust Energ Rev* **11**, 1460--1480, 2007.

[67] Ramachandra, T.V. RIEP: Regional integrated energy plan, *Renew Sust Energ Rev* **13**, 285--317, 2009.

[68] Fargione, J., et al. Land clearing and the biofuel carbon debt, *Science* **319**, 1235--1238, 2008.

[69] Lapola, D.M., et al. Indirect land-use changes can overcome carbon savings from biofuels in Brazil, *Proc Natl Acad Sci* **107**, 3388--3393, 2010.

[70] Searchinger, T., et al. Use of U.S. croplands for biofuels increases greenhouse Gases through emissions from land-use change, *Science* **319**, 1238--1240, 2008.

[71] Danielsen, F., et al. Biofuel plantations on forested lands: Double jeopardy for biodiversity and climate, *Conserv Biol* **23**, 348--358, 2009.

[72] Hill, J., et al. Climate change and health costs of air emissions from biofuels and gasoline, *Proc Natl Acad Sci* **106**, 2077--2082, 2009.

[73] Dominguez-Faus, R., et al. The water footprint of biofuels: A drink or drive issue? *Environ Sci Technol* **43**, 3005--3010, 2009.

[74] Gnansounou, E., et al. Life cycle assessment of biofuels: Energy and greenhouse gas balances, *Bioresour Technol* **100**, 4919--4930, 2009.

[75] International Standard Organisation. *ISO 14044-Environmental management - life cycle assessment - requirements and guidelines*, International Standard Organisation, Geneve, Switzerland, 2006.

[76] Schlamadinger, B., et al. Towards a standard methodology for greenhouse gas balances of bioenergy systems in comparison with fossil energy systems, *Biomass Bioenerg* **13**, 359--375, 1997.

[77] Wang, Z., et al. Lifecycle assessment of the economic, environmental and energy performance of Jatropha curcas L. biodiesel in China, *Biomass Bioenerg* **35**, 2893--2902, 2011.

[78] Adler, P.R., et al. Life-cycle assessment of net greenhouse-gas flux for bioenergy cropping systems, *Ecol Appl* **17**, 675--691, 2007.

[79] Heller, M.C., et al. Life cycle energy and environmental benefits of generating electricity from willow biomass, *Renew Energ* **29**, 1023--1042, 2004.

[80] Cherubini, F., et al. Energy-and greenhouse gas-based LCA of biofuel and bioenergy systems: Key issues, ranges and recommendations, *Resour Conserv Recy* **53**, 434--447, 2009.

[81] Gmunder, S.M., et al. Life cycle assessment of village electrification based on straight jatropha oil in Chhattisgarh, India, *Biomass Bioenerg* **34**, 347--355, 2010.

[82] Achten, W.M.J., et al. Life cycle assessment of Jatropha biodiesel for transportation in rural India, *Appl Energy* **87**, 3652--3660, 2010.

[83] Geyer, R., et al. Coupling GIS and LCA for biodiversity assessments of land use Part 1: Inventory modeling, *Int J Life Cycle Assess* **15**, 454--467, 2010.

[84] Gasol, C.M., et al., Environmental assessment: (LCA) and spatial modelling (GIS) of energy crop implementation on local scale, *Biomass Bioenerg* **35**, 2975--2985, 2011.

[85] Mutel, C.L., et al. GIS-Based Regionalized Life Cycle Assessment: How big is small enough? Methodology and case study of electricity generation, *Environ Sci Technol* **46**, 1096--1103, 2012.

CHAPTER 2

LITERATURE REVIEW

CHAPTER 2

LITERATURE REVIEW

In this Chapter, literature pertaining to the use of biomass resources including rice straw for renewable energy generation, application of remote sensing and GIS in biomass resource mapping and assessment of environmental performance of biomass energy through life cycle assessment (LCA) is presented.

2. 1. Agricultural residue as a biomass energy resource

Use of agricultural residues as a feedstock of biomass energy has been gaining popularity in many countries. Agricultural residues could be a significant source of biomass energy in agriculturally dominant countries like India and China. Successful R&D have been demonstrated in many parts of the world concerning the use of agricultural residues including rice straw as a potential feedstock for biomass energy. Some of such researches with particular emphasis on rice residue are briefly discussed below.

Matusumura et al., 2005 [1] reported that rice straw and rice husk are the two main agricultural residues in Japan. Rice residue could provide 0.47% of Japan's total electricity demand. At present, the cost of electricity production from rice straw is double than the current cost of electricity. Nevertheless, with the improvement in conversion technology and introducing cost incentives, rice residue based power generation could be an attractive option in Japan and GHG emission reduction achieved through this process can be counted under the Kyoto Protocol.

Considering the importance of sound technology for biomass energy generation, Zeng et al., 2007 [2] reviewed direct combustion, biogas, straw gasification and straw briquetting, including improved stove, biogas, straw gasification and straw briquette in China. The authors observed that enhancing combustion efficiency of improved stove, developing comprehensive biogas eco-agricultural technology, popularising straw gasification systems for central gas supply, developing straw direct combustion and briquetting equipments are the key technologies of large scale and efficient utilization of straw in biomass energy in the future in China.

Jenkins et al., 1998 [3] presented a comprehensive discussion on the properties (composition, proximate, ultimate, elemental, heating value, alkali index) of different types of biomass feedstocks (woody, loose) relevant to combustion. The compositions of biomass with respect to inorganic constituents which is variable among fuel types is critically important with regards to fouling and slagging problems associated with biomass combustion. Alkali and alkaline earth metals and other biomass fuel elements such as silica, sulphur, and chlorine are responsible for many undesirable reactions in combustion furnaces and power boilers. Concentration of alkali metals and chlorine can be reduced from biomass fuel by leaching with water and thus lead to improvements in ash fusion temperatures.

Zhang et al., 1999 [4] investigated the suitability of rice straw for biogasification with an anaerobic-phased solids digester system. Ammonia is used as a supplemental nitrogen source for rice straw digestion. It is found that a combination of grinding (10-mm length), heating (110°C), and ammonia treatment (2%) resulted in the highest biogas yield, which is 17.5% higher than the biogas yield of untreated whole straw. The pretreatment temperature is critical and has a significant effect on the digestibility of straw.

Gadde et al., 2009 [5] investigated rice straw availability as a source of power generation and GHG emission due to its current uses and also GHG saving potential if straw is utilised for power generation. India, Thailand, and the Philippines produces 97.19, 21.86, and 10.68 Mt of rice straw residue per annum, respectively. In India, 23% of rice straw residue produced remains as surplus or un-used. Punjab, Haryana and Uttar Pradesh are the three major rice straw producing states in India. About 48% and 95% of rice straw residue is open-field burnt in Thailand and the Philippines, respectively. The GHG emissions due to open-field burning of rice straw in India, Thailand, and the Philippines are 0.05%, 0.18%, and 0.56% respectively. The GHG emissions mitigation potential from rice straw based power would be 0.75%, 1.81%, and 4.31% in India, Thailand and the Philippines respectively, compared to the total country GHG emissions.

Kim and Dale, 2004 [6] estimated the global annual potential bioethanol production from the major crops such as corn, barley, oat, rice, wheat, sorghum, and sugar cane. Overall, total potential bioethanol production from crop residues and wasted crops is 491 GL yr^{-1}, about 16 times higher than the current world ethanol production. The potential bioethanol production could replace 353 GL of gasoline (32% of the global gasoline consumption) when bioethanol is used in E85 fuel for a midsize passenger vehicle. Asia is the largest potential producer of bioethanol from crop residues and wasted crops, and could produce up to 291 GL yr^{-1} of bioethanol. Rice straw, wheat straw, and corn stover are the most favourable bioethanol feedstocks in Asia. Globally rice straw can produce 205 GL of bioethanol, which is the largest amount from single biomass feedstock.

Lim et al., 2012 [7] reviewed the key factors of the utilisation of rice husk and rice straw as renewable energy sources. The reviewed (i) physical and chemical characteristics that influence the quality of rice biomasses, (ii) various chemical and physical pretreatment techniques that can facilitate handling and transportation of rice straw and husk, and (iii) the state-of-the-art on thermo-chemical and bio-chemical technologies to convert rice husk and rice straw into energy. Rice producing countries like China, India and Indonesia can take the advantage of the environmental and economic benefits from utilisation of rice straw and rice husk for energy. Heat and electricity produced from rice residue cogeneration systems could be used to meet local energy demands. The excess amount of electricity produced can be fed in to the national grid. Methane and hydrogen generated via various rice biomass conversion processes can also produce energy for heat and power generation. Ethanol, as a transportation fuel can also be derived from rice straw. Further research for successful commercialisation of rice straw and rice husk based technologies for small scale and industrial scale utilisation is also suggested in the paper.

Binod et al., 2010 [8] reviewed the current available technologies for bioethanol production from rice straw. Bioethanol produced from rice straw can be used as transportation fuel. Rice straw is abundantly available and is an attractive lignocellulosic material for bioethanol production. It has high cellulose and hemicelluloses, which can be readily hydrolysed into fermentable sugars. However, the presence of high ash and silica content in rice straw is a hindrance for ethanol production. Selecting an appropriate pretreatment technique for rice straw is also a major challenge. The choice of suitable pretreatment methods is to increase the efficiency of enzymatic saccharification and thereby making the whole process economically viable. However, with the introduction of genetically modified yeast, synthetic hydrolysing enzymes, other sophisticated technologies and their efficient combination, the process of bioethanol production from rice straw will be a feasible technology in coming years.

Suramaythangkoor and Gheewala, 2010 [9] reported that rice straw is a potential source for heat and power generation in Thailand. Although the cost of rice straw for power generation is not competitive with coal but comparable with other biomass. They suggested two alternatives for utilisation of rice straw in industrial boilers (i) installing rice straw fired boilers instead of heavy oil or natural gas fired boilers, and (ii) fuel switching from coal to rice straw for existing boilers. Considering the properties of rice straw (such as slagging index, fouling index), there should not be significant operating problems or different emissions when compared with wheat straw and rice husk under similar operating conditions.

Delivand et al., 2011 [10] evaluated the economic feasibility of rice straw based combustion projects of various capacities (ranging from 5 MWe to 20 MWe) in Thailand. For an assumed lifespan of 20 years, rice straw-fueled combustion power plants would generate Net Present Values (NPV) of −3.15, 0.94, 2.96, 9.33, and 18.79 million USD for projected 5, 8, 10, 15, and 20 MWe plants, respectively. Furthermore, examining the effects of scale on the cost of generated electricity (COE) over the considered range of capacities indicates that COE varies from 0.0676 USD kWh^{-1} at 20 MWe to 0.0899 USD kWh^{-1} at 5 MWe. Nevertheless, to ensure a secure fuel supply, smaller scale power plants, *i.e.*, 8 and 10 MWe may be more practicable.

Hassan et al., 2014 [11] demonstrated electricity generation from rice straw without pretreatment in a two-chambered microbial fuel cell (MFC) inoculated with a mixed culture of cellulose-degrading bacteria (CDB). The CBD is a mixed culture of bacteria which can hydrolyze cellulosic biomasses under anaerobic conditions. Their work demonstrated that electricity can be produced from rice straw by exploiting CDB as the biocatalyst. This method provides a promising way to utilise rice straw for bioenergy production.

Mussoline et al., 2014 [12] used untreated rice straw in combination with piggery wastewater in a farm-scale biogas system to generate electricity. The authors recommended an overall straw (dry wt.) to wastewater ratio (wet wt.) of 1 to 1.4 to improve gas production and decrease the acclimation period. They also recommended improvements such as continuous leachate recirculation, a more efficient heat exchange system to maintain mesophilic conditions year round, and periodic addition of fresh wastewater and sludge acclimated to lignocellulosic material to achieve a more sustainable and profitable system.

Hu et al., 2013 [13] investigated diffusion of rice straw cofiring systems in the Taiwanese power market. They developed a linear complementarily model to simulate the power market equilibrium with cofiring systems in Taiwan. The GIS based analysis is also used to analyze the geospatial relationships between rice farms and power plants to assess potential biomass for straw power generation.

Ranjan et al., 2013 [14] studied the feasibility of using rice straw as a substrate for biobutanol production. They studied clostridial fermentation of stress assisted-acid hydrolyzed rice straw that exhibited a typical trend of acidogenesis followed by solventogenesis. The concluded that higher solvents yield and significant sugar utilization makes rice straw a potential feedstock for biofuels production.

Mussoline et al., 2013 [15] reviewed the anaerobic digestion of rice straw. Removal of rice straw from rice fields can reduce greenhouse gas emission significantly as rice fields are regarded as a major source of methane emission. Through anaerobic digestion process, methane yields from rice straw ranges from 92 to 280 l/kg of volatile solids. Operating conditions such as pH (6.5–8.0), temperature (35–40°C), and nutrients (C:N ratio of 25–35) are important for optimum digestion of rice straw. Furthermore, pretreatment (*i.e.*, fungi, acid, and alkali solutions) and microbial engineering can increase biogas production.

Thus, from the above literatures, it is evident that agricultural residues including rice straw are a prospective source of renewable energy generation. However, spatial tools and technique are required to assess the spatio-temporal availability and distribution of agricultural residue biomass.

2.2. GIS in biomass energy resource assessment

Biomass resources are geographically distributed over large areas and there is variation in its spatio-temporal availability also. Conventional methods such as surveys, secondary data analysis are not adequate to precisely estimate bioresource potential particularly when analysis in done at regional or national level. However such limitation could be overcome by using spatial tools such as GIS. The uses of GIS in biomass energy resource assessment have been reported in many literatures. Some of them are discussed below.

According to Ramachandra et al., 2005 [16] biomass provides about 75% of the rural energy needs in India. Sustainable management of these resources requires better and timely decisions to increase cost-efficiency and productivity. To assist in strategic decision-making activities, considering spatial and temporal variables, Spatial Decision Support Systems (SDSS) are required. The SDSS is defined as an interactive computerized system that gathers data from a wide range of data sources, analyze the collected data, and then present it in a way that can be interpreted by the decision maker to deliver the precise information needed to make timely decisions. The authors also proposed a Biomass Energy Potential Assessment (BEPA) decision support system to assist planners to plan and manage bioresources in a sustainable way for implementation at regional level.

Fiorese et al., 2010 [17] proposed a GIS based method to maximize energy production from arboreous and herbaceous dedicated crops considering local environmental conditions such as geo-morphology, climate, natural heritage, land use pattern in Emilia-Romagna area of Northern Italy.

Thomas et al., 2013 [18] presented a GIS based analysis of spatial supply and demand relationships for biomass energy potential for England. Of the 2521996 ha viable land for cultivation of Miscanthus, 1998435 ha are within 25 km of the identified potential end uses of feedstock, and 2409541 ha are within 40 km. Potential generation exceeds the 2020 UK biomass generation target of 259 PJ, whichever radius is applied.

Zhang et al., 2011 [19] emphasised that the location decision is especially important for woody biomass feedstock owing to the distributed nature of biomass and the significant costs associated with transportation. The authors used a two-stage methodology to identify the best location for biofuel production based on multiple attributes. In Stage I, GIS is used to identify feasible biofuel facility locations. The approach employs county boundaries, a county-based pulpwood distribution, a population census, city and village distributions, and railroad and state/federal road transportation networks. In Stage II, the preferred location is selected using a total transportation cost model. The methodology is applied in the Upper Peninsula of Michigan state to locate a biofuel production facility. It is found that the best possible location for biofuel production is at the Village of L'anse in Baraga County. Furthermore, by applying sensitivity analysis based on limited availability of feedstock, the City of Ishpeming emerged as another viable location for the production facility.

Ćosića et al., 2011 [20] used spatial tools for regional analysis of biomass energy potential and for assessing the cost of the biomass at the power plant (PP) location considering transport distance, transport costs and size of the power plants in Croatia taking wheat straw, corn stover and forestry residues as feedstocks. They also proposed a methodology for determination of an upper-level price of the biomass which energy plant can pay to the external suppliers. They found average energy potential of wheat straw, corn stover and forestry residues is 8.5 PJ, 7.2 PJ and 5.9 PJ, respectively.

Using GIS, Fernandes et al., 2010 [21] assessed the potential of biomass residues, both forest and agricultural residues, for energy production and utilisation in Marvão region of Portugal. They found that the annual biomass residues potential for Marvão is about 10600 tonnes, equivalent to about 106000 GJ per annum. Furthermore, to illustrate the potential of biomass residues for energy utilization in Marvão, heating system of a hotel located in Marvão village is used as a case study. From this case study, they found that the conversion of the existing fossil fuel-based heating system to a biomass-based system would have economical and environmental advantages for local investors.

Jiang et al., 2012 [22] mentioned that precise estimation of the availability of crop residue biomass is very important for the development of bioenergy sector in agriculturally dominant China. The authors used GIS based approach to assess availability and distribution of crop residues in China, taking into account a number of conservation issues such as resources (total amount, spatial and temporal distribution), economy (transportation costs), environment, and technology. It is estimated that, China produces a net amount of about 505.5 million tonnes crop residues per year equivalent to 7.4 EJ per year.

Tenerelli et al., 2012 [23] proposed a GIS based multi-criteria approach to assess range of possibilities for perennial energy crops conversion. They implemented the method at regional level in the Yorkshire and the Humber Region in Northern UK. In the first phase, a land capability model is designed to assess the potential of different typologies of perennial energy crops, on the basis of specific pedo-climatic and topographic factors. In the second phase, an uncertainty analysis of the land capability model is performed to interpret the influence of assumptions and uncertainty on input data and model parameters. In the final phase of the model, energy crop conversion areas are allocated according to specific environmental constraints, nature protection targets, food production priorities and land capability values. The authors observed that the land capability model and the parameter uncertainty analysis used, showed that the land which are more sensitive in terms of environmental risk correspond to the land with both the lowest capability for bioenergy production and the highest model error. In such areas, the introduction of intensive energy crop system would not be sustainable. The authors opined that the proposed model would ideally allow the analysis of different scenarios based on policy-economic perspectives (food versus energy security and nature conservation), and stakeholders' preferences and those different scenario could be finally integrated in a Decision Support System which could sustain the environmental planning when implementing different bioenergy routes.

Yoshioka et al., 2011 [24] used GIS to assess the feasibility of utilisation of forest biomass for energy in a mountainous region in Japan. GIS is used to map the distribution of forest biomass and to prepare topographical information. Next, harvesting and transportation systems for biomass are prepared. Cost of biomass procurement and transportation is also estimated. Finally, the relationship between mass and procurement cost of biomass is estimated and it is observed that logging residues were the least costly followed by broad-leaved forests while thinned trees were the most costly.

Sacchelli et al., 2013 [25] argued that specific Decision Support System (DSS) is required to handle the complexity of interaction among ecological, economic and political variables while environmental assessment is conducted. Furthermore, lack of data availability is also drawback in bringing together large scale analysis and local planning systems. Considering these loopholes, the authors conducted a GIS based research to quantify the potential amount of woody biomass from forest sector at several evaluation scales, to consider the theoretical impact of biomass removal on forest multifunctionality and to estimate the potential trade-off between forest functions in case of bioenergy chain development in a case study in Italy. They observed that the model is able to depict territorial differences in several contexts and to consider respective influence on estimation of biomass availability. The model is also able to define the optimal quantity of residues removal in different compartments according to priority forest function.

Zhuang et al., 2011 [26] mentioned that bioenergy development on the marginal lands has multiple benefits, such as mitigating energy crisis, and reducing greenhouse gas emission. GIS based multi-factor analysis is used to identify marginal lands for bioenergy development in China. The total area of marginal land exploitable for development of energy plants on a large scale is about 43.75 million ha. If 10% of this marginal land was fully utilised for growing the energy plants, the production of bio-fuel would be 13.39 million tonne. However, to achieve a win-win result, its ecological and environmental effects together with social and economic benefits should be analysed.

Angelis-Dimakisa et al., 2011 [27] provided a survey regarding methods and tools presently available to determine potential and exploitable renewable energy such as solar, wind, wave, biomass and geothermal energy. All these renewable energy resources are distributed in nature and site specific. Therefore, they all need tools to determine their spatial dimension and geostatistical tools or remote sensed spatial information can be very useful in this regard. Studies concerning all these renewable resources require GIS to process data and to demonstrate their local impacts.

Sun et al., 2013 [28] successfully demonstrated the importance of effective spatial planning for cost-effective and sustainable development biomass energy resources through a case study in Fujian Province, China. They used spatial analysis technology, economic models and scenario analysis, in a spatial planning framework to identify the appropriate developing areas of biomass energy at regional level. The developed methodology can be applied to a wide area and can support the local authorities to define and implement a strategy for future biomass energy development.

Long et al., 2013 [29] emphasised that knowledge of spatial distribution of bioenergy potential would guide several steps on the industry chain more effectively and efficiently, such as the collection of raw material, the allocation of primary production factories and projects, the cost-benefits analysis. Furthermore, spatial database of biomass and bioenergy potential, not only in global, regional and national scale, but also in county scale or even smaller spatial scales, will play a great role in the for the further progress of bioenergy industry.

Through a case study in Northern Spain, Panichelli and Gnansounou, 2008 [30] presented a GIS-based decision support system for selecting least-cost bioenergy locations when there is a significant variability in biomass farmgate price and when more than one bioenergy plant with a fixed capacity has to be placed in the region. The developed approach allows allocation of biomass quantities in a least-cost way and selects best energy facilities locations based on marginal delivery costs.

Lovett et al., 2009 [31] integrated GIS with an empirical model to produce a Miscanthus yield map and to estimate regional energy generation potentials in England. They concluded that GIS-based yield and suitability mapping as described in their study can help identify important issues in bioenergy generation potentials and land use implications at regional or finer spatial scales that would be missed in analyses at the national level. Further, GIS-based method as described in the paper provides an effective approach for identifying the land areas where biomass crops are most likely to be planted, the possible locations of expansions under different scenarios and the different conflicts that will inevitably need to be resolved when large-scale expansion occurs.

Yue and Wang, 2006 [32] commented that GIS aids in evaluation of various renewable energy sources according to local land uses which is useful for more-integrated and accurate decision-making process for policy-makers and investors. Such

GIS based approach can further be expanded to conduct study at the national level in order to evaluate renewable energy potential at country level.

Frombo et al., 2009 [33] proposed a GIS-based Environmental Decision Support System (EDSS) to define planning and management strategies for the optimal logistics for energy production from woody biomass, such as forest biomass, agricultural scraps and industrial and urban untreated wood residues. The EDSS has three modules *viz*. GIS, database and optimization. The optimisation module is further sub-divided into three sub-modules to tackle different kinds of decision problems such as strategic planning, tactical planning, and operational management. The EDSS is successfully demonstrated in the Liguria Region (Savona Province) of Italy.

Singh et al., 2008 [34] assessed agricultural residue biomass availability in the state of Punjab, India using GIS and mathematical model. A total amount of unused or surplus agricultural biomass potential in Punjab is about 13.73 Mt yr^{-1}, equivalent to 900 MW power. The collection cost in the field up to the carrier unit is estimated to be US\$3.90 $tonne^{-1}$ of biomass. It is observed that the unit collection cost in the field decreases with increase in spatial density of biomass, while it marginally increases with increase in carrying capacity of transport unit.

Beccali et al., 2009 [35] developed a GIS methodology to assess technical and economic potential of biomass exploitation for energy production in Sicily. The methodology is based on the use of agricultural, economic, climatic, and infrastructural data in a GIS. Data about land use, transportation facilities, urban cartography, regional territorial planning, terrain digital model, lithology, climatic types, and civil and industrial users are also integrated in the GIS system to identify potential areas for collecting residues coming from the pruning of olive groves, vineyards, and other agricultural crops, and to assess biomass available for energy cultivation. Through this GIS model, it was possible to assess the potential of biodiesel production, supposing the cultivation of rapeseed in arable crop areas. This study showed the opportunities stemming from the harmonisation of energy policy with the waste management system and rural development plan.

Masera et al., 2006 [36] argued that, for sustainable production and use of woodfuel as energy source requires a holistic view and a better knowledge of the spatial patterns of woodfuel supply and demand. However, studies concerning multi-scale spatially explicit analyses of woodfuel supply and demand that are able to articulate local heterogeneity at the regional and national levels are very limited. Considering these limitations, the authors developed a GIS based Woodfuel Integrated Supply/Demand Overview Mapping model (WISDOM) to analyze woodfuel demand and supply. They tested the model through three case studies in Mexico, Slovenia, and Senegal. Their results indicate that the WISDOM approach allows an integrated and comprehensive system for wood energy management which can sound decision making.

Frombo et al., 2009 [37] developed a GIS assisted Environmental decision support systems (EDSS) for the optimal planning of forest biomass use for energy production. The model regards decisions over a long-term period (*e.g.* years) and includes decision variables related to plant locations, biomass conversion processes, harvested biomass. Furthermore, different energy products and different definitions of the harvesting and pre-treatment operations are incorporated in the model.

Ma et al., 2005 [38] proposed a GIS based model for land-suitability assessment for energy generation at farm scale using centralised anaerobic digester systems in Tompkins County, New York. A number of environmental and social constraints, as well as economic factors are integrated in the model to help determine the optimal sites for installing such systems. They also used analytic hierarchy process (AHP) method to estimate the factors' weights in order to establish their relative importance in site selection. Using the GIS model, the authors produced a siting suitability map to identify optimal areas for distributed AD bioenergy systems. The results indicates that GIS based model, by integrating both spatial and non-spatial data, capable of providing a broad-scale and multidimensional view on the potential bioenergy systems development in a region to account for environmental and social constraints as well as economic factors. The proposed model is flexible enough to use for assessment of other biomass resources with some modification.

Ramachandra and Shruthi, 2007 [39] used spatial tools to assess potential renewable energy resources including biomass in Karnataka state of India. Through this study, usefulness of spatial tools in renewable energy resources assessment at regional level is successfully demonstrated. GIS is used to map renewable energy potential at taluk level. Taluk is an administrative division in the federal set-up in India to implement developmental programmes. Bioenergy availability from agricultural residue, forest, horticulture, plantation and livestock is the highest in Channagiri taluk of Shimoga district. On the other hand, Siddapur taluk in Uttara Kannada district has the highest bioenergy status of 2.004 (ratio of bioresource availability and demand). Resource wise analysis of the study area reveals that bioresource from horticulture constitutes the major share of 43.6%, forest 39.8%, agriculture 13.3%, livestock 3.01% and plantation15%. The availability of bioresources in different taluks depends on the agroclimatic zones.

Thus, the usefulness of remote sensing and GIS in biomass resource assessment including crop residue biomass is evident from the above literatures. However, to utilise agro-residue as a clean and environment friendly biomass energy feedstock, evaluation of its greenhouse has emission performance is important from life cycle prospective. This aspect is discussed below.

2.3. Life Cycle Assessment (LCA) of agricultural residue based biomass energy

Finnveden et al., 2009 [40] described the Life Cycle Assessment (LCA) as a tool to assess the potential environmental impacts and resources used throughout a product's lifecycle, *i.e.*, from raw material acquisition, via production and use phases, to waste management.

Shafiea et al., 2014 [41] performed a LCA study of rice straw based power generation in Malaysia. Rice straw based power generation can save GHG emissions of about 1.79 kg CO_2e kWh^{-1} and 1.05 kg CO_2e kWh^{-1} compared to coal-based and natural gas based power generation, respectively. Rice straw based power plants not only could solve the problem of removing rice straw from fields without open burning, but also could reduce GHG emissions.

Silalertruksa et al., 2013 [42] conducted a comparative LCA of four rice straw utilisation pathways *viz.* (i) direct combustion for electricity, (ii) biochemical conversion to bio-ethanol and biogas, (iii) thermo-chemical conversion to bio-DME, and (iv) incorporation into the soil as fertiliser. It is found that per tonne of dry rice straw basis, the bio-ethanol pathway results in the highest environmental benefit with regard to reduction in global warming and resource depletion potential. Rice straw electricity and fertiliser also could provide several environmental benefits. The major environmental benefit of rice straw utilisation comes from avoiding the harmful impacts of in situ burning of rice straw in the field.

Fiorentino et al., 2014 [43] evaluated the energy and environmental performance (global warming, acidification, abiotic depletion, human toxicity, eutrophication and photochemical oxidation) of the production of biodiesel from seeds and platform chemicals from *Brassica carinata* from LCA prospective. The system is compared with an equivalent system that produces only biodiesel and thermal energy. Their results shows that both the systems rely on large fractions of non-renewable energy sources (around 90% of the total use) and mostly affect the same impact categories (abiotic depletion and global warming). The agricultural phase contributes to the total impact more than the industrial extraction and conversion steps, being the nitrogen fertilisers responsible for most of impacts of both systems. However, the conversion of lignocellulosic residues into chemicals instead of heat, conserves the structural quality of natural polymers in the form of marketable value added products (ethyl levulinate and formic acid), also translating into large energy savings compared to traditional chemical routes.

Shie et al., 2014 [44] compared different scenarios to evaluate the energy balance of rice straw gasification in Taiwan using energy life-cycle assessments (ELCAs). There is a positive energy benefits at all on-site scenario cases. As the capacity is increased, the energy consumption required for transportation increases and the values of the energy indicators decrease.

Liska et al., 2014 [45] cautioned that removal of corn residue for biofuels can decrease soil organic carbon and increase CO_2 emissions because residue C in biofuels is oxidized to CO_2 at a faster rate than when added to soil. In addition, net CO_2 emissions from residue removal are not adequately characterized in biofuel LCA. The authors used a model to estimate CO_2 emissions from corn residue removal across the US Corn Belt at 580 million geospatial cells. The authors estimated residue removal of 6 Mg per ha^{-1} yr^{-1}

over 5 to 10 years could decrease regional net SOC by an average of 0.47–0.66 Mg C ha^{-1} yr^{-1}. These emissions add an average of 50–70 g CO_2 per megajoule of biofuel and are insensitive to the fraction of residue removed. They also mentioned that unless lost carbon is replaced, life cycle emissions will probably exceed the US legislative mandate of 60% reduction in greenhouse gas (GHG) emissions compared with gasoline.

Sanscartier et al., 2014 [46] used a life cycle approach to estimate the greenhouse gas (GHG) emission impacts associated with the use of pellets produced from corn cobs as the sole fuel for the generation of electricity at a hypothetically retrofitted coal-fired generating station in Ontario, Canada. Pellets are compared with current coal and hypothetical natural gas combined cycle (NGCC) facilities. Corn cob product system's life cycle emissions are 40% and 80% lower than those of the NGCC and coal product systems, respectively. If corn cobs are left in the field to decompose, some carbon is sequestered in the soil, thus their removal from the field and combustion at the generation station represents a net GHG emission, accounting for 60% of life cycle emissions. In addition to the GHG impacts of combustion, removing agricultural residues from fields may reduce soil health, increase erosion and affect soil fertility through loss of soil organic carbon and nutrients. Their sustainable use should therefore consider the maintenance of soil fertility over the long-term. Nevertheless, the use of the feedstock in place of coal may provide substantial GHG emissions mitigation.

Nguyen et al., 2013 [47] analysed the environmental performance of crop residue as an alternative source of energy. They compared the environmental performance of wheat straw based energy production with coal and natural gas systems. Substitution of straw either for coal or for natural gas reduces global warming, non-renewable energy use, human toxicity and ecotoxicity, but increases eutrophication, respiratory inorganics, acidification and photochemical ozone. However, the results at the aggregate level show that the use of straw biomass for conversion to energy scores better than that of coal but worse than natural gas.

Yang et al., 2014 [48] reported that amongst the various biomass to energy conversion technologies, gasification of crop residue is regarded as a promising technology owing to its higher energy efficiency compared to direct combustion. It is also important to investigate environmental performance of bioenergy system from a life cycle prospective. However, traditional static LCA does not include temporal information for dynamic processes and therefore the authors proposed a dynamic life cycle assessment approach, which improves the static LCA approach by considering time-varying factors, *e.g.*, greenhouse gas characterization factors and energy intensity. The proposed LCA methodology was applied to estimate the life cycle global warming impact of a crop residue gasification system in China. Their results show that the crop residue gasification has high net global warming mitigation benefit and a short global warming impact mitigation period, indicating its potential in reducing global warming impact. During the lifetime of the project, the largest emitters of the crop residue gasification project are the operation and construction stages, attributed mainly to the consumption of crop residue, electricity and steel. In addition, the comparison of the results obtained with both traditional and dynamic LCA approaches indicates that there is an exaggeration of the global warming impact reduction potential of crop residue gasification projects. The authors also emphasized that the proposed dynamic LCA can also assist decision maker in knowing the real-time GHG performance during the lifetime of a production process, and thus make timely decisions to minimize the lifetime GHG emissions.

Kunimitsu and Ueda, 2013 [49] used LCA to evaluate economic and environmental performance of rice-straw bioethanol production in Vietnam. Parameters such as total costs, total production, and total added value are used for economic impacts, while the environmental impacts are assessed by greenhouse gas emissions considering life-cycle, *i.e.*, plant construction phase, production phase, and plant scrapping phase. The authors assumed three technology scenarios (i) present technology, (ii) advanced technology with higher conversion rates, and (iii) innovative technology with a new production method and economies of scale. Their findings show that (i) rice-straw bioethanol production can reduce annual gasoline consumption by more than 20%, and plant construction costs account for 8–22% of the total investment in Vietnam; (ii) under the present technology, both economic and environmental net benefits are negative but the innovative technology makes both benefits positive; (iii) under the advanced technology, environmental net benefit is positive, but the economic net benefit is negative. Thus the authors concluded that achieving economic viability is more difficult than attaining environmental viability in rice-straw bioethanol production and hence technological development and transfer are necessary to make rice-straw bioethanol production feasible.

Muench, 2014 [50] argued that earlier literatures are not adequate to clearly explain the suitability of bioenergy to mitigate greenhouse gases. Considering this gap, Muench conducted a LCA of biomass systems to identify the greenhouse gas mitigation potential of different biomass systems used for electricity generation. The results show that biomass based electricity generation can provide significant GHG reduction benefits in the European Union. He also recommended the deployment of (i) non-dedicated lignocellulosic biomass with thermochemical conversion, (ii) dedicated lignocellulosic biomass with thermochemical conversion, and (ii) dedicated lignocellulosic biomass with direct combustion for enhance GHG reduction benefit. Furthermore, along with GHG emission analysis, future research should also focus on other environmental, economic, and social impact categories.

2.3.1. Spatial Life Cycle Assessment of biomass energy

Spatial LCA is the use of spatial tools and techniques such as remote sensing and GIS in LCA study. Use of spatial tools helps in biomass LCA studies since biomass is geographically distributed over large areas and its impacts are also spatial in nature. Certain impacts categories such as impact of land use change, impact on biodiversity could be better understood if LCA is done on spatial platform. However, use of spatial tools in LCA is recently introduced and hence literatures are also limited. Some of the available literatures regarding use of spatial tools in LCA are presented here.

Azapagic et al., 2013 [51] developed a decision-support methodology and software tool for sustainable management of urban pollution. The PUrE decision support system integrates a number of different methods and tools such as GIS, LCA, fate and transport modeling, health impact assessment and multi-criteria decision analysis in one platform. They used this tool to demonstrate its applicability in evaluating environmental and health impacts of pollution arising from different industrial, domestic and transport sources in a case study area, Sheffield, UK. Major pollutants like NOx, SO_2 and PM10 are considered in this study. In absence of current large industrial sources in Sheffield, there would be 90% reduction of SO_2 and 70% of reduction NO_2 ground concentrations, thus preventing 27 deaths and 18 respiratory hospital admissions per annum for a population of 500000. Overall such emission reductions would lead to prevention of 0.53% of premature deaths and 0.49% of respiratory hospital admissions per year.

Humpenöder et al., 2011 [52] coupled spatial model, in combination with GIS, to a LCA of biofuels to investigate land use impacts on the carbon balance of biofuels in the European Union (EU). They used the spatially explicit simulation model LandSHIFT in combination with GIS to determine land-use change and associated GHG emissions for each cell of a 5 arc minutes grid map and finally the results are transferred to a LCA biofuel framework to understand the impacts in life cycle prospective. The LandSHIFT (Schaldach et al. 2011, Schaldach et al. 2010) is a model for the simulation of land-use change on the national up to global scale in the context of medium to long-term (20-50 years) scenario analysis. The LandSHIFT model has two main-modules (i) LUC-Module, and (ii) Productivity-Module. The LUC-Module simulates land-use change within and between the land-use activities settlement (METRO), crop cultivation (AGRO) and Livestock grazing (GRAZE). The Productivity-Module calculates crops yields and the net primary production (NPP) of grassland, which serve as important input for the LUC-sub-modules AGRO and GRAZE. The LandSHIFT operates on three hierarchically structured spatial scales viz. macro-level, intermediate-level and micro-level. Using this spatial-LCA platform, the authors found that land-use change has a major impact on the GHG performance of biofuels and remarked that biofuel use is not an adequate measure for the mitigation of global warming.

Land use impact on biodiversity is a complex matter of investigation because of the spatial heterogeneity of biodiversity, un-availability of precise impact analysis model. But, the use of GIS in conjunction with LCA could give important information how land use change leave footprint on biodiversity. Geyer and co-workers (Geyer et al., 2010) presented a proof-of-concept approach for coupling GIS and LCA for biodiversity assessments of land use and applies it to a case study of ethanol production from agricultural crops in California. They used GIS modelling to generate crop production scenarios for corn and sugar beets that met a range of ethanol production targets. The resulting land use maps were translated into maps of habitat types. From these maps, vectors were created that contained the total areas for each habitat type in the study region. These habitat compositions are treated as elementary input flows and used to calculate different biodiversity impact indicators. Using this method, 10 ethanol production scenarios were developed considering current land use is added as baseline scenario. Their study demonstrated that GIS-based inventory modelling of land use allows important refinements in LCA theory and practice. Using GIS, land use can be modelled as a geospatial and nonlinear function of output. For each spatially explicit process, land use can be expressed within the conventional structure of LCA methodology as a set of elementary input flows of habitat types.

Gasol et al., 2011 [53] used a GIS and LCA combined tool to develop an integrated methodology to determine suitable areas for cultivating *Brassica* spp. (*B. carinata* and *B. napus*) and *Populus* spp. and for proposing local and decentralized energy production and consumption scenario in a case study region (Catalonia- southern Europe). The authors also mentioned that the methodology can be extrapolated to other Mediterranean regions with similar agro-climatic conditions. GIS is used to determined energy demand, biomass supplies and transport distance. On the other hand, LCA is used to understand whether a local biomass production and consumption system as proposed in their study ensures a reduction in greenhouse gases compared to non-renewable energy systems such as natural gas in power production plants, and diesel in decentralised heat production. The study shows that in the case study, a decentralised power system based on biomass would be possible with power plants lower than 10 MW. The authors concluded that integrating GIS and LCA could provide enough information to determine an energy crop implementation strategy for reducing energy consumption and GHGs emissions.

Mutel et al., 2012 [54] introduced a new methodology for performing regionalised life cycle assessment on spatial platform. The methodology couple regionalised impact assessment methods with regionalised inventories. They used a new version of the open source Brightway software that directly includes GIS capabilities in the LCA calculation. This methodology is tested in a case study of electricity production in the United States. Case study results show important differences between site-generic and regionalised calculations, and provide specific guidance for future improvements of inventory data sets and impact assessment methods.

Reap et al., 2003 reviewed limitations of LCA, discussed proposed improvements (lumped parameter, static, site-independent modeling) and suggested an improvement for LCA analysis. They suggested that linking industrial models with spatially explicit, dynamic and site-specific ecosystem models could improve the impact assessment phase of LCA.

Dresen and Jandewerth, 2012 [55] combined geoinformation system with LCA to conduct spatial analysis of LCA. In this study the authors presented a geoinformation systems-based calculation tool which combines geodata on biomass potentials, infrastructure, land use, cost and technology databases with analysis tools for the planning of biogas plants to identify the most efficient plant locations, to calculate balances of emissions, biomass streams and costs. They opined that GIS tools do not only allow the assessment of individual plants, but also the determination of the GHG reduction potential, the biogas potential as well as the necessary investment costs for entire regions. Thus, the exploitation of regional biogas potentials in a way that is sustainable and climate-friendly becomes simple.

Baan et al., 2013 [56] presented a work to highlight land use impact on biodiversity at global scale. The study is based on the United Nations Environment Programme (UNEP)/Society of Environmental Toxicology and Chemistry (SETAC) land use assessment framework and focuses on occupation impacts, quantified as a biodiversity damage potential (BDP). Species richness of different land use types was compared to a (semi-)natural regional reference situation to calculate relative changes in species richness. Data on multiple species groups were derived from a global quantitative literature review and national biodiversity monitoring data from Switzerland. Differences across land use types, biogeographic regions (*i.e.*, biomes), species groups and data source were statistically analyzed. For a data subset from the biome (sub-) tropical moist broadleaf forest, different species-based biodiversity indicators were calculated and the results compared. The authors observed an overall negative land use impact for all analyzed land use types, but results varied considerably. Different land use impacts across biogeographic regions and taxonomic groups explained some of the variability. The choice of indicator also strongly influenced the results. Relative species richness was less sensitive to land use than indicators that considered similarity of species of the reference and the land use situation. Possible sources of uncertainty, such as choice of indicators and taxonomic groups, land use classification and regionalization are critically discussed and further improvements are suggested. Data on land use impacts were very unevenly distributed across the globe and considerable knowledge gaps on cause–effect chains remain. The presented approach allows for a first rough quantification of land use impact on biodiversity in LCA on a global scale. As biodiversity is inherently heterogeneous and data availability is limited, uncertainty of the results is considerable. The presented characterization factors for BDP can approximate land use impacts on biodiversity in LCA studies that are not intended to directly support decision-making on land management practices. For such studies, more detailed and site-dependent assessments are required. To assess overall land use impacts, transformation impacts should additionally be quantified. Therefore, more accurate and regionalized data on regeneration times of ecosystems are needed.

Geyer et al., 2013 [57] presented a spatially explicit LCA of Sun-to-Wheels transportation pathways in the U.S. They argued that assessments need to be spatially explicit, since solar insolation and crop yields vary widely between locations. In this work, the authors compares direct land use, life cycle GHG emissions and fossil fuel requirements of five different sun-to-wheels conversion pathways for every county in the contiguous U.S. It is found that even the most land-use efficient biomass based pathway (*i.e.*, switchgrass bioelectricity in U.S. counties with hypothetical crop yields of over 24 tonnes/ha) requires 29 times more land than the PV-based alternative in the same locations.

Corporations are facing increasing risks associated with ecosystems from both natural drivers, such as climate change, as well as institutional drivers resulting from retailers and brands, increasingly making supplier decisions based on life cycle reporting and indexing [58]. These efforts reflect a transition from traditional firm sustainability to a more quantitative product focus, within which the importance and weight of earth resources and ecosystems is dramatically increasing. O'Shea et al., 2013 [58] provided an overview of the limitations traditional LCA methods and presents emerging developments to improve on LCA for resources and ecosystems. This includes LCA efforts to account for spatial relevance, indices of stress, stocks and flows and integrated valuation of services and trade-offs. The authors also highlighted that the approaches discussed in the paper for incorporating ecosystem services into LCA reflect the growing number of bridges between ecological science and economics, industrial ecology, and systems engineering. By developing ways to incorporate biodiversity, consumption of fresh water, and flows of ecosystem energy and resources into LCA, these methodological innovations are establishing more accurate ways to represent and account for impacts on ecosystems and ecosystem services in quantified sustainability assessments. The recent work of researchers to couple LCA with GIS also suggests a continued evolution of spatial considerations within the LCA framework. While these methods present a variety of innovative approaches, further research and data will be needed to refine them and make them operational.

Bengtsson et al., 1998 [59] developed a data model to handle information relevant to site-specific life cycle assessments LCA. The model is orientated towards GIS-representations of three generalized subsystems; the technical, the environmental and the social subsystems. The technical and environmental systems are mainly linked through flows of energy and matter, which are the causes of environmental impacts, which subsequently is perceived, evaluated and acted upon by the social subsystem. For all three systems important differences, attributable to geographical locations can be determined. With the new data model a possibility to enhance LCA and reach more relevant results emerge due to higher site specificity. The high level data model is expressed as relations between different entities using the entity relationship (ER) modeling language. An existing LCA-database, SPINE, which is already used by several companies for decision support in product development, can be utilized since the structure of the database supports geographical information. So far, applications with GIS-data are limited, but examples of area specific LCA impact characterization factors exist.

Blengini and Garbarino, 2010 [60] conducted a research to analyse energy and environmental implications of the C&DW recycling chain in Northern Italy. A combined GIS and LCA model was developed using site-specific data and paying particular attention to land use, transportation and avoided landfill: crucial issues for sustainable planning and management. The C&DW recycling chain was proved to be eco-efficient, as avoided impacts were found to be higher than the induced impacts for 13 out of 14 environmental indicators. It was also estimated that the transportation distance of recycled aggregate should increase 2-3 times before the induced impacts outweigh the avoided impacts.

Tendall et al., 2013 [61] discussed outcome of the Water in life cycle assessment-50th Swiss Discussion Forum on Life Cycle Assessment-Zürich, 4 December 2012. Many efforts have been made to include water related issues in life cycle assessment (LCA) in various ways, from the long-standing eutrophication, acidification, and ecotoxicity methods, to the more recent water consumption aspects. Although numerous developments have occurred, significant challenges still remain and certain impacts are still not considered. The 50th Swiss Discussion Forum on Life Cycle Assessment (DF-50) gave a brief overview of the current status of water use in LCA, and then focused on the following topics in three main sessions: (1) a selection of recent research developments in the field of impact assessment modelling; (2) identification of new and remaining challenges where future effort could be concentrated, with a focus on spatial and temporal resolution; (3) and experiences and learnings from application in practice. Furthermore, several short presentations addressed the issues of inventory requirements and comparison of impact assessment approaches. The DF-50 was concluded with a discussion workshop, focusing on four issues: which degree of regionalization is desirable, how to address data gaps in inventories, the comparability of different impact assessment approaches, and the pros and cons of including positive impacts (benefits). Numerous recent developments in life cycle impact assessment have tackled impact pathways, spatial and temporal resolutions, and uncertainties. They have led to an increase of the completeness of impact assessment, but also of its complexity. Although developments have also occurred in inventories, the gap between impact assessment and inventory is challenging, which in turn limits the applicability of the methods. Regionalization is confirmed as an essential aspect in water footprinting; however, its implementation requires concerted effort by impact assessment developers and software developers. Therefore, even though immense progress has been made, it may be time to think of putting the pieces together in order to simplify the applicability of these tools: enabling the support of improvements in companies and policy is the ultimate goal of LCA.

2.4. Summary

Review of literatures presented in this Chapter highlighted three important points regarding the potential use of biomass resources including rice straw residue biomass (i) successful utilisation of rice straw residue as renewable energy feedstock for both centralised and decentralised heat and power generation, (ii) need and usefulness of spatial tools in biomass resource assessment, and (iii) importance of life cycle assessment study of biomass energy to determine environmental performance. Although spatio-temporal analysis based on remote sensing and GIS has gained impetus in India and many parts of the globe, however, research gaps still exist pertaining to spatio-temporal local level decentralised agro-residue biomass energy planning in India. Limited biomass energy database particularly for region specific decentralised energy generation, limited GHG emission database on biomass energy from life cycle prospective are some major research gaps. The present research work aims to address these issues taking Sonitpur district of Assam, India as a study region.

REFERENCES

[1] Matsumura, Y., et al. Amount, availability, and potential use of rice straw (agricultural residue) biomass as an energy resource in Japan, *Biomass Bioenerg* **29**, 347--354, 2005.

[2] Zeng, X., et al. Utilization of straw in biomass energy in China, *Renew Sust Energ Rev* **11**, 976--987, 2007.

[3] Jenkins, B.M., et al. Combustion properties of biomass, *Fuel Process Technol* **54**, 17--46, 1998.

[4] Zhang, R., & Zhang, Z. Biogasification of rice straw with an anaerobic-phased solids digester system, *Bioresour Technol* **68**, 235--245, 1999.

[5] Gadde, B., et al. 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 Bioenerg* **33**, 1532--1546, 2009.

[6] Kim, S., & Dale, B.E. Global potential bioethanol production from wasted crops and crop residues, *Biomass Bioenerg* **26**, 361--375, 2004.

[7] Lim, J., et al. A review on utilisation of biomass from rice industry as a source of renewable energy, *Renew Sust Energ Rev* **16**, 3084--3094, 2012.

[8] Binod, P., et al. Bioethanol production from rice straw: An overview, *Bioresour Technol* **101**, 4767--4774, 2010.

[9] Suramaythangkoor, T., & Gheewala, S.H. Potential alternatives of heat and power technology application using rice straw in Thailand, *Appl Energ* **87**, 128--133, 2010.

[10] Delivand, M.K., et al. Economic feasibility assessment of rice straw utilization for electricity generating through combustion in Thailand, *Appl Energ* **88**, 651--3658, 2011.

[11] Hassan, S.H.A., et al. Electricity generation from rice straw using a microbial fuel cell, *Int J Hydrogen Energy* **39**, 9490--9496, 2014.

[12] Mussoline, W., et al. Electrical energy production and operational strategies from a farm-scale anaerobic batch reactor loaded with rice straw and piggery wastewater, *Renewable Energy* **62**, 399--406, 2014.

[13] Ming-Che, H., et al. GIS-based biomass resource utilization for rice straw cofiring in the Taiwanese power market, *Energy* **55**, 354--360, 2013.

[14] Ranjan, A., et al. Feasibility of rice straw as alternate substrate for biobutanol production, *Appl Energ* **103**, 32--38, 2013.

[15] Mussoline, W., et al. The anaerobic digestion of rice straw: A review, *Crit Rev Env Sci Technol* **43**, 895--915, 2013.

[16] Ramachandra, T.V., et al. Decision support system to assess regional biomass energy potential, *Int J Green Energy* **1**, 407--428, 2005.

[17] Fiorese, G., & Guariso, G. A GIS-based approach to evaluate biomass potential from energy crops at regional scale, *Environ Modell & Softw* **25**, 702--711, 2010.

[18] Thomas, A., et al. A GIS based assessment of bioenergy potential in England within existing energy systems, *Biomass Bioenerg* **55**, 107--121, 2013.

[19] Zhang, F., et al. A GIS-based method for identifying the optimal location for a facility to convert forest biomass to biofuel, *Biomass Bioenerg* **35**, 3951--3961, 2011.

[20] Ćosića, B., et al. Geographic distribution of economic potential of agricultural and forest biomass residual for energy use: Case study Croatia, *Energy* **36**, 2017--2028, 2011.

[21] Fernandes, U., & Costa, M. Potential of biomass residues for energy production and utilization in a region of Portugal, *Biomass Bioenerg* **34**, 661--666, 2010.

[22] Jiang, D., et al. Bioenergy potential from crop residues in China: Availability and distribution, *Renew Sust Energ Rev* **16**, 1377--1382, 2012.

[23] Tenerelli, P., & Carver, S. Multi-criteria, multi-objective and uncertainty analysis for agro-energy spatial modeling, *Appl Geogr* **32**, 724--736, 2012.

[24] Yoshioka, T., et al. A GIS-based analysis on the relationship between the annual available amount and the procurement cost of forest biomass in a mountainous region in Japan, *Biomass Bioenerg* **35**, 4530--4537, 2011.

[25] Sacchelli, S., et al. Bioenergy production and forest multifunctionality: A trade-off analysis using multiscale GIS model in a case study in Italy, *Appl Energ* **104**, 10--20, 2013.

[26] Zhuang, D., et al. Assessment of bioenergy potential on marginal land in China. *Renew Sust Energ Rev* **15**, 1050--1056, 2011.

[27] Angelis-Dimakisa, A., et al. Methods and tools to evaluate the availability of renewable energy sources, *Renew Sust Energ Rev* **15**, 1182--1200, 2011.

[28] Sun, Y., et al. Spatial planning framework for biomass resources for power production at regional level: A case study for Fujian Province, China, *Appl Energ* **106**, 391--406, 2013.

[29] Long, H., et al. Biomass resources and their bioenergy potential estimation: A review, *Renew Sust Energ Rev* **26**, 344--352, 2013.

[30] Panichelli, L., & Gnansounou, E. GIS-based approach for defining bioenergy facilities location: A case study in Northern Spain based on marginal delivery costs and resources competition between facilities, *Biomass Bioenerg* **32**, 289--300, 2008.

[31] Lovett, A.A., et al. Land use implications of increased biomass production identified by GIS-based suitability and yield mapping for Miscanthus in England, *BioEnergy Research* **2**, 17--28, 2009.

[32] Cheng-Dar, Y., & Shi-Sian, W. GIS-based evaluation of multifarious local renewable energy sources: a case study of the Chigu area of southwestern Taiwan, *Energy Policy* **34**, 730--742, 2006.

[33] Frombo, F., et al. Planning woody biomass logistics for energy production: A strategic decision model, *Biomass Bioenerg* **33**, 372--383, 2009.

[34] Singh, J., et al. Energy potential through agricultural biomass using geographical information system-A case study of Punjab, *Biomass Bioenerg* **32**, 301--307, 2008.

[35] Beccali, M., et al. Assessment of bioenergy potential in Sicily: A GIS-based support methodology, *Biomass Bioenerg* **33**, 79--87, 2009.

[36] Masera, A., et al. WISDOM: A GIS-based supply demand mapping tool for woodfuel management, *Biomass Bioenerg* **30**, 618--637, 2006.

[37] Frombo, F., et al. A decision support system for planning biomass-based energy production, *Energy* **34**, 362--369, 2009.

[38] Ma, J., et al. Siting analysis of farm-based centralized anaerobic digester systems for distributed generation using GIS, *Biomass Bioenerg* **28**, 591--600, 2005.

[39] Ramachandra, T.V., & Shruthi, B.V. Spatial mapping of renewable energy potential, *Renew Sust Energ Rev* **11**, 1460--1480, 2007.

[40] Finnveden, G., et al. Recent developments in Life Cycle Assessment, *J. Environ Manage* **91**, 1--21, 2009.

[41] Shafiea, S.M., et al. Life cycle assessment of rice straw-based power generation in Malaysia, *Energy* **70**, 401--410, 2014.

[42] Silalertruksa, T., & Gheewala, S.H. A comparative LCA of rice straw utilization for fuels and fertilizer in Thailand, *Bioresour Technol* **150**, 412--419, 2013.

[43] Fiorentino, G., et al. Life cycle assessment of *Brassica carinata* biomass conversion to bioenergy and platform chemicals, *J Cleaner Production* **66**, 174--187, 2014.

[44] Shie, J.L., et al. Scenario comparisons of gasification technology using energy life cycle assessment for bioenergy recovery from rice straw in Taiwan, *Energy Convers Manage* **87**, 156--163, 2014.

[45] Liska, A.J., et al. Biofuels from crop residue can reduce soil carbon and increase CO_2 emissions, *Nature Climate Change* **4**, 398--401, 2014.

[46] Sanscartier, D., et al. Life cycle greenhouse gas emissions of electricity generation from corn cobs in Ontario, Canada, *Biofuels, Bioprod Biorefin* **8**, 568--578, 2014.

[47] Nguyen, T.L.T., et al. Environmental performance of crop residues as an energy source for electricity production: The case of wheat straw in Denmark, *Appl Energ* **104**, 633--641, 2013.

[48] Yang, J., & Chen, B. Global warming impact assessment of a crop residue gasification project-A dynamic LCA perspective, *Appl Energ* **122**, 269--79, 2014.

[49] Kunimitsu, Y., & Ueda, T. Economic and environmental effects of rice-straw bioethanol production in Vietnam, *Paddy Water Environ* **11**, 411--421, 2013.

[50] Muench, S. Greenhouse gas mitigation potential of electricity from biomass. *J Cleaner Production*, DOI: 10.1016/j.jclepro.2014.08.082.

[51] Azapagic, A., et al. An integrated approach to assessing the environmental and health impacts of pollution in the urban environment: Methodology and a case study, *Process Safe Environ prot* **91**, 508--520, 2013.

[52] Humpenöder, F., et al. Analysing land-use effects on the carbon balance of biofuels by coupling a spatial model to LCA. EnviroInfo 2011: Innovations in Sharing Environmental Observations and Information 2011; Shaker Verlag Aachen, ISBN: 978-3-8440-0451-9.

[53] Geyer, R., et al. Coupling GIS and LCA for biodiversity assessments of land use Part 1: Inventory modeling, *Int J Life Cycle Assess* **15**, 454--467, 2010.

[54] Gasol, C.M., et al. Environmental assessment: (LCA) and spatial modelling (GIS) of energy crop implementation on local scale, *Biomass Bioenerg* **35**, 2975--2985, 2011.

[55] Mutel, C.L., et al. GIS-based regionalized Life Cycle Assessment: How big is small enough? Methodology and case study of electricity generation, *Environ Sci Technol* **46**, 1096--1103, 2012.

[56] Reap, J., et al. Improving life cycle assessment by including spatial, dynamic and place based modeling. Proceedings of DETC'03 ASME 2003 Design Engineering Technical Conferences and Computers and Information in Engineering Conference Chicago, Illinois, USA, September 2-6, 2003.

[57] Dresen, B., & Jandewerth, M. Integration of spatial analyses into LCA—calculating GHG emissions with geoinformation systems, *Int J Life Cycle Assess* **17**, 1094--1103, 2012.

[58] Baan, de L., et al. Land use impacts on biodiversity in LCA: a global approach, *Int J Life Cycle Assess* **18**, 1216--1230, 2013.

[59] Geyer, R., et al. Spatially-explicit Life Cycle Assessment of sun-to-wheels Transportation pathways in the U.S., *Environ Sci Technol* **47**, 1170--1176, 2013.

[60] O'Shea, T., et al. Sustainability and earth resources: Life Cycle Assessment modeling, *Bus Strat Env* **22**, 429--441, 2013.

[61] Bengtsson, M., et al. An approach for handling geographical information in life cycle assessment using a relational database, *J Hazard Mater* **61**, 67--75, 1998.

[62] Blengini, G.A., & Garbarino, E. Resources and waste management in Turin (Italy): the role of recycled aggregates in the sustainable supply mix, *J Cleaner Production* **18**, 1021--1030, 2010.

[63] Tendall, D.M., et al. Water in life cycle assessment—50th Swiss Discussion Forum on Life Cycle Assessment—Zürich, 4 December 2012, *Int J Life Cycle Assess* **18**, 1174--1179, 2013.

CHAPTER 3

SPATIAL TOOL FOR CROP RESIDUE BIOMASS RESOURCE ASSESSMENT

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3.1. Remote sensing and GIS in biomass resource assessment

Remote sensing (RS) and Geographic Information System (GIS) have been gaining increased applications in renewable energy resources assessment, particularly in the assessment of biomass resources due to their distinct advantages over traditional methods of assessment [1-5]. Development of GIS assisted spatial tool for assessment of biomass energy resources have been reported in many literatures. For example, Ramachandra et al., 2005 [6], proposed a Biomass Energy Potential Assessment (BEPA) decision support system to assist planners to plan and manage bioresources in a sustainable way for implementation at regional level. Tenerelli et al., 2012 [7] proposed a GIS based multi-criteria approach to assess range of possibilities for perennial energy crops conversion. Frombo et al., 2009 [8] developed a GIS-based Environmental Decision Support System (EDSS) to define planning and management strategies for the optimal logistics for energy production from woody biomass, such as forest biomass, agricultural scraps and industrial and urban untreated wood residues. Similarly, Kaundinya et al., 2013 [9], developed a GIS based data mining approach for optimal selection of locations and determining installed capacities for distributed biomass power generation systems applicable for rural regions.

In the present research work, a RSGIS based spatial tool is developed to assess spatial distribution and availability of crop residue in the study area *i.e.* Sonitpur district of Assam, India. Furthermore, the output of this modelling tool, in the form of spatial maps loaded with other relevant information such as area of each rice cropland polygon, location (village, development block) of a cropland, amount of rice grain produce per cropland and subsequently amount of rice straw available per cropland are used with mathematical models to quantify crop residue based power potential in the study area. The procedure of spatial tool development is shown in Fig.3.1 and also described below.

3.2. Software, data and mathematical model

3.2.1. Software

(i) ERDAS Imagine (version 9.1) developed by ERDAS ®, Inc., USA is used for satellite image processing, georeferencing and accuracy assessment.

(ii) ArcGIS 9.2 developed by ESRI (Environmental Systems Research Institute), USA is used to map spatial distribution of rice cropland and subsequently crop residue in the study area.

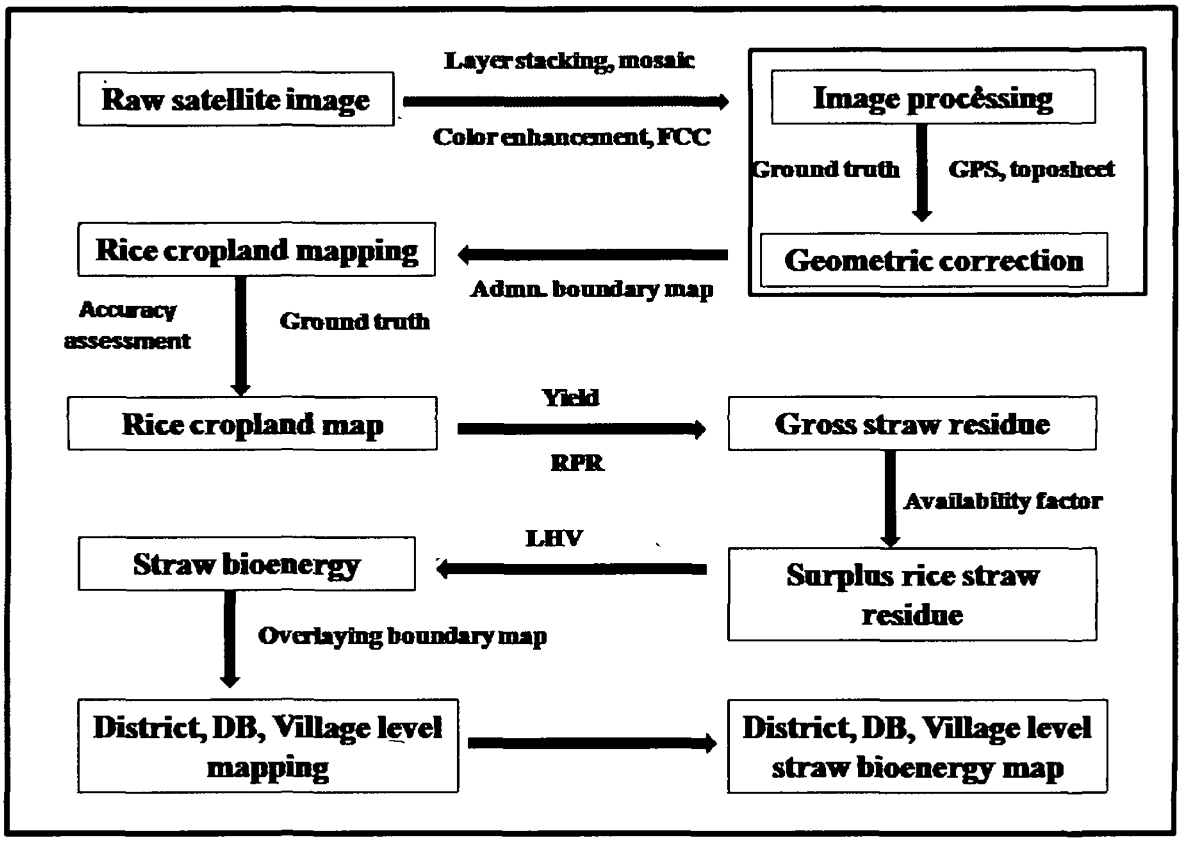


Fig. 3.1: Flow diagram of spatial tool development

3.2.2. Data

Two categories of data *i.e.* spatial and non-spatial are used in the development of the spatial tool as discussed below.

3.2.2.1. Spatial data

3.2.2.1a. Remote sensing data

Remote sensing is the science of obtaining information about an object of interest without coming direct contact with it from a distance, typically using aircraft or satellites. The principle of remote sensing is that solar radiation (electromagnetic radiation) after striking various objects of the earth surface (soil, water, vegetation, buildings *etc.*), reflected back into the atmosphere according their reflective properties. The reflected radiation is detected and recorded by the remote sensor place high in the atmosphere. The sensor than send back the radiation to ground station where the radiations are analysed according to their properties and classifies them into meaningful categories which are generally termed as satellite image.

In the present study, IRS-P6 (Indian Remote sensing Satellite) LISS III (Linear Imaging and Self Scanning Sensor) multi-spectral satellite images (spatial resolution 23.5 m) pertaining to Sonitpur district are used. The images are procured from the National Remote Sensing Centre (NRSC, Govt. of India) [6]. The images are of the month November *i.e.* winter rice harvesting period (details in Table 3.1). Image pertaining to rice growing period could not be used because of the presence of cloud cover in the images. It is difficult to accurately identify and classify ground features in presence of clouds cover in satellite image [7, 8]. The study area falls across multiple satellite scenes, hence each of the scenes are first pre-processed separately and then mosaicked together to make a single raster image covering the entire study area. Data normalisation is done using standard procedure available in ERDAS Imagine software. In addition to the LISS III images, high resolution IRS-P6 LISS IV satellite images (5.8 m spatial resolution) collected from National Remote Sensing Centre (NRSC, Government of India) and very high resolution WorldView 2 multispectral (1.84 m spatial resolution) satellite image developed by DigitalGlobe are also used for the study of certain aspects such as road network, rural settlement of some selected regions the study area [9]. A brief description of satellite images used in this study is given in Table 3.1.

Table 3.1: Specifications of satellite images used in the present study

Specifications	**LISS-III**	**LISS-IV**	**WorldView 2**
Satellite	IRS-P6	IRS-P6	WorldView 2
Sensor	LISS-III	LISS-IV	
Spatial resolution	23.5 meter	5.8 meter	1.84 meter
Swath	141 km	23.9 km (multispectral)	16.4 km
Image size (km×km)	142×141	23×23 (multispectral)	
Spectral band	B2 0.52-0.59	B2 0.52-0.59	
	B3 0.62-0.68	B3 0.62-0.68	
	B4 0.77-0.86	B4 0.77-0.86	
	B5 1.55-1.87		
Cloud cover	Less than 3%	Less than 3%	Less than 1%
Acquisition dates	19 Nov, 2008	05 Feb, 2008	10 Oct, 2010
	24 Nov, 2008	12 April, 2009	

3.2.2.1b. Global Positioning System (GPS) data

Global Positioning System (GPS) is a satellite based navigation system that provides user's location. GPS can also be used to identify elevation, distance between two points, tracking *etc.* This navigation system is launched into orbit by the US Department of Defence and it is made up of a network 24 navigation satellites. There could be multiple sources of errors in GPS (errors due to satellite clock, atmospheric effects, ground receiver). In the present work, to minimise error, GPS coordinates are recorded when there are atleast 10-12 satellites signals are available for the GPS receiver.

Prior to mapping of rice croplands of the study area, handheld GPS (make: Garmin) is used to collect ground control points (GCPs) of randomly selected locations of the study area. The GCPs are then compared with the satellite image to ascertain whether spectral signature of a particular feature present in the image matches with ground reality. GPS data are also collected post-mapping period from randomly selected fields for accuracy assessment.

3.2.2.1c. Geographical Map data

Following geographical data are also used in the development of the spatial tool.

(a) Survey of India (SOI) topographical maps

Survey of India (SOI) topographical maps of 1:50000 scale (published during 1966-1984) are used as reference maps to georeference the raw satellite image and also to identify and verify features such as railways, major roads, government establishments, tea gardens which are visible both in the toposheets and satellite images. Temporal variation between SOI maps and satellite images is not considered since SOI maps are mainly used for georeferencing and features identification purposes. The hard copy maps (later converted to digital format) are collected from SOI Zonal Office, Shillong, Meghalaya. A 1:50000 scale SOI map covers an area of 27×27 km (15° ×15°).

(b) District administrative boundary maps

District administrative boundary maps (not in scale, published in 2007) in hard copy format (later converted to digital format) are collected from the district administration of Sonitpur district. The maps are used to identify and extract district, development block and village boundaries and also to extract protected forest areas boundary of Sonitpur district. The maps are also used as a reference mapping of road network of the study area.

(c) Road network map

Road network map of Sonitpur district in hard copy format (later converted to digital format) is collected from the Public Works Department, Sonitpur district. The map contains information of national highway, major roads, urban as well as rural roads running through the district.

3.2.2.2. Non-spatial data

3.2.2.2a. Agricultural data

The satellite image provides information on area coverage by a crop. However, quantification of the crop residue requires the productivity data of a crop. The spatially varying productivity data could not be generated from the satellite image. Therefore, district level rice productivity data of Sonitpur, collected from standard source is used.

3.2.2.2b. Field survey and laboratory analysis data

Field survey and laboratory analysis data such as residue production ratio (RPR) of crop residue, availability factor of crop residue and lower heating value (LHV) of crop residue are also used in the development of the spatial tool.

3.2.3. Mathematical model for spatial assessment of crop residue

Four mathematical models have been developed and incorporated in the spatial tool to assess crop residue availability and subsequently biomass power potential in the study area.

$$TCRB(j) = \sum_{i=1}^{n} R(i,j) \times Y(i,j) \times A(i,j) \tag{3.1}$$

$$PCRB(j) = \sum_{i=1}^{n} R(i,j) \times Y(i,j) \times A(i,j) \times F(i,j) \tag{3.2}$$

$$CRBE(j) = \sum_{i=1}^{n} R(i,j) \times Y(i,j) \times A(i,j) \times F(i,j) \times C(i,j) \tag{3.3}$$

$$CRBP(j) = \frac{K \times \sum_{i=1}^{n} R(i,j) \times Y(i,j) \times A(i,j) \times F(i,j) \times C(i,j)}{T} \tag{3.4}$$

where $TCRB(j)$ is the theoretical crop residue biomass availability at j^{th} location, tonne; $R(i,j)$ is the residue production ratio of i^{th} crop at j^{th} location; $Y(i,j)$ is the yield of i^{th} crop at j^{th} location, tonne ha^{-1} and $A(i,j)$ is area of i^{th} crop at j^{th} location, ha; $PCRB(J)$ is the practically available crop residue biomass at j^{th} location, tonne; $F(i,j)$ is the residue availability factor of i^{th} crop at j^{th} location; $CRBE(j)$ is the crop residue biomass energy at j^{th} location, MJ and $C(i,j)$ is the lower heating value of the i^{th} crop at j^{th} location, MJ tonne^{-1}; $CRBP(J)$ is the crop residue biomass power at j^{th} location, kW; K is the overall energy conversion efficiency, and T is the annual operating duration, seconds. Continuous operation throughout the year is considered for assessment of power.

3.3. Image processing and georeferencing

Preprocessing of raw satellite data is an important aspect in remote sensing and GIS. Image rectification and restoration are collectively termed as image preprocessing and it involves initial correction of raw image data to correct for geometric distortions, radiometric calibration, and noise removal [10]. On the other hand, image enhancement is performed in order to display more effectively image data for better visual interpretation. Image preprocessing is done using ERDAS Imagine software.

Three LISS-III satellite image scenes were required to cover the entire study area. To make and display the scenes as a single layer, image mosaic is done using ERDAS Imagine software. Since the area of interest (AOI) in the present study is only the Sonitpur district, therefore image subset is done to extract the AOI from the mosaic layer by overlying the digitised district boundary map over the mosaic layer.

The AOI is further processed and enhanced to make the image ready for georeferencing. Image georeferencing is the process of providing geographical location (latitude and longitude) to a non-georeferenced physical or raster image for further analysis. Georeferencing can be done taking reference from an already georeferenced image of the same study area or by giving GPS based ground control points (GCPs), which are randomly collected from fields. While a reference image is used to georeference an image, the process is termed as image to image registration. In this study, SOI toposheets are used as a reference map to georeference the satellite image. First, the digitised SOI toposheets are georeferenced into Universal Transverse Mercator-

World Geodetic System 84 (UTM-WGS 84). Second, Ground Control Points (GCP) taken from the georeferenced 1:50000 SOI toposheets are used to georeference the satellite image. Road and railway crossings and prominent buildings are considered as GCPs during georeferencing as they can be easily identified both in the toposheet and image. Image registration is also verified with the GCPs collected from fields using handheld GPS. The image is resampled using Nearest Neighbour method and an RSM (root mean square) error of less than 0.5 pixels is achieved during image registration. A false colour composite (FCC) of the bands 2 (green), 3 (red) and 4 (near IR) displayed to blue, green and red colour, respectively, is then created.

Similar procedure is also applied to process and georeference the IRS P6 LISS-IV satellite image. The WorldView-2 satellite image is collected in processed format and thus, did not require further processing. The WorldView-2 image is also georeferenced in to the UTM-WGS 84 projection system.

Once georeferencing is done, the image is ready for further GIS analysis such as rice cropland mapping. Information available from the cropland map along with other spatial and non-spatial inputs are used to map crop residue availability and crop residue biomass power in the study area.

3.4. Summary

Thus, satellite image, spatial and non-spatial data, GPS data, field survey and laboratory analysis data and mathematical models are integrated together in remote sensing and GIS environment to develop the spatial tool. Application of the spatial tool in mapping of crop residue biomass and subsequently biomass power in the study area is discussed in the next Chapters of the thesis.

REFERENCES

[1] Elmore, A.J., et al. Spatial distribution of agricultural residue from paddy for potential biofuel production in China, *Biomass Bioenerg* **32**, 22--27, 2008.

[2] Ramachandra, T.V. Mapping of fuelwood trees using geoinformatics, *Renew Sust Energ Rev* **14**, 642--654, 2010.

[3] Kinoshita, T., et al., A spatial evaluation of forest biomass usage using GIS, *Appl Energ* **86**, 1--8, 2009.

[4] Hoskinson, R.L., et al. Using a decision support system to optimize production of agricultural crop residue biofeedstock, *Biomass Bioenerg* **31**, 186--194, 2007.

[5] Ramachandra, T.V., & Shruthi, B.V. Spatial mapping of renewable energy potential, *Renew Sust Energ Rev* **11**, 1460--1480, 2007.

[6] Ramachandra T.V., et al. Decision support system to assess regional biomass energy potential, *Int J Green Energy* **1**, 407--428, 2005.

[7] Tenerelli, P., & Carver, S. Multi-criteria, multi-objective and uncertainty analysis for agro-energy spatial modeling, *Appl Geogr* **32**, 724--736, 2012.

[8] Frombo, F., et al. Planning woody biomass logistics for energy production: A strategic decision model, *Biomass Bioenerg* **33**, 372--383, 2009.

[9] Kaundinya, D.P., et al. A GIS (geographical information system)-based spatial data mining approach for optimal location and capacity planning of distributed biomass power generation facilities: A case study of Tumkur district, India, *Energy* **52**,77--88, 2013.

[10] National Remote Sensing Centre (NRSC), Govt. of India. http://www.nrsc.gov.in/.

[11] Hansen, M.C., et al. Humid tropical forest clearing from 2000 to 2005 quantified by using multitemporal and multiresolution remotely sensed data, *Proc Natl Acad Sci* **105** (27), 9439--9444, 2008.

[12] Eva, H., et al. Monitoring forest areas from continental to territorial levels using a sample of medium spatial resolution satellite imagery, *ISPRS J Photogramm Remote Sens* **65** (2), 191--197, 2010.

[13] DigitalGlobe. http://www.digitalglobe.com/about-us/content-collection.

[14] Lillesand, T.M. & Kiefer, R.W. *Remote sensing and image interpretation* (4th ed), John Wiley & Sons, Inc., New York, 1999.

CHAPTER 4

SPATIAL ASSESSMENT OF RICE STRAW RESIDUE POWER

CHAPTER 4

SPATIAL ASSESSMENT OF RICE STRAW RESIDUE POWER

4.1. Study area

In this research work, Sonitpur district of Assam, India is selected as a study area considering the following reasons.

(i) Sensitive to power crisis: Like many other districts of Assam, Sonitpur have been also facing severe power crisis, thus resulting in hindrance in daily activities in almost all the sectors: households, commercial, industrial, service. There is no coal fired power plant or hydro power plant installed in the district.

(ii) Tea dominating region: Tea is the major commercial crop of the district with tea gardens spreading all over the district. Sonitpur is the third largest tea produce of Assam. Assured and adequate supply of electricity supply is required in tea industries. However, power crisis in the district has been greatly hampering the tea sector of the district. Major share of electricity demand in tea industries of the district is met through diesel generator sets.

(iii) Growth in infrastructures: The district has been witnessing a growth in infrastructures, not only industrial or commercial but also in service sector such as Tezpur Central University, Tezpur Medical College. Thus demand for electricity has been also increasing in the district.

(iv) Rich biological resources: Owing to its agrarian nature and rich biological resources, the district has potential for biomass resources based energy generation. Rice is cultivated all over the district and hence there is a prospect for rice residue based biomass energy programme. However, prior to the present study, no other research has been carried out in the district to precisely assess rice residue availability.

(v) Initiative by private farms for bioenergy: Realising the potential for biomass energy in the district, there are initiates by private farms to generate biomass energy. For example, a 2.5 MW biomethanation power plant in the district by Cleanopolis Energy Systems India Pvt. Ltd., Assam (India) is under commission. Similarly, Nezone Biscuit Factory, Tezpur has been taking initiative to use biomass resources for thermal energy. Furthermore, the Department of Energy, Tezpur University has been conducting teaching and research programme in renewable energy including biomass energy. Findings of the present study would encourage similar initiates in the future.

Sonitpur is an agrarian economy with about 80% population dependent on agriculture for their livelihood. Rice is cultivated in the district in two seasons, *viz.* winter (June/July to November/December) and summer (December/February to May/June). However, only winter rice is widely practiced in the district. Cultivation of summer rice is not common expects in few pockets, mostly due to scarcity of rain and lack of irrigation facilitates. Majority of farmers of the district follows traditional methods of rice cultivation with human and animal sources of power. Moreover, the consumption of chemical fertiliser is also low. Perhaps lower level of rice productivity is attributed to these factors. It is true that lesser level of mechanised power and inputs of chemical fertiliser could be beneficial on sustainability point of view. However, increasing production through inputs intensification has been a requirement, and therefore an optimal strategy is needed.

As mentioned above, winter rice is widely cultivated in Sonitpur district and therefore, in the present work, only rice straw available from winter rice is considered for assessment of straw residue availability for biomass power generation. Assessment of rice straw availability concerning the study area has been done using remote sensing data, spatial and non-spatial data.

Sonitpur is one of the 28 districts of Assam lying in between $92^0 16'$ E, $93^0 43'$ E longitudes and $26^0 30'$ N, $27^0 0'$ N latitudes (Fig. 4.1). The total geographical area of the district is 5324.00 sq. km. Agro-climatically the state of Assam is divided into 6 agro-climatic zones *viz.* North Bank Plain Zone (NBPZ), Upper Brahmaputra Valley Zone (UBVZ), Central Brahmaputra Valley Zone (CBVZ), Lower Brahmaputra Valley Zone (LBVZ), Barak Valley Zone (BVZ) and Hills Zone (HZ). Sonitpur district falls under the

North Bank Plain Zone (NBPZ). The climate of the district is sub-tropical type with average summer and summer monsoon (March to September) and winter (December to February) temperature is 29 ^{0}C and 16 ^{0}C, respectively. The annual rainfall in the district varies between 1355 to 2348 mm. Sonitpur is rich in biodiversity. The district falls under the Indo-Burma biodiversity hotspot. Land use land cover pattern of the district can be divided as tropical semi-evergreen forest (Assam valley semi-evergreen forest, eastern alluvial semi-evergreen forest), moist deciduous forest (east Himalayan moist deciduous forest), riverain forest, grassland, agricultural land and tea garden [1]. For convenience of local administration, the district is geographically divided into 3 sub-divisions, 5 circles, 14 development blocks, 158 gram panchayats and 1615 villages. Village is the smallest administrative unit. Tezpur is the head quarter of the district. Out of the total geographical area of 5324 sq. km. in the district, the 14 development blocks cover 3051 sq. km. area. The remaining areas (2273 sq. km.) are covered by protected areas, rivers which doesn't fall within the 14 development blocks boundaries.

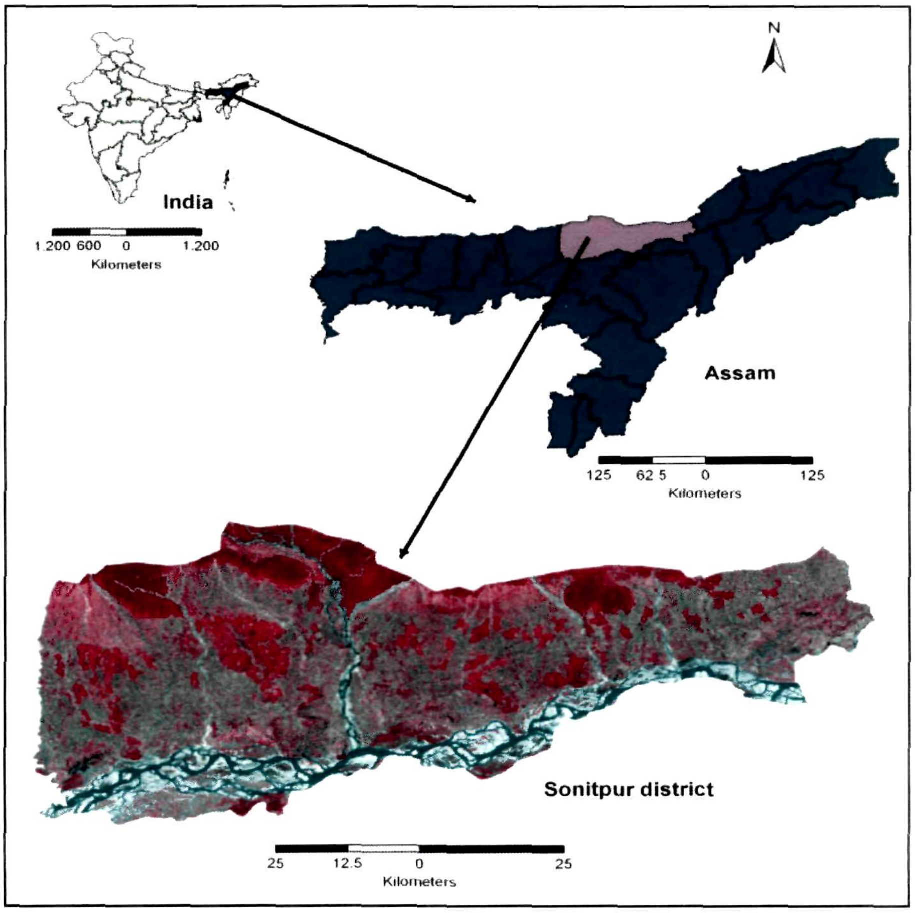


Fig.4.1: Sonitpur district, Assam, India and FCC of IRS P6 LISS III

Table 4.1: A brief profile of Sonitpur district [2]

Parameters	**Statistics**
Geographical location	26°30′-27°01′N and 92°16′-93°43′E
Geographical area, sq. km.	5324.00
Borders	North: Arunachal Pradesh South: River Brahmaputra East: Lakhimpur District West: Darrang District
Population (as per 2011 census)	1924110
Male: female	983904:940206
Literacy rate	67.34%
Population density, people per sq. km.	370
Sex ratio, per 1000	956
Villages	1615
Development blocks	14
Circles	7
Towns	5
Major forests	Nameri National park, Sonai-Rupai sanctuary and Bordikorai wildlife sanctuary
Major rivers	Brahmaputra, Jiabharali, Gabharu, Borgang, Buroi

4.2. Technological consideration for crop residue to energy conversion

There are two main technologies for converting biomass to energy *viz.*, thermochemical and biochemical. Combustion, pyrolysis, gasification, and liquefaction are distinguishable thermochemical conversion processes while biochemical conversion encompasses digestion (biogas) and fermentation (ethanol) [3].

Among the thermochemical conversion technologies, combustion is a mature technology specifically suitable for loose biomass [4]. The combustion process converts chemical energy stored in biomass into heat, mechanical power and electricity using various equipments, *e.g.* furnaces, boilers, steam turbines and generators. It is possible to burn any type of biomass with a moisture content of less than 50% [3]. Typical size of combustion based biomass power plant ranges from a few kWe up to hundreds MWe with net conversion efficiency between 20% and 40% [3-5].

Heating value of a biomass fuel is important factor in determining its fuel quality. It is the amount of heat produced when a certain quantity of fuel is combusted. The heating value can be expressed either as higher (or gross) heating value (HHV) or lower heating value (LHV). The HHV of a fuel is defined as the amount of heat released by a specified quantity (initially at 25 °C) once it is combusted and the products have returned to a temperature of 25 °C, which takes into account the latent heat of vaporization of water in the combustion products. On the other hand, the LHV of a fuel is defined as the amount of heat released by combusting a specified quantity (initially at 25 °C) and returning the temperature of the combustion products to 150 °C, which assumes the latent heat of vaporization of water in the reaction products is not recovered [6].

The procedure for assessment of rice straw availability and subsequently biomass power potential in the study is described below. Before that, a brief description of the study area is presented.

4.3. Methodology

4.3.1. Mapping of rice straw residue

Mapping for rice straw residue is done using information of spatial distribution of rice straw in the study area. Winter rice based farming system prevails in Sonitpur district. Therefore, available satellite image concerning the growing period of winter rice (June/July to November/December) is considered to map the cropland. The detail of the mapping procedure is given below.

4.3.1a. Identification of rice cropland in the satellite image

Each spectral signature of a satellite image specifies a particular object of the earth surface. Accurate identification of spectral signature is important to classify the object of interest correctly. Sometimes spectral signatures of two different ground objects are almost similar, thus, making it difficult to visually distinguish ground objects. For example, spectral signatures of rice cropland after grain harvesting (*i.e.* when only straw is left in the field) and barren land are almost similar. However, rice fields can be distinguished from other vegetations based on texture, colour, tone, shape, size, neighbourhood pattern. Furthermore, rice fields in the study are fragmented in nature and rectangular in shape, which is not observed in case of natural forest vegetation. Therefore, prior knowledge of spectral signature, analyser experience, pre-mapping and post-mapping field verification are very important to accurately map the object of interest. Rice cropland after grain harvesting (*i.e.* when only straw is left in the field) appear as bluish green in LISS-III image under FCC band 3-2-1 (Near IR, Red, Green). Prior to mapping of rice croplands, field visits have been done to randomly selected locations of the study area using GPS. Guidelines for identification and mapping of land use land cover including rice cropland using LISS-III image provided by National Remote Sensing Centre (NRSC, Government of India) are also followed [7].

4.3.1b. Mapping of rice cropland

Mapping of rice cropland is carried out using GIS software ArcGIS 9.2. As mentioned earlier, while interpreting and delineating the rice fields, guidelines for LISS-III image interpretation provided by NRSC are followed. Mapping of rice cropland is carried out in polygon mode using ArcGIS shapefile format. Mapping of rice cropland of the study area is also shown in Fig.4.2. Co-ordinate system of the shapefile is defined by importing the same co-ordinate system given to the satellite image (*i.e.* UTM-WGS 84). The attribute table of the shapefile contains all the relevant information, such as district name, development block name, village name, rice cropland area per polygon. Expansion of rice cropland into the protected forest areas of the district is also noticed in the satellite image for some of the development blocks such as Balipara, Rangapara, and Behali. However, rice croplands inside protected areas are not included in this study since such cropping practice inside protected areas is not allowed by the concerned government authorities. It is also noticed that the rice crop areas are typically sandwiched between rural settlement and the rivers of the district.

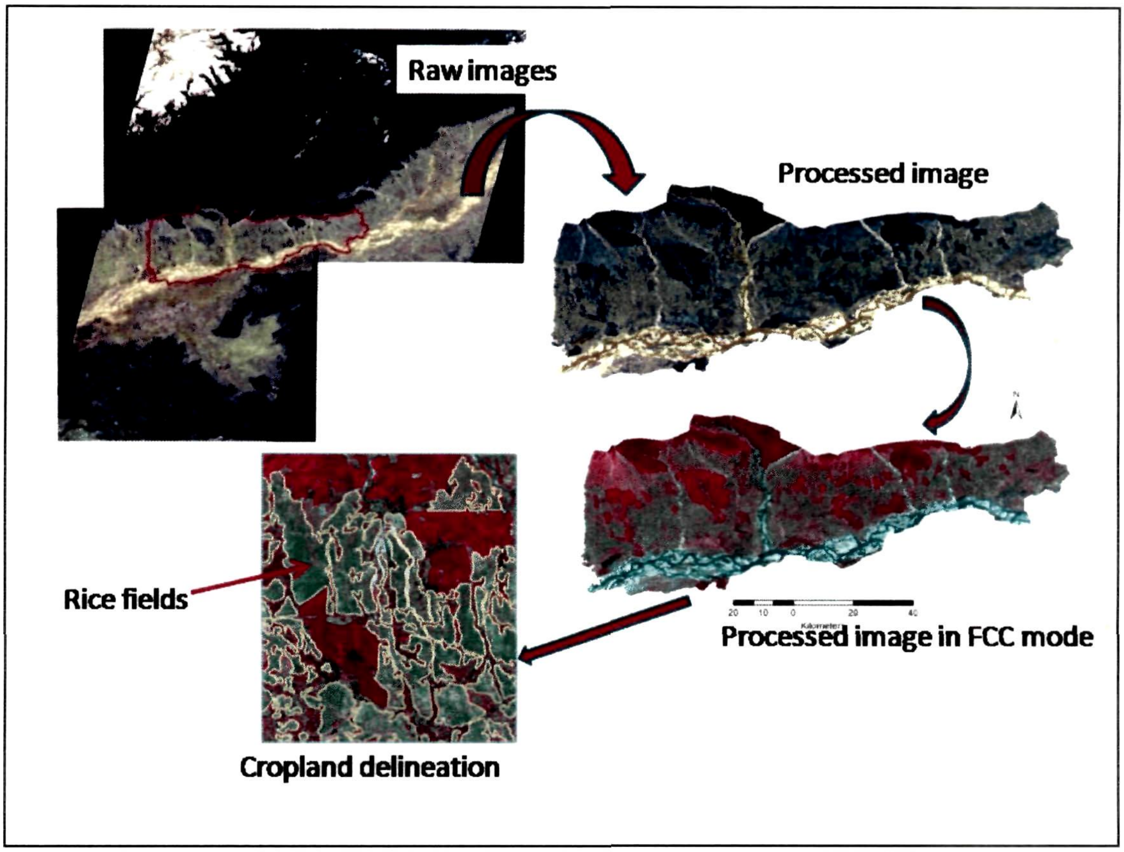


Fig.4.2: Rice croplands mapping of Sonitpur in FCC band (3-2-1; Near IR-Red-Green)

Once mapping is completed, accuracy assessment of the mapping procedure is conducted in terms of Kappa accuracy. After mapping the rice fields, development block and village wise availability of rice crop area is estimated by overlaying the rice field vector layer with the development block and village vector layer using Overlay Analysis function of ArcGIS 9.2.

4.3.1c. Mapping of other land use land cover

In the present study other land use land cover such as protected forest areas, tea gardens, rivers and road network of the study area is also mapped using the LISS-III image. Reserve forests of the district are situated in the northern border. The forest and tea garden areas appear as light to dark red in FCC mode of LISS-III satellite image. All the rivers of the district are identified and mapped. Rivers could be easily identified in satellite image because of its light to deep bluish water colour (depending on water depth and other characteristics) in FCC mode and distinct water channel pattern. The Brahmaputra is the major river of the district. Beside Brahmaputra, there are also many small river tributaries such as Jiabharali, Gabharu, Borgang, and Buroi. Furthermore, road network of the district is also mapped. From biomass energy planning prospective, road network mapping is important as biomass feedstocks have to be transported from field to power plant location. Identification of shortest road network could save both time and transportation cost and also reduces greenhouse gas emission due to transportation. Road networks such as national highway, district roads, major roads, urban and rural roads of the district are identified and mapped. All the land use land cover mentioned above are mapped as separate layer.

4.3.2. Estimation of rice straw residue availability

After mapping the rice croplands at district, development block and village level, spatial availability of straw residue biomass is estimated using the Eq. (3.1) as presented in Chapter 3.

Spatial variations of residue production ratio, attributed mainly by crop variety, agricultural practice are considered in the present study. The value of residue production ratio is determined through field visits to randomly selected rice fields and laboratory analysis. However, spatial variations in rice crop yield is not considered and therefore five year average yield of rice, grown in Sonitpur district during 2003 to 2007 as reported by the Ministry of Agriculture, Govt. of India is used [8].

The residue production ratio (RPR) is the amount of residue produced per unit of grain. To determine RPR value, randomly selected rice fields of 7 development blocks are visited. In each development block, 4-5 distantly located villages are visited and in each village, 2-3 different rice fields are visited during grain harvesting time. Furthermore, from each rice field, 3-4 rice samples are collected. Whole rice plants (*i.e.* root, grain, leafs, straw) are collected and taken to the lab for further analysis. Before collecting the rice samples, farmers are also consulted to ascertain variety name, application of fertilizer, height of cut and uses of rice straw. Height of the rice plant is also recorded in the field. In the laboratory, grains and roots are separated from the rice plant. For each rice plant, grains and plant biomass is weighted separately on dry basis. The ratio of weight between grains and biomass is the RPR. Average of RPR of all the rice samples collected within a development block is considered as block average RPR.

Eq. (3.1) is used to estimate the theoretically available straw residue biomass. However, the practical or surplus availability of straw residue is limited by its competitive uses, harvesting and threshing practices, and methods of collection of leftover portion. Traditional uses of crop residue, particularly rice straw as feeds for livestock and as fuel are common for farmers in Assam. However, in some special cases, compost making to support soil fertility and soil organic matter and papermaking are also practiced. More are the competitive uses, lesser is the availability. Various competing uses of agricultural residues including rice straw is discussed in detail later. The harvesting and threshing practices have remarkable influences on practical availability of *SRB*. With manual methods of harvesting, there are wide variations of height of cut and accordingly its availability. To incorporate such uncertainties, practically or surplus available rice straw residue is estimated using Eq. (3.2) as given in Chapter 3.

The value of rice straw residue availability factor is taken as 50% based on field and laboratory observations. To determine the straw availability factor, rice plant samples collected from the fields are analysed in the laboratory: (i) different parts of straw such as (a) harvested with grains, (b) and (b) left in the field are identified and biomass contribution of each parts are assessed by measuring the weight on dry basis. This measurement is based on interview conducted with farmers to ascertain how much straw is taken home and how much left in the field. It is found that, on average about 35% straw is taken home during grain harvesting and 65% is left in field. Furthermore, it is assumed that 10% of straw left in the field could not be collected efficiently and 5% is lost during collection process. As a result, 50% (*i.e.*, 0.5 availability factor) straw is available as surplus for bioenergy purpose. Gadde et al., 2009 [9] reported a similar value of 48% surplus rice straw availability for the states of Punjab and Haryana of India. Singh et al., 2008 [10] reported surplus rice straw availability in Punjab as high as 83.5%.

4.3.3. Estimation of rice straw availability intensity

The spatial distribution of practical or surplus straw residue biomass are also presented as rice straw residue biomass intensity at development block and village level (*i.e.* residue availability per ha of geographical area). Based on the rice straw residue biomass intensity (tonne ha^{-1}), development blocks and villages are classified as high (>1), medium (0.5-1) and low (<0.5).

4.3.4. Estimation of rice straw residue biomass energy potential

Rice straw residue biomass energy potential is estimated using the Eq. (3.3) given in Chapter 3. The spatial variation of lower heating value (LHV) of rice straw is not accounted in the present investigation. The LHV of collected rice straw samples is determined in the laboratory using standard procedure. A uniform value of LHV of rice straw is taken as 15400 MJ $tonne^{-1}$ based on laboratory measurements of some locally available rice straw samples. Similar values of LHV are also available in literature [10].

4.3.5. Estimation of rice straw residue biomass power potential

Incorporating net conversion efficiency for biomass combustion and duration of operation, power potential is determined using Eq. (3.4) given in Chapter 3. Continuous operation throughout the year is considered for assessment of power. Net conversion efficiency is considered as 20%.

Generally, conversion efficiency is a function of technology, fuel characteristics and plant size. Yang et al., 2007 [11] have reported efficiency of a 38 MWe straw fired power plant above 32% where wheat straw (LHV 14.58 MJ kg^{-1}) was used as primary fuel. There are also reports of plants operating at as low as 20% overall conversion efficiency. With technological upgradation, increase in efficiency is expected. However, to avoid probable overestimation, a conservative figure of conversion efficiency is taken as 20% for all the straw fired power plants in the present study. Moreover, spatial variation of power plant operational time is also ignored and uniform continuous plant operation is considered. It is expected that rice straw could be stored for the annual requirements as is currently done for other uses.

4.4. Results and discussion

4.4.1. Spatial distribution of rice cropland in Sonitpur district

Spatial distribution of rice cropland in the study area is estimated using the spatial tool developed and discussed in the previous Chapter. District level cropland area is estimated by overlying district boundary map with the rice cropland map, whereas development block level area under rice crop is estimated by overlying block boundary map of each block with the rice cropland map. On the other hand, village level rice area is estimated by overlying village boundary map with the rice cropland map. Overlying is done using Overlying function of ArcGIS software. The results are presented at district, development block and village level in the following sections.

4.4.1a. Spatial distribution of rice cropland in the district

Out of the total geographical area of 305144 ha under the 14 development blocks in Sonitpur district, 96844 ha of area is under winter rice cropland (31% of total area). Spatial distribution of winter rice cropland in the district is shown in Fig.4.3. It is observed from Fig.4.3 that, rice croplands are sandwiched between tea gardens and rural settlements of the district. Further, rice croplands are fragmented in nature.

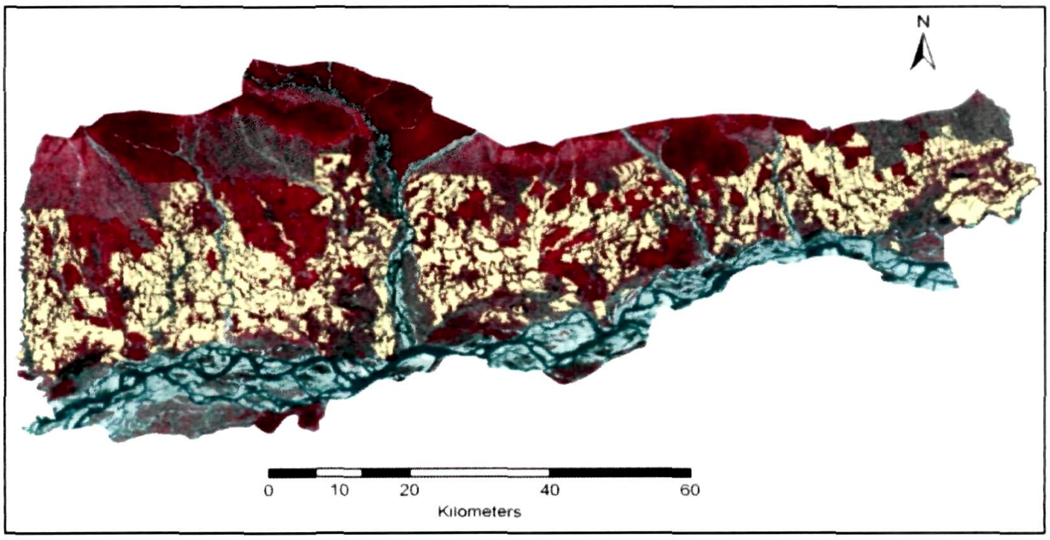


Fig.4.3: Spatial distribution of rice cropland in Sonitpur district (yellow and red patches in the image indicates rice croplands and forest areas, respectively)

4.4.1b. Spatial distribution of rice cropland at development block level

There are variations in area under rice cropland among the 14 development blocks. This variation is mainly due to variation in the geographical areas among the blocks. Development block wise distribution of rice cropland in the district is shown in Table 4.2. On the other hand, spatial distribution of rice cropland among the development blocks is shown in Fig.4.4. Gabharu development block has the smallest area under rice cropland (1530 ha), whereas Dhekiajuli development block has the largest area under rice cropland (13469 ha). However, in terms of percentage share of rice cropland to geographical area, Bihaguri and Pub-Choiduar development blocks has 41% of total area under rice cropland and Gabharu development block has 18% area under rice cropland.

Table 4.2: Development block wise distribution of rice cropland in Sonitpur district

Dev. block	Dev. block area, ha	Rice area, ha	% Rice area
Gabharu	8346	1530	18
Biswanath	8977	2135	24
Sakomatha	12126	4199	35
Baghmara	20261	4902	24
Behali	19453	4756	24
Sootea	18097	6158	34
Bihaguri	15537	6359	41
Pub-Choiduar	19598	7962	41
Rangapara	26077	6858	26
Balipara	26074	7811	30
Naduar	29812	9614	32
Borchola	25608	9313	36
Choiduar	34991	11778	34
Dhekiajuli	40187	13469	34
Sonitpur total	**305144**	**96844**	**31**

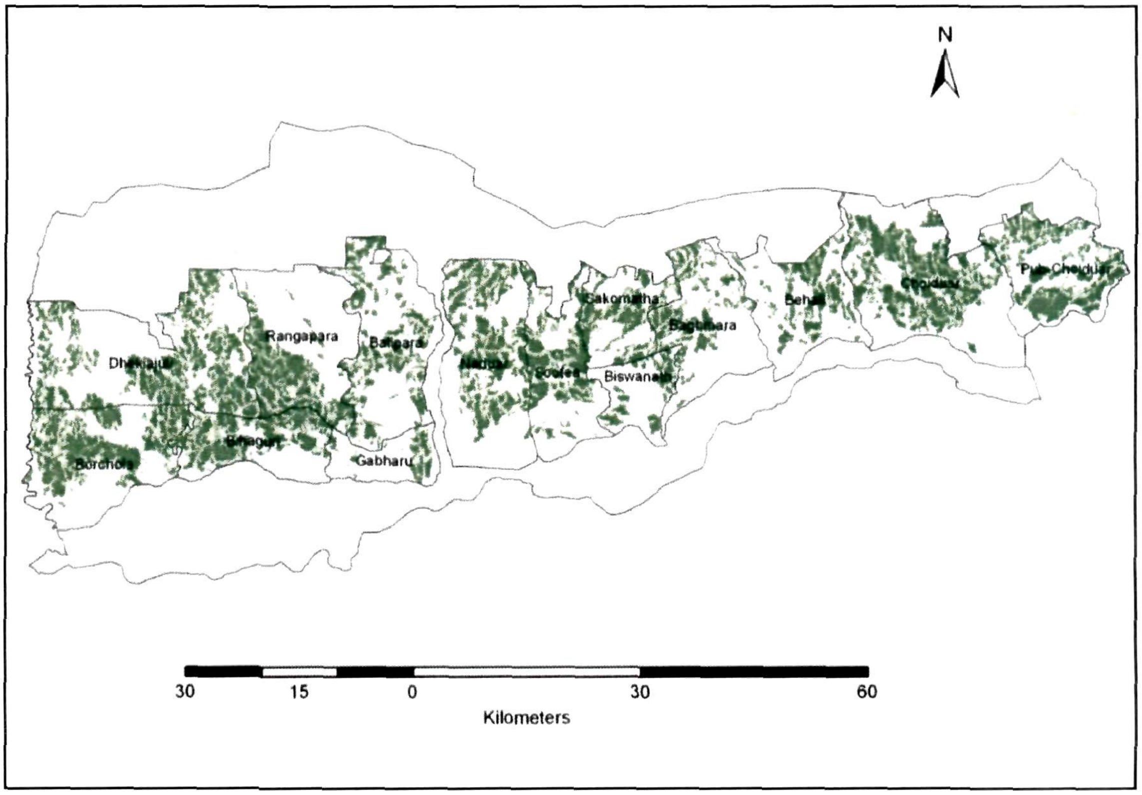


Fig.4.4: Development block wise spatial distribution of rice cropland in Sonitpur district (green patches indicates development block wise distribution of rice croplands)

4.4.1c. Spatial distribution of rice cropland at village level

Village is the smallest administrative unit in Assam. There are 1615 villages in Sonitpur district. The rice crop areas are typically sandwiched between reserve forests, rural settlement and the rivers. From the GIS mapping of village level rice cropland in the study area, it is observed that there are 401 villages in the district which doesn't have any rice croplands. On the other hand, only 5 villages have rice cropland more 300 ha each. Thus, out of the 1615 villages of the district, only 1214 villages have rice cropland. Majority of the villages which doesn't have rice cropland are affected by the flood water of river Brahmaputra and its tributaries. Some of the villages are also under tea garden (termed as tea garden villages) without rice croplands. Furthermore, there are forest fringe villages without any rice croplands. Village wise distribution of rice cropland in the district is shown in Table 4.3.

Table 4.3: Village wise distribution of rice cropland in Sonitpur district

Rice area, ha	No. of village
1-50	501
50-100	325
100-150	230
150-200	102
200-250	36
250-300	15
>300	5

4.4.2. Spatial distribution of rice straw residue in Sonitpur district

Availability of rice straw residue for bioenergy generation is greatly influenced by the area under rice crop production, residue production ratio (RPR) and residue availability factor. Area under rice cropland is estimated through GIS as discussed earlier. The RPR and residue availability factor is determined through field survey and laboratory analysis of collected rice straw samples. The RPR is determined at development block level. On the hand, district level average of availability factor of rice straw is considered for all the blocks. Results of district, development block and village wise spatial distribution of rice straw residue is presented and discussed below.

4.4.2a. Available rice straw residue in the district

Altogether, Sonitpur district produces 0.22 million tonne of gross rice straw residue on annual basis. However, considering only 50% of gross residue available as surplus for biomass energy, the surplus (or net) residue potential in the district is 0.11 million tonne per annum.

4.4.2b. Spatial distribution of rice straw residue at development block level

It is observed that rice straw residue availability greatly varies among the development blocks of the district. Development block wise variation in RPR of rice straw is given in Table 4.4. Development block wise variation in left over rice straw residue is also shown for some blocks in Fig.4.5a-5d. Development block level variation in residue availability factor could not be determined in this study and therefore district level average residue availability factor of 50% is considered for all the blocks.

Table 4.4: Development block wise residue production ratio (RPR) of rice straw in Sonitpur district

Development block	RPR, rice straw
Gabharu	1.30
Biswanath	1.72
Sakomatha	1.44
Baghmara	1.72
Behali	1.40
Sootea	1.44
Bihaguri	1.59
Pub-Choiduar	1.43
Rangapara	1.76
Balipara	1.76
Naduar	1.30
Borchola	1.32
Choiduar	1.40
Dhekiajuli	1.36

Fig.4.5a. Balipara block

Fig.4.5b. Dhekiajuli block

Fig.4.5c. Naduar block

Fig.4.5d. Sootea block

Fig.4.5a-5d: Development block wise variation in left over rice straw in Sonitpur district

Development block wise gross and surplus rice straw residue availability in the study area is presented in Table 4.5. Variations exist among the development block in terms of residue availability, which varies from the lowest of net or surplus *1591 tonne* in Gabharu to the highest of 16468 tonne in Dekiajuli (Table 4.5). Variations observed in terms of per capita rice straw availability amongst the development block. The highest per capita rice straw availability is observed for Bihaguri and Borchola while the lowest is observed for Gabharu and Biswanath development blocks (Table 4.5).

Table 4.5: Development block wise rice straw residue availability in Sonitpur district

Development block	Gross rice straw, tonne	Net rice straw, tonne	Net per capita rice straw, tonne
Gabharu	3183	1591	0.04
Biswanath	4406	2203	0.04
Sakomatha	7255	3628	0.05
Baghmara	14334	7136	0.10
Behali	10653	5764	0.09
Sootea	11528	6096	0.07
Bihaguri	17188	8594	0.23
Pub-Choiduar	15941	7970	0.07
Rangapara	15691	7845	0.17
Balipara	24744	12372	0.09
Naduar	16497	8249	0.08
Borchola	24585	12293	0.23
Choiduar	24734	12367	0.12
Dhekiajuli	32971	16486	0.14
Sonitpur total	**223710**	**112594**	**0.10**

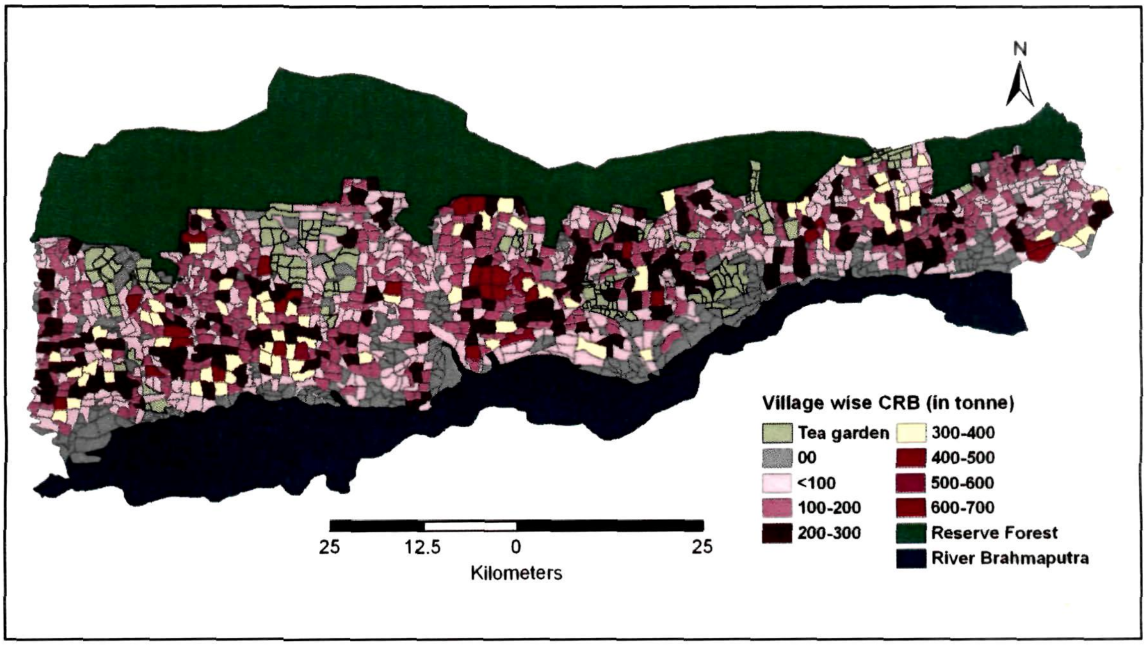
Note: Development block level population data are from 2001 Census data

4.4.2c. Spatial distribution of rice straw residue at village level

As mentioned earlier, out of the 1615 villages of Sonitpur district, 1214 villages have rice cropland. Thus, residue availability among the villages is accounted only for the 1214 villages. Village wise variation in residue availability is shown in Table 4.6. Furthermore, spatial distribution of residue availability among the villages is also shown in Fig.4.6. The villages are also categories into three intensity groups *viz.* low, medium and high based on village wise residue intensity (tonne of residue per ha of village area) as shown in Fig.4.7. Villages having residue less than 0.5 tonne per ha of village area are termed as low intensity villages, while villages having residue intensity in between 0.5 to 1 tonne per ha of village area and greater than 1 tonne per ha of village area are termed as medium intensity and high intensity villages, respectively.

Table 4.6: Village wise availability of net (surplus) rice straw in Sonitpur district

No. of villages	Net rice straw, tonne
401	0
501	<50
333	50-100
223	100-150
102	150-200
35	200-250
15	250-300
5	>300



Note: CRB in the legend is Crop Residue Biomass

Fig.4.6: Village wise spatial distribution of rice straw residue in Sonitpur district

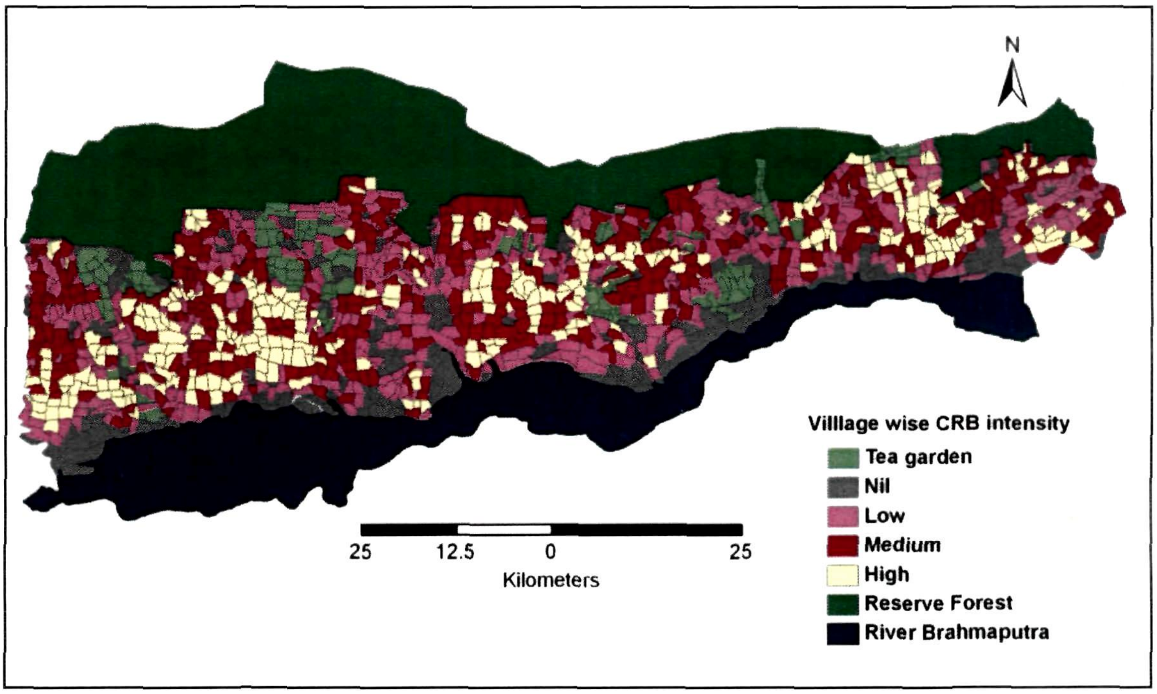


Fig.4.7: Village wise rice straw residue intensity (tonne ha^{-1}) in Sonitpur district

The prevailing practice of single cropping with the field remain vacate for about six months opens up possibilities of growing some other suitable crop. This would increase the prospect of crop residue availability in the region. Further, the productivity of rice in Sonitpur district is 12% lower than state average and 30% lower than the national average [12]. Lack of modern farming facilities, poor economic condition of the farmers and lack of awareness are believed to be some causes of lower productivity. Introduction of modern farm machineries such as tractor, reaper, harvester, irrigation facilities, high yielding varieties as well as additional generation and assured supply of electricity to the rural communities are expected to take care of these issues.

4.4.3. Competing uses of agricultural residues

Biomasses such as fuelwood, animal dung, crop residue are widely used as a source of energy in developing countries. Some of the traditional uses of agricultural residues in rural households of India are already discussed in the introduction section. There are many competing uses of the agricultural residues. It can primarily be divided into off-site and on-site uses. Offsite uses include being used for cooking and packaging purposes, as an animal fodder and as an industrial raw material. For instance, agricultural residues are used in small scale industries for manufacturing handicraft items. On-site uses include soil quality enhancement by means of carbon sequestration, soil and water conservation as well as biodiversity improvement. When used as green manures these crop residues help in nutrient recycling and improves soil productivity.

The pattern of uses of agricultural residues as domestic energy source is not homogenous amongst India. For example, people of Uttarakhand depend primarily on fuel wood as energy for cooking. However, in other regions of India, where forest resources are not sufficient, people use easily available agricultural residues and dung cake as energy for cooking. In Uttarakhand region, agricultural residues are mostly used as food for the livestock. Similarly, as mentioned earlier farmers of Haryana, Punjab and UP do not consider rice straw residue as animal feed; rather they prefer burning of rice straw in-situ. Top of sugarcane is used as animal feed in many states. In Punjab, residues generated from wheat, fine rice and top of sugarcane are used as ex-situ animal feed, whereas, coarse grain rice is mostly burnt in the field before tilling and sawing of another crop [13]. Burning of the cereal residue is prominent over northwest and central Uttar Pradesh, whereas rice straw burning is limited and wheat straw burning is almost absent. Beri et al., 2003 [14] estimated that 22% of rice straw and 10% of wheat straw are burned in-situ in U.P. In case of Bihar, the uses of agricultural residues like rice straw; wheat straw and gram as fuels are limited. The prevalence of the use of crop residues as animal feed among the rural households in Trans-Gangetic plains (TGP), Uttar Pradesh and Bihar is particularly widespread for wheat and rice [15]. Wheat straw prevails as the preferred feed with near universal use in the northern plains, from the TGP to the Bihar sub-regions. As mentioned earlier, use of rice straw as animal feed is common among the rural people of West Bengal. Wheat straw is relatively sturdy and its use as animal feed becomes possible due to mechanical threshing that now prevails in the wheat-growing areas [15]. Mechanical threshing chops the wheat straw into bhusa (small pieces which are more palatable). The relative use of maize residue and other crops varies over site but also provide important feed sources.

Nutrient cycling in the soil-plant ecosystem is an essential component of sustainable productive agricultural enterprise. Incorporation of crop residues improves soil environment, which influences the microbial population and activity in the soil and subsequent nutrient transformations [16]. Principal benefits of retaining crop residue include carbon sequestration, soil erosion control, maintenance of soil structure, moderation of soil moisture and temperature regimes, energy source for soil biota and maintenance of soil organic matter (SOM) content. Therefore, management of left-over straw for soil quality improvement is also important. Further research will be required to assess when and how much amount of residue should be left in field for soil improvement. The recycling of the char or digested slurry to the crop field after extraction of energy from the residue biomass could be another prospective path.

4.4.4. Spatial distribution of rice straw residue biomass energy in Sonitpur district

Results of rice straw residue based biomass energy potential in the study area is presented below at three levels, *viz.* district, development block and village.

4.4.4a. Rice straw residue biomass energy in the district

Overall, biomass energy potential from the gross amount of rice straw available in Sonitpur district is estimated to be 3445134 GJ per annum. However, since only 50% of gross straw is available for biomass energy purpose, the net rice straw based biomass energy potential in the district would be 1733978 GJ per annum.

4.4.4b. Spatial distribution of rice straw residue biomass energy at development block level

Net biomass energy potential from rice straw at development block level varies from the lowest amount of 24501 GJ per annum in Gabharu to 253884 GJ annum in Dhekiajuli. Development block wise biomass energy potential is presented in Table 4.7.

Table 4.7: Development block wise rice straw residue biomass energy in Sonitpur district

Dev block	**Gross energy, GJ**	**Net energy, GJ**	**Net per capita energy, GJ**
Gabharu	49018	24501	0.62
Biswanath	67852	33926	0.60
Sakomatha	111727	55871	0.75
Baghmara	220744	109894	1.62
Behali	164056	88766	1.37
Sootea	177531	93878	1.06
Bihaguri	264695	132348	3.54
Pub-Choiduar	245491	122738	1.02
Rangapara	241641	120813	2.63
Balipara	381058	190529	1.36
Naduar	254054	127035	1.26
Borchola	378609	189312	3.57
Choiduar	380904	190452	1.82
Dhekiajuli	507753	253884	2.18
Sonitpur total	**3445134**	**1733948**	

Note: Development block level population data are from 2001 Census data

4.4.4c. Spatial distribution of rice straw residue biomass energy at village level

As mentioned earlier, out of the 1615 villages of the study area, there are 401 villages which doesn't have rice croplands and hence there is no possibility of having straw based biomass energy in those villages. In rest of the villages, there is variation of biomass energy potential as shown in Table 4.8. It is seen from Table 4.8 that, out of the 1214 rice growing villages, 1080 villages have biomass energy potential less than 500000 MJ. There are only 27, 23 and 14 villages which have potential in the range of 600000-700000 MJ, 700000-800000 MJ and 800000-900000 MJ, respectively. There are also 9 villages which have straw based biomass energy potential more than 900000 MJ. The highest individual level biomass energy potential of 1243629 MJ is observed in No. 1 Charaibari village.

Table 4.8: Village level rice straw residue biomass energy in Sonitpur district

No. of villages	Rice straw biomass energy, MJ
401	0
361	<100000
248	100000-200000
211	200000-300000
148	300000-400000
112	400000-500000
59	500000-600000
27	600000-700000
23	700000-800000
14	800000-900000
11	>900000

4.4.5. Spatial distribution of rice straw residue biomass power in Sonitpur district

Results of rice straw residue based biomass power potential in the study area is presented below at all three levels, *viz*. district, development block and village.

4.4.5a. Rice straw residue biomass power in the district

Annual rice straw residue based biomass power potential in Sonitpur district is estimated as 11 MW considering net conversion efficiency of 20% and throughout the year power plant operation.

4.4.5b. Spatial distribution of rice straw residue biomass power at development block level

Development block wise rice straw biomass power potential in Sonitpur district is presented in Table 4.9. It is seen from Table 4.9 that, biomass power potential among the development blocks varies from a minimum of 0.16 MW in Gabharu to a maximum of

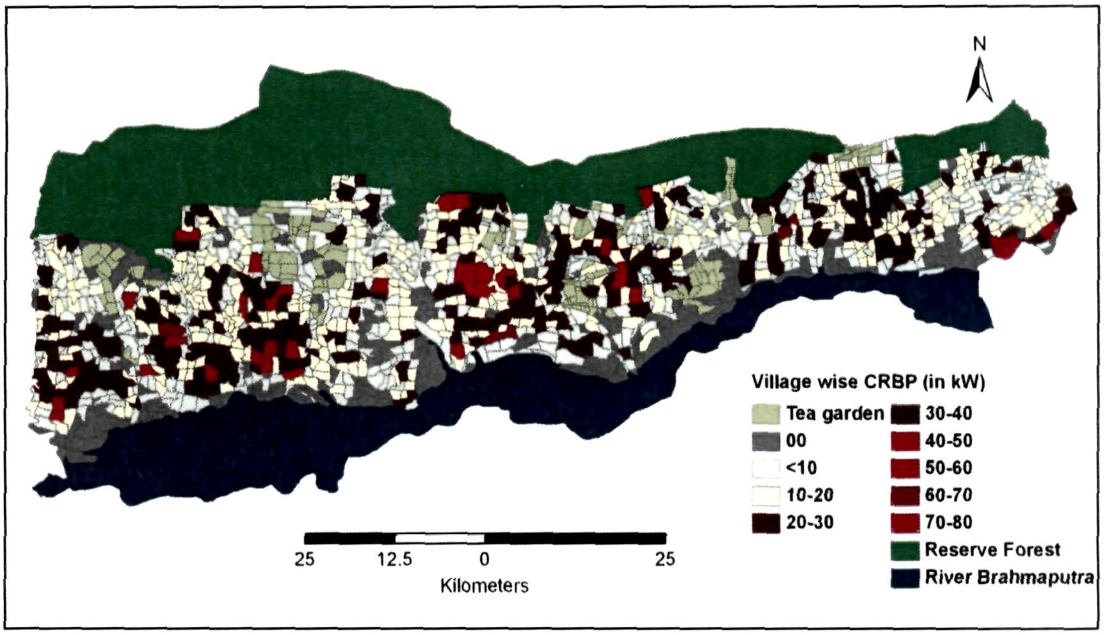
1.61 MW in Dhekiajuli. Furthermore, out of the 14 development blocks, only 4 blocks have biomass power potential more than 1 MW.

Table 4.9: Development block wise rice straw residue biomass power in Sonitpur district

Development block	**Net energy, GJ**	**Power, MW**
Gabharu	24501	0.16
Biswanath	33926	0.22
Sakomatha	55871	0.35
Baghmara	109894	0.70
Behali	88766	0.56
Sootea	93878	0.60
Bihaguri	132348	0.84
Pub-Choiduar	122738	0.78
Rangapara	120813	0.77
Balipara	190529	1.21
Naduar	127035	0.81
Borchola	189312	1.20
Choiduar	190452	1.21
Dhekiajuli	253884	1.61
Sonitpur total	**1733948**	**11.00**

4.4.5c. Spatial distribution of rice straw residue biomass power at village level

Since there are village level variations in rice straw availability in the study area, hence rice straw based biomass power potential also varies among the villages. Spatial variation in village level biomass power potential is shown in Fig.4.8.



Note: CRBP in the legend is Crop Residue Biomass Power

Fig.4.8: Spatial distribution of village level rice straw biomass power in Sonitpur district

Furthermore, it is observed that, there are 548 villages which have biomass power potential less than 10 kW at individual village level. On the other hand, there are 363, 202, 72 and 30 villages which have biomass power potential in the range of 10-20 kW, 20-30 kW, 30-40 kW and 40-50 kW, respectively. There are only 8 villages which have biomass power potential more than 50 kW at individual village level.

As reported by Kamalapur and Udaykumar, 2011 [17], there are several advantages of decentralised electricity generation, such as avoiding reliance on state owned grid connected power, decreased dependence on fossil fuel-based (mostly coal fired) electricity generation, reduced transmission loss, income generation opportunities for rural people. It is also reported that with a higher percentage of electrification and biomass availability, the gap between energy and income poverty can be widen [18]. Furthermore, provision for higher quality of electricity (in terms of fewer outages and more hours per day) could increase non-agricultural incomes among the rural masses, thus bringing economic benefits [19].

The plan for appropriate pattern of decentralised generation (size and number) would require further study involving transport network and demand pattern. The output of the present investigation is expected to promote such plan. The village level electricity demand needs to be investigated for determining straw-fired power plant sizes.

Electricity consumption pattern in all the villages could not be investigated in the present study. However, from a related study conducted in Napaam village of Sonitpur, the peak electricity demand in rural household cluster was found to range between 18 kW and 65 kW [20]. From LULC mapping of a selected rural area of Sonitpur, it is seen that households and business settlements are adjoining to crop areas (Fig. 4.9). Thus, power available from rice straw could meet a portion of electricity demand in nearby localities.

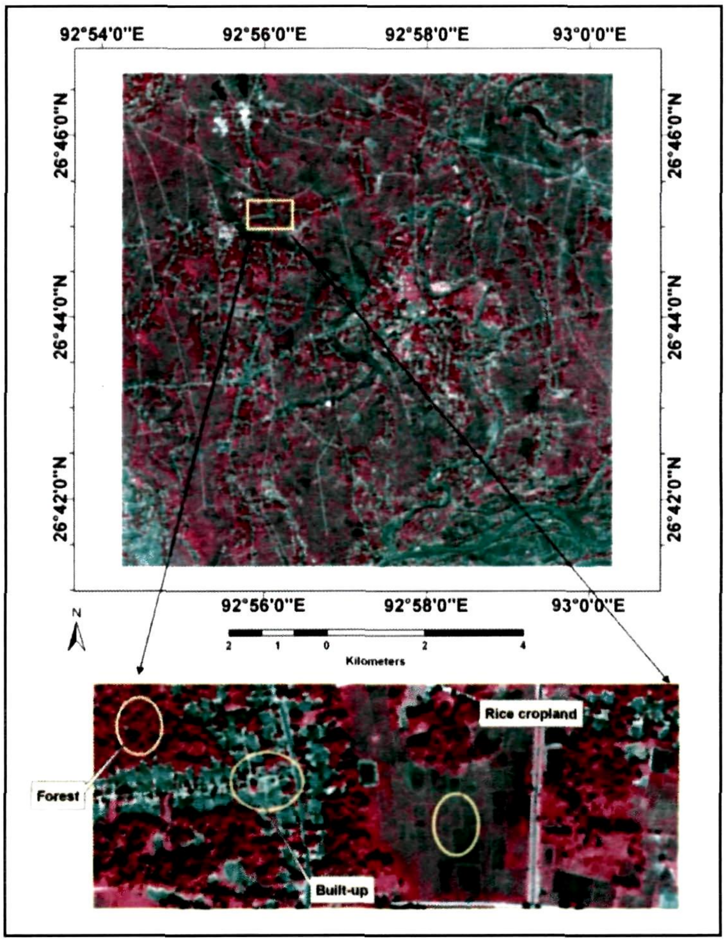


Fig. 4.9: Land use land cover (LULC) in a typical rural area of Sonitpur district

4.5. Summary

Annual rice straw residue potential in the district is 0.11 million tonne (1733948 GJ), equivalent to 11 MW continuous electrical power. Straw residue availability among the 14 development blocks varies from the lowest of 1591 tonne (equivalent to 0.61 MW in *Gabharu*) to the highest of 16468 tonne (equivalent to 1.61 MW *Dekiajuli*). Moreover, out of the 1615 villages of Sonitpur district, rice straw residue alone can support more than 10 kW continuous electrical power generations in each of the 667 villages.

REFERENCES

[1] Srivastava, S., et al. Assessment of large-scale deforestation in Sonitpur district of Assam, *Curr Sci* **82**, 1479--1484, 2002.

[2] Census of India. *Census of India, 2011.* (http://www.census2011.co.in/census/district/165-sonitpur.html. (accessed 07/08/2014).

[3] Mckendry, P. Energy production from biomass (part 2): conversion technologies, *Bioresour Technol* **83**, 47--54, 2002.

[4] Nussbaumer, T. Combustion and co-combustion of biomass: Fundamentals, technologies, and primary measures for emission reduction, *Energy Fuels* **17**, 1510--1521, 2003.

[5] Demirbas, A. Biomass resource facilities and biomass conversion processing for fuels and chemicals, *Energy Convers Manage* **42,** 1357--1378, 2001.

[6] Hydrogen Analysis Resource Centre, US Department of Energy. http://hydrogen.pnl.gov/cocoon/morf/hydrogen/site_specific/fuel_heating_calculator. (accessed 28/10/2014).

[7] National Remote Sensing Centre (NRSC). Natural Resource Census: National land use and land cover analysis using multitemporal LISS-III (LULC-LIII: 50K)−Project Manual, 2006. http://www.nrsc.gov.in/.

[8] Directorate of Economics and Statistics, Ministry of Agriculture, Govt. of India, *Agriculture Statistics at a glance 2008.* http://dacnet.nic.in/eands/At_Glance_2008.htm.

[9] Gadde, B., et al. 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 Bioenerg* **33**, 1532--1546, 2009.

[10] Singh, J., et al. Energy potential through agricultural biomass using geographical information system−A case study of Punjab, *Biomass Bioenerg* **32**, 301--307, 2008.

[11] Yang, Y.B., et al. Mathematical modelling of straw combustion in a 38 MWe power plant furnace and effect of operating conditions, *Fuel* **86**, 129--142, 2007.

[12] Directorate of Economics and Statistics, Ministry of Agriculture, Govt. of India.

[13] Devendra, C., & Thomas, D. Crop–animal interactions in mixed farming systems in Asia, *Agricultural Systems* **71**, 27--40, 2002.

[14] Saud, T., et al. Spatial distribution of biomass consumption as energy in rural areas of the Indo-Gangetic plain, *Biomass Bioenerg* **35**, 932--941, 2011.

[15] Beri, V., et al. *Organic resources of a part of Indo-Gangetic Plain and their utilization. Ludhiana: Dept. of Soils*, Punjab Agricultural University, 2003.

[16] Blanco-Canqui, H., & Lal, R. Crop residue removal impacts on soil productivity and environmental quality, *Crit Rev Plant Sci* **28**, 139--163, 2009.

[17] Kamalapur, G.D., & Udaykumar, R.Y. Rural electrification in India and feasibility of Photovoltaic Solar Home Systems, *Int J Electrical Power & Energy Systems* **33** (3), 594--599, 2011.

[18] Srivastava, L., et al. Energy access: Revelations from energy consumption patterns in rural India, *Energy Policy* **47**, 11--20, 2012.

[19] Chakravorty, U., et al. Does the quality of electricity matter? Evidence from rural India, *J Economic Behavior & Organization* **107**, 228--247, 2014.

[20] Hazarika, S. *Reduction of line losses (I^2R) in electrical network using geo-electrical options: a case study in a rural area of Assam (India)*, Unpublished M. Tech thesis, Department of Energy, Tezpur University, Tezpur, Assam (India), 2010.

CHAPTER 5

GREENHOUSE GAS EMISSION FROM RICE STRAW BIOMASS POWER

CHAPTER 5

GREENHOUSE GAS EMISSION FROM RICE STRAW BIOMASS POWER

5.1. Life cycle assessment for crop residue based power generation

The prime aim of promoting renewable power including biomass power is to reduce the burden of fossil energy crisis and help mitigate climate change. However, unsustainable exploitation of biomass resources may even release more GHG than its fossil counterpart and jeopardise many ecosystem functions [1-5]. Therefore, it is important to assess net GHG balance of biomass power from life cycle prospective. Life cycle assessment (LCA) is an internationally recognised methodology for evaluating the global environmental performance of a product, process or pathway along its partial or whole life cycle, considering the impacts generated from ''*cradle to grave*'' [6]. LCA has been widely used to assess GHG balance of biomass power projects around the world [7-11].

Like fossil fuels, combustion of biomass residues including rice straw also releases GHG. Furthermore, GHG is also emitted due to various inputs in different life stages of biomass power generation. For example, farm machinery, diesel, fertiliser, pesticide are required for rice farming and their uses release GHG. Hence, assessing GHG emission from rice straw based power generation is also important considering all the stages of rice straw production, collection & transport, conversion.

LCA has been found useful to assess a wide range of impacts such as acidification, and eutrophication in addition to GHG [8]. In the present work, LCA is conducted to assess GHG emission from rice straw biomass power. The emission is estimated at district and development block level in Sonitpur district of Assam. Village level emission estimation is not considered in this work. Three major GHGs, *viz.* carbon dioxide (CO_2), Methane (CH_4) and Nitrous Oxide (N_2O), emitted during the life cycle of rice straw power generation is assessed through standard procedure which is discussed in this Chapter.

5.2 Production practices of rice crop in study area

GHG emission is basically attributed by the consumption of various inputs in rice production. There are variations of the level of such inputs depending upon the level of mechanisation of rice cultivation. Based upon the wide ranges of mechanization level prevailed in the locality, four different rice cultivation scenarios (detail discussion in Section 5.3.1) are considered for GHG emission. The scenarios are based on a work conducted in Assam by Baruah and Bora, 2008 [12]. For all the scenarios, GHG emission is estimated at three stages, *viz.* (i) rice cultivation, (ii) collection and transportation of rice straw residue, and (iii) conversion of rice straw to power as shown in Fig. 5.1. Furthermore, GHG emission from rice straw biomass power is compared with a typical coal fired reference power plant. The detail methodology is described below.

5.3. Methodology

5.3.1. Description of the rice crop production scenarios

As mentioned earlier, four different rice farming scenarios *viz.,* S-I or BAU, S-II, S-III and S-IV are considered in this research work based on a work conducted by Baruah and Bora, 2008 [12]. While S-I (BAU) is a traditional or baseline scenario, S-II, S-III and S-IV are mechanised rice farming scenarios with improved technologies.

Power tillers and tractors are two common mechanical power sources in Indian agriculture. The shift from muscle power to mechanical power would result in increased demand for power tiller (S-II) and tractor (S-III and S-IV). The introduction of IC engine driven self-propelled transplanter and self-propelled reaper harvester has been reported to be successful in Assam [12]. Both these technologies are incorporated in S-III. Scenario S-IV incorporates a tractor-drawn reaper harvester. Use of tractor is also common in transporting rice straw residue.

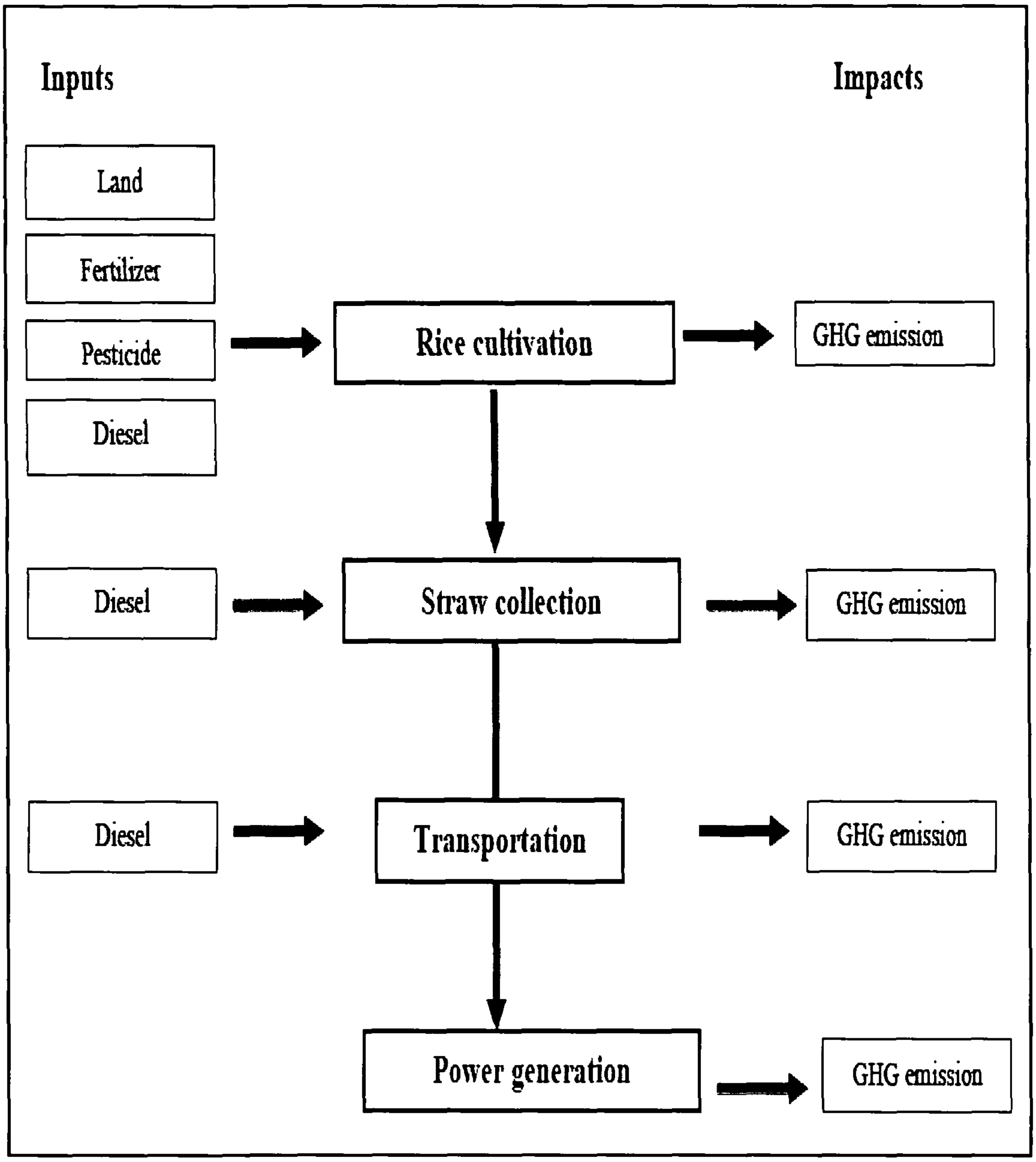


Fig.5.1: Rice straw residue biomass power LCA

Parameters considered under the four scenarios are given in Table 5.1a. Four different resources, *viz.*, human, animal, diesel and machinery are required to perform the selected farm operations. It should be noted that amount of fertiliser and pesticide application is considered same in all the scenarios.

Table 5.1a: Input requirements for four different rice production scenarios [12]

Operations	Human-h ha^{-1}	Bullock pair-h ha^{-1}	Engine-h ha^{-1}	Power tiller-h ha^{-1}	Tractor-h ha^{-1}	Diesel, l ha^{-1}
S-I (BAU)						
Land preparation	221	191	0	0	0	0
Transplanting	252	0	0	0	0	0
Irrigation	45	0	45	0	0	46
Harvesting	235	0	0	0	0	0
S-II						
Land preparation	79	38	0	11	0	18
Transplanting	252	0	0	2	0	2
Irrigation	45	0	45	0	0	46
Harvesting	217	0	0	7	0	6
S-III						
Land preparation	36	0	0	0	6	32
Transplanting	10	0	9	0	1	9
Irrigation	45	0	45	0	0	46
Harvesting	30	0	7	0	3	15
S-IV						
Land preparation	35	0	0	0	5	29
Transplanting	10	0	9	0	1	9
Irrigation	45	0	45	0	0	46
Harvesting	26	0	0	0	6	24

Note: S-I (BAU): manual harvesting, manual transplanting, bullock treading; S-II: manual harvesting, manual transplanting, power tiller used in land preparation and transportation; S-III: self-propelled (SP) reaper harvesting, SP transplanting, tractor used in land preparation and transportation; S-IV: tractor drawn reaper harvesting, SP transplanting, tractor used in land preparation, harvesting, and transportation.

Some other parameters considered for emission attributed by operation of farm machineries are given in Table 5.1b.

Table 5.1b: Parameters related to farm machinery applications [13]

Input	Weight, kg	Useful life, h	Power rating
Engine	130	10000	3.73 kW
Power tiller	500	10000	7.46 kW
Tractor	1730	10000	26.11 kW

The emissions attributed by the application of chemical fertiliser and pesticides to the rice crop are assessed from the related emission factors available in the literature as presented in Table 5.2. Inputs specific GHG emission values for other inputs taken from standard sources are also presented in Table 5.2.

Table 5.2: Inputs input specific emission from rice production

Input	Input specific emission	Reference
Human hour engagement	0.009 kg CO_2 h^{-1}	[14]
Bullock hour engagement	0.67 kg CO_2e h^{-1}	[15]
Farm machinery (power tiller, tractor, engine)	12.80 kg CO_2e kg^{-1} of farm machinery	[15]
Fertiliser*	226.48 kg CO_2e N_2O ha^{-1}	[16]
Pesticide	3.60 kg CO_2e ha^{-1}	[17]
Diesel (direct emission)	2.6595 kg CO_2 l^{-1} 0.0009 kg CO_2e CH_4 l^{-1} 0.0191 kg CO_2e N_2O	[18]
Diesel (indirect emission)	0.5644 kg CO_2e l^{-1}	

* Global warming potential of N_2O is taken as 298

5.3.2. GHG emission attributed by inputs for rice cropping

The inputs for the four scenarios are categorised into five groups *viz.* (i) human work, (ii) animal work, (iii) machinery (power tiller, tractor, engine), (iv) diesel and (v) chemical fertiliser and pesticides. Furthermore, the entire crop production activities are divided into four unit operations such as land preparation, transplanting, irrigation and harvesting. As shown in Table 5.1a, human workers are used invariably for all the scenarios. Bullock is used under S-I and S-II. Engine is also used in all the four scenarios. On the other hand, power tiller is used only under S-II, while tractor is used under S-II and S-III. Diesel is required in all the scenarios in order to operate the farm machineries considered (Table 5.1a).

Hours of engagement of farm machinery (engine, power tiller, and tractor) can be converted into kilogram (kg) of inputs using the parameters presented in Table 5.1a and 5.1b.

Finally, the net GHG emission attributed by a specific area of rice production is assessed using the following relationship.

$$E(j) = F \times \sum_{j=1} \left(\sum_{i=1}^{i=n} (C_i \times I_i\right) \times A_j \times 10^{-3} \tag{5.1}$$

where, *E(j)* is emission attributed rice straw production in jth location, tonne; *F* is emission attributing factor for rice straw production; C_i is emission coefficient for the i^{th} input, kg of CO_2e per unit of input as presented in Table 5.2; I_i is quantity of i^{th} input, unit ha^{-1} (Table 5.1a and 5.1b); A_j is area under j^{th} location, ha.

Rice gain is the main product and straw is a by-product of rice farming. The key purpose of using/applying farm inputs is the higher production rice grain. Thus it can be argued that major part of the greenhouse gas emitted due to using/applying farm inputs should be attributed to rice grain. However, since parts of the farm inputs are also necessary for the plant growth, therefore, emission attributed by rice farming is divided into 60:40 for rice grain and rice straw. The emission attributing factor for straw production (*F*) is uniformly considered as 0.4 for all the inputs (human labour, bullock labour, farm machineries, chemical fertiliser, and pesticide). The emission coefficient for the i^{th} input (C_i) is taken as per Table 5.2. On the other hand, quantity of i^{th} input (I_i) is taken as per Table 5.1a and 5.1b. Area under rice cropping (A_j) at j^{th} location is taken from GIS mapping (as described in Chapter 4).

Thus, using the above equation, scenario wise emission attributed by rice farming operations is estimated and presented below.

5.3.3. GHG emission attributed by diesel used for rice straw collection and transportation

Biomass residue has to be made available from field to power plant site. In this study, it is assumed that rice straw available in the field will be collected and transported using tractor. During collection and transportation processes, GHG is emitted due to burning of diesel for tractor operation. Three major GHGs *viz.* CO_2, CH_4 and N_2O emission from diesel used are considered.

Following equation is used to estimate GHG emission attributed by diesel used for rice straw collection and transportation:

$$E_{st}(j) = \left(\frac{T_d \times RS_{(j)} \times D_d \times E_f}{T_{cc}}\right) \times 10^{-3} \qquad (5.2)$$

where, $E_{st}(j)$ is GHG emission (both direct and indirect) due to collection and transportation of rice straw at j^{th} location, tonne; T_d is average transport distance (both way: loaded and unloaded), km; $RS(j)$ is amount of rice straw to be collected and transported from j^{th} location, kg; D_d is diesel demand for transportation, l km^{-1}; E_f is emission factor, kg l^{-1} of diesel; and T_{cc} is tractor carrying capacity, kg $trip^{-1}$.

Average transport distance from field to power plant site per rice straw loaded trip is considered as 25 km, thus both way (loaded and unloaded) transport distance is 50 km. The average transport distance is estimated based on GIS mapping of road network of Sonitpur district. There may be several roads available from a particular straw collection point to a power plant location. However, selecting the shortest transport network will not only save time and diesel demand but also reduce GHG emission due to transportation. Thus, once road network is mapped, shortest transport distance between rice straw collection points to a power plant location is mapped using Network Analyst function of ArcGIS software. While measuring the shortest transport distance, it is also assumed that, in each development block, rice straw biomass power plant will be installed at the centre of the block.

On the other hand, amount of rice straw (*RS*) to be transported is estimated as per availability (Chapter 4). Considering a standard medium size tractor (26 kW), diesel demand (D_d) is considered as 0.11 l km^{-1} of tractor transportation while carrying capacity (T_{cc}) is taken as 1500 kg trip^{-1}.

Emission factor (E_f) values (direct emission) for CO_2, CH_4 and N_2O are taken as 2.6595 kg l^{-1}, 0.0009 kg CO_2e l^{-1} and 0.0191 kg CO_2e l^{-1}, respectively. Indirect emission factor is considered as 0.5644 kg CO_2e l^{-1} (Table 5.2).

5.3.4. GHG emission attributed by rice straw combustion in power plant

As mentioned in Chapter 4, biomass combustion technology is considered for generation of power utilising rice straw. While estimating, GHG emission due to rice straw combustion for power generation, parameters such as lower heating value (LHV) of rice straw, amount of rice straw produced, GHG emission factor are considered. Following Equation is used to estimate this component of GHG emission.

$$E_{sc}(j) = RS_{(j)} \times LHV_{RS} \times E_f \times 10^{-3} \qquad (5.3)$$

where, $E_{sc}(j)$ is GHG emission due to rice straw combustion for power generation at j^{th} location, tonne; $RS_{(j)}$ is amount of rice straw at j^{th} location, kg; LHV_{RS} is lower heating value of rice straw, MJ kg^{-1}; and E_f is emission factor, kg MJ^{-1}.

Amount of rice straw is estimated as described in Chapter 4; Lower heating value of rice straw (LHV_{RS}) is experimentally determined as 15.4 MJ kg^{-1}. Emission factors (E_f) for CO_2, CH_4 and N_2O are taken as 0.36 kg MJ^{-1}, 0.0163 kg MJ^{-1} and 0.000286 kg MJ^{-1} [19]. Global warming potential (GWP) of CH_4 and N_2O is considered as 25 and 298, respectively [20].

Thus, using Eq. (5.1-5.3), overall GHG emission attributed by rice straw production in three stages (i) rice cultivation, (ii) straw collection and transportation and (iii) straw conversion in power plant is estimated.

To compare the GHG emission performance of rice straw biomass power plant with coal fired power plant, hypothetical coal fired power plants at district and development block level are also considered. As mentioned in Chapter 4, rice straw biomass power potential at district level in Sonitpur district is 11 MW and at development block level, it varies from 0.16 MW to 1.61 MW. Therefore, the coal power plants at district and development block level are also considered to be same power generating capacity.

GHG emission attributed by coal power plant is estimated under two stages, emission due to coal (i) transportation and (ii) conversion in power plant. The procedures are given below.

5.3.5. GHG emission attributed by coal transportation

Since, Sonitpur district doesn't have any coal mine, therefore it is planned that coal would be transported from other place. Coal required for power plant in Sonitpur district will be transported from coal mine located 370 km road transport distance in Ledo, Tinsukia district, Assam. GHG emission due to coal transportation using truck from Ledo to Sonitpur district is estimated using the following equation.

$$E_{ct}(j) = \left(\frac{T_d \times C_{(j)} \times D_d \times E_f}{T_{cc}}\right) \times 10^{-3} \tag{5.4}$$

where, $E_{ct}(j)$ is GHG emission (both direct and indirect) due to coal transportation at j^{th} location, tonne; T_d is average transport distance (both way: loaded and unloaded), km; $C_{(j)}$ is amount of coal to be transported to j^{th} location, kg; D_d is diesel demand for transportation, l km^{-1}; E_f is emission factor, kg l^{-1} diesel; and T_{cc} is truck carrying capacity per load, kg.

Average transport distance per coal loaded trip is considered as 370 km from coal mine to power plant site, thus both way (loaded and unloaded) transport distance is 740 km. Amount of coal, $C_{(j)}$ to be transported is based on amount of rice straw equivalent coal demand at district and development block level. District and development block level rice straw amount is given in Chapter 4. Diesel demand (D_d) is considered as 0.28 l km^{-1} for truck transportation. Truck carrying capacity (T_{cc}) is taken as 9000 kg $trip^{-1}$.

Emission factor (E_f) (direct emission) for CO_2, CH_4 and N_2O are taken as 2.6595 kg l^{-1}, 0.0009 kg CO_2e l^{-1} and 0.0191 kg CO_2e l^{-1}, respectively. On the other hand, indirect emission factor is considered as 0.5644 kg CO_2e l^{-1}. The emission factor values are as per Table 5.2 [refer 18].

5.3.6. GHG emission attributed by coal combustion in power plant

There are two pathways of GHG emission due to coal burning, (i) direct: due to combustion of coal in power plant, and (ii) indirect: due to mining and processing of coal. Both these direct and indirect emissions are accounted for in this study.

While estimating GHG emission due to coal combustion for power generation, parameters such as lower heating value (LHV) of coal, coal demand, and emission factor are considered. Following equation is developed to estimate GHG emission:

$$E_c(j) = C_{(j)} \times E_f \times 10^{-3} \tag{5.5}$$

where, $E_c(j)$ is GHG emission due to coal combustion for power generation at j^{th} location, tonne; $C_{(j)}$ is amount of coal required at j^{th} location, kg; and E_f is emission factor, kg kg^{-1}.

Amount of coal (C_a(j)) demand is based on amount of rice straw equivalent coal required at district level and in each development block level. On the other hand, emission factor (E_f) (direct emission) for CO_2, CO_2e CH_4 and N_2O is taken as 2.238 kg kg^{-1}, 0.0004 kg kg^{-1} and 0.0195 kg kg^{-1} [18]. On the other hand, indirect CO_2e emission is considered as 0.3696 kg kg^{-1} [18].

Findings of Eq. (5.4) and (5.5) are added together to estimate total GHG emission attributed by coal power plant. The results are presented below.

5.4. Results and discussion

The findings of this LCA phase of research work on rice straw based power generation in the study area concerning four scenarios are presented and discussed below.

5.4.1. GHG emission attributed by human engagement in rice straw production

GHG emission in the form of CO_2 attributed by human labour engagement for rice cultivation is estimated and the results are presented in Table 5.3. The highest emission is observed in S-I and the lowest in S-IV. Operation wise, the highest emission is observed for transplanting in S-I and S-II and for irrigation in S-III and S-IV.

Total human work attributed CO_2 emission in rice straw production in Sonitpur district are estimated as 263 tonne, 207 tonne, 42 tonne, and 42 tonne corresponding to S-I, S-II, S-III and S-IV scenarios, respectively. At development block level, total CO_2 emission varies from the lowest in Gabharu to the highest in Dhekiajuli for all the scenarios (Table 5.3).

5.4.2. GHG emission attributed by bullock engagement in rice straw production

Results of GHG emission, in the form of CO_2, attributed by bullock engagement for rice cultivation are presented in Table 5.4. Among the two scenarios (S-I and S-II), highest CO_2 emission is observed in S-I.

Overall, at district level, total CO_2 emission in S-I and S-II are estimated to be 496 tonne and 99 tonne, respectively on annual basis. There is variation in CO_2 emission among the development blocks as shown in Table 5.4.

The variations of human and animal work engagement attributed GHG emission for straw production amongst the scenarios are due to variation of the level of mechanization. The dominancy of human and bullock engagement is prevalent in Sonitpur district and therefore, the result of the present study seems to be meaningful.

Table 5.3: GHG emission attributed by human engagement for rice straw production in Sonitpur district

Scenario	CO_2e emission, tonne	Development block														Sonitpur *total*
		Ga	Bis	Sak	Bag	Beh	Soo	Bih	Pub-c	Ran	Bal	Nad	Bor	Cho	Dhe	
S-I	**LP**	1.22	1.70	3.34	3.90	3.78	4.90	5.06	6.33	5.46	6.21	7.65	7.41	9.37	10.72	77
	T	1.39	1.94	3.81	4.45	4.31	5.59	5.77	7.22	6.22	7.09	8.72	8.45	10.69	12.22	88
	I	0.25	0.35	0.68	0.79	0.77	1.00	1.03	1.29	1.11	1.27	1.56	1.51	1.91	2.18	16
	H	1.29	1.81	3.55	4.15	4.02	5.21	5.38	6.74	5.80	6.61	8.13	7.88	9.96	11.39	82
	Total	**4.15**	**5.79**	**11.38**	**13.29**	**12.89**	**16.69**	**17.24**	**21.58**	**18.59**	**21.17**	**26.06**	**25.25**	**31.93**	**36.51**	**263**
S-II	**LP**	0.44	0.61	1.19	1.39	1.35	1.75	1.81	2.26	1.95	2.22	2.73	2.65	3.35	3.83	28
	T	1.39	1.94	3.81	4.45	4.31	5.59	5.77	7.22	6.22	7.09	8.72	8.45	10.69	12.22	88
	I	0.25	0.35	0.68	0.79	0.77	1.00	1.03	1.29	1.11	1.27	1.56	1.51	1.91	2.18	16
	H	1.20	1.67	3.28	3.83	3.72	4.81	4.97	6.22	5.36	6.10	7.51	7.28	9.20	10.52	76
	Total	**3.27**	**4.56**	**8.96**	**10.46**	**10.15**	**13.15**	**13.58**	**17.00**	**14.64**	**16.67**	**20.52**	**19.88**	**25.14**	**28.75**	**207**
S-III	**LP**	0.20	0.28	0.54	0.64	0.62	0.80	0.82	1.03	0.89	1.01	1.25	1.21	1.53	1.75	13
	T	0.06	0.08	0.15	0.18	0.17	0.22	0.23	0.29	0.25	0.28	0.35	0.34	0.42	0.48	3
	I	0.25	0.35	0.68	0.79	0.77	1.00	1.03	1.29	1.11	1.27	1.56	1.51	1.91	2.18	16
	H	0.17	0.23	0.45	0.53	0.51	0.67	0.69	0.86	0.74	0.84	1.04	1.01	1.27	1.45	10
	Total	**0.67**	**0.93**	**1.83**	**2.14**	**2.07**	**2.68**	**2.77**	**3.47**	**2.99**	**3.40**	**4.19**	**4.06**	**5.13**	**5.87**	**42**
S-IV	**LP**	0.19	0.27	0.53	0.62	0.60	0.78	0.80	1.00	0.86	0.98	1.21	1.17	1.48	1.70	12
	T	0.06	0.08	0.15	0.18	0.17	0.22	0.23	0.29	0.25	0.28	0.35	0.34	0.42	0.48	3
	I	0.25	0.35	0.68	0.79	0.77	1.00	1.03	1.29	1.11	1.27	1.56	1.51	1.91	2.18	16
	H	0.17	0.23	0.45	0.53	0.51	0.67	0.69	0.86	0.74	0.84	1.04	1.01	1.27	1.45	10
	Total	**0.66**	**0.92**	**1.81**	**2.12**	**2.05**	**2.66**	**2.75**	**3.44**	**2.96**	**3.37**	**4.15**	**4.02**	**5.09**	**5.82**	**42**

Note: LP: Land preparation, T: Transplanting, I: Irrigation, H: Harvesting

Gab: Gabharu, Bis: Biswanath, Sak: Sakomatha, Bag: Baghmara, Beh: Behali, Soo: Sootea, Bih: Bihaguri, Pub-c: Pub-choiduar, Ran: Rangapara, Bal: Balipara, Nad: Naduar, Bor: Borchola, Cho: Choiduar, Dhe: Dhekiajuli

Table 5.4: GHG emission attributed by bullock engagement for rice straw production in Sonitpur district

Scenario	**CO_2e emission, tonne**	**Development block**														**Sonitpur total**
		Ga	Bis	Sak	Bag	Beh	Soo	Bih	Pub-C	Ran	Bal	Nad	Borc	Cho	Dhe	
S-I	**LP**	8	11	21	25	24	32	33	41	35	40	49	48	60	69	496
	T	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	I	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	H	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Total	**8**	**11**	**21**	**25**	**24**	**32**	**33**	**41**	**35**	**40**	**49**	**48**	**60**	**69**	**496**
S-II	**LP**	2	2	4	5	5	6	6	8	7	8	10	9	12	14	99
	T	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	I	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	H	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Total	**2**	**2**	**4**	**5**	**5**	**6**	**6**	**8**	**7**	**8**	**10**	**9**	**12**	**14**	**99**

Note: LP: Land preparation, T: Transplanting, I: Irrigation, H: Harvesting

Gab: Gabharu, Bis: Biswanath, Sak: Sakomatha, Bag: Baghmara, Beh: Behali, Soo: Sootea, Bih: Bihaguri, Pub-c: Pub-choiduar, Ran: Rangapara, Bal: Balipara, Nad: Naduar, Bor: Borchola, Cho: Choiduar, Dhe: Dhekiajuli

5.4.3. GHG emission attributed by power tiller engagement in rice straw production

Power tiller engagement is considered for S-II only. Development block level CO_2e GHG emission pertaining to the engagement of power tiller is presented in Table 5.5. Overall, CO_2e emission for Sonitpur district estimated to be 496 tonne. GHG emissions are estimated as 273 tonne CO_2e, 50 tonne CO_2e and 174 tonne CO_2e, from land preparation, transplanting and harvesting, respectively. Power tiller attributing CO_2e emission varies from the lowest of 8 tonne CO_2e in Gabharu to the highest of 69 CO_2e in Dhekiajuli amongst the 14 development blocks of Sonitpur district (Table 5.5).

5.4.4. GHG emission attributed by tractor engagement in rice straw production

District and development block level CO_2e emission for both S-III and S-IV are presented in Table 5.6. Overall, CO_2e emission at district level is estimated to be 858 tonne and 1029 tonne for S-III and S-IV, respectively on annual basis. Emission at development block level varies from the lowest in Gabharu to the highest in Dhekiajuli under both the scenarios (Table 5.6).

5.4.5. GHG emission attributed by engine engagement in rice cultivation

CO_2e emission results are presented in Table 5.7. Scenario wise, district level, CO_2e emission are estimated to be 576 tonne CO_2e, 576 tonne CO_2e, 587 tonne CO_2e and 589 tonne CO_2e for S-I, S-II, S-III and S-IV, respectively. Thus, the highest emission is observed in S-IV and the lowest in S-I and S-II. At development block level, the lowest emission is estimated to be in Gabharu and the highest in Dhekiajuli as shown in Table 5.7.

Table 5.5: GHG emission attributed by power tiller engagement for rice straw production in Sonitpur district

Scenario	CO_2e emission, tonne	Development block														Sonitpur total
		Gab	Bis	Sak	Bag	Beh	Soo	Bih	Pub-c	Ran	Bal	Nad	Bor	Cho	Dhe	
S-II	**LP**	4	6	12	14	13	17	18	22	19	22	27	26	33	38	273
	T	1	1	2	3	2	3	3	4	4	4	5	5	6	7	50
	I	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	H	3	4	8	9	9	11	11	14	12	14	17	17	21	24	174
	Total	**8**	**11**	**21**	**25**	**24**	**32**	**33**	**41**	**35**	**40**	**49**	**48**	**60**	**69**	**496**

Table 5.6: GHG emission attributed by tractor engagement for rice straw production in Sonitpur district

Scenario	CO_2e emission, tonne	Development block														Sonitpur total
		Gab	Bis	Sak	Bag	Beh	Soo	Bih	Pub-c	Ran	Bal	Nad	Bor	Cho	Dhe	
S-III	**LP**	8	11	22	26	25	33	34	42	36	42	51	49	63	72	515
	T	1	2	4	4	4	5	6	7	6	7	9	8	10	12	86
	I	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	H	4	6	11	13	13	16	17	21	18	21	26	25	31	36	257
	Total	**14**	**19**	**37**	**43**	**42**	**55**	**56**	**71**	**61**	**69**	**85**	**82**	**104**	**119**	**858**
S-IV	**LP**	7	9	19	22	21	27	28	35	30	35	43	41	52	60	429
	T	1	2	4	4	4	5	6	7	6	7	9	8	10	12	86
	I	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	H	8	11	22	26	25	33	34	42	36	42	51	49	63	72	515
	Total	**16**	**23**	**45**	**52**	**51**	**65**	**68**	**85**	**73**	**83**	**102**	**99**	**125**	**143**	**1029**

Note: LP: Land preparation, T: Transplanting, I: Irrigation, H: Harvesting
Gab: Gabharu, Bis: Biswanath, Sak: Sakomatha, Bag: Baghmara, Beh: Behali, Soo: Sootea, Bih: Bihaguri, Pub-c: Pub-choiduar, Ran: Rangapara, Bal: Balipara, Nad: Naduar, Bor: Borchola, Cho: Choiduar, Dhe: Dhekiajuli

Table 5.7: GHG emission attributed by engine engagement for rice straw production in Sonitpur district

Scenario	**CO_2e emission, tonne**	**Development block**														**Sonitpur total**
		Gab	Bis	Sak	Bag	Beh	Soo	Bih	Pub-C	Ran	Bal	Nad	Bor	Cho	Dhe	
S-I	**LP**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	T	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	I	6	13	15	14	18	19	24	21	23	29	28	35	40	290	576
	H	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Total	6	13	15	14	18	19	24	21	23	29	28	35	40	290	576
S-II	**LP**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	T	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	I	6	13	15	14	18	19	24	21	23	29	28	35	40	290	576
	H	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Total	6	13	15	14	18	19	24	21	23	29	28	35	40	290	576
S-III	**LP**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	T	0.10	0.15	0.29	0.33	0.32	0.42	0.43	0.54	0.47	0.53	0.66	0.64	0.80	0.92	6.62
	I	6	13	15	14	18	19	24	21	23	29	28	35	40	290	576
	H	0.08	0.11	0.22	0.26	0.25	0.33	0.34	0.42	0.36	0.42	0.51	0.49	0.63	0.72	5.15
	Total	7	13	15	15	19	20	25	22	24	30	29	36	42	292	587
S-IV	**LP**	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	T	0.10	0.15	0.29	0.33	0.32	0.42	0.43	0.54	0.47	0.53	0.66	0.64	0.80	0.92	6.62
	I	6	13	15	14	18	19	24	21	23	29	28	35	40	290	576
	H	0.10	0.15	0.29	0.33	0.32	0.42	0.43	0.54	0.47	0.53	0.66	0.64	0.80	0.92	6.62
	Total	7	13	15	15	19	20	25	22	24	30	29	37	42	292	589

Note: LP: Land preparation, T: Transplanting, I: Irrigation, H: Harvesting

Gab: Gabharu, Bis: Biswanath, Sak: Sakomatha, Bag: Baghmara, Beh: Behali, Soo: Sootea, Bih: Bihaguri, Pub-c: Pub-choiduar, Ran: Rangapara, Bal: Balipara, Nad: Naduar, Bor: Borchola, Cho: Choiduar, Dhe: Dhekiajuli

5.4.6. GHG emission attributed by diesel consumption

As mentioned earlier, there are two pathways of diesel combustion related GHG emission: (i) direct, and (ii) indirect. Direct emission is associated with actual combustion of diesel in farm machineries while indirect emission associated with the production, processing of diesel fuel. GHG emission in the form of CO_2, CH_4 and N_2O is estimated and the results are presented in Table 5.8(a)-5.8(d) separately for each scenario.

5.4.6a. GHG emission in S-I

GHG emission results under scenario S-I are presented in Table 5.8(a). In S-I, there are no GHG emission in land preparation, transplanting and harvesting since these operations are performed utilising human or bullock energy only. Diesel is only used for irrigation purpose. The CO_2e total direct emission is estimated to be 4764 tonne, while indirect emission is 1004 tonne. Thus, overall total emission (direct and indirect) in Sonitpur district is estimated to be 5768 CO_2e. On the other hand, at development block level, overall total emission varies from the lowest of in Gabharu to the highest in Dhekiajuli as shown in Table 5.8(a).

5.4.6b. GHG emission in S-II

GHG emission results under scenario S-II are presented in Table 5.8(b). Diesel is used for all the operations in S-II, however, with variation in requirement. Operation wise in Sonitpur district, total CO_2e GHG emission (direct and indirect) are estimated to be 2301 tonne CO_2e, 207 tonne CO_2e, 5768 tonne CO_2e and 725 tonne CO_2e for land preparation, transplanting, irrigation and harvesting purposes, respectively. Thus, overall, grand total emission is 9001 tonne CO_2e (7435 tonne CO_2e from direct and 1566 tonne CO_2e from indirect emissions). The grand total emission (direct and indirect) at development block level varies from the lowest in Gabharu to the highest in Dhekiajuli Table 5.8(b).

5.4.6c. GHG emission in S-III

GHG emission results under scenario S-III are presented in Table 5.8(c). Operation wise in Sonitpur district, total CO_2e GHG emission (direct and indirect) are estimated to be 4040 tonne CO_2e, 1160 tonne CO_2e, 5868 tonne CO_2e and 1889 tonne CO_2e for land preparation, transplanting, irrigation and harvesting purposes, respectively. Thus, overall, grand total emission is 12856 tonne CO_2e (10620 tonne CO_2e from direct and 2237 tonne CO_2e from indirect emissions). At development block level, the grand total emission (direct and indirect) varies from the lowest in Gabharu to the highest in Dhekiajuli Table 5.8(c).

5.4.6d. GHG emission in S-IV

GHG emission results under scenario S-IV are presented in Table 5.8(d). Operation wise in Sonitpur, total CO_2e emission (direct and indirect) are estimated to be 3657 tonne CO_2e, 1160 tonne CO_2e, 5768 tonne CO_2e and 3005 tonne CO_2e for land preparation, transplanting, irrigation and harvesting purposes, respectively. Thus, overall, grand total emission is 13589 tonne CO_2e (11225 tonne CO_2e from direct and 2364 tonne CO_2e from indirect emissions). At development block level, the grand total emission (direct and indirect) varies from the lowest in Gabharu to the highest in Dhekiajuli Table 5.8(d).

5.4.7. Comparison of scenario wise GHG emission

Comparing the scenarios in Sonitpur district, the lowest grand total GHG emission is observed in S-I and the highest in S-IV. At development block level, the lowest emission is observed in Gabharu and the highest in Dhekiajuli for all the four scenarios. Operation wise, the lowest emission (direct and indirect) is observed in transplanting and the highest in irrigation for all the scenarios. In fact, GHG emission due to irrigation purpose is same for all the scenarios. GHG species wise, the lowest emission is contributed by CH_4 and the highest emission is contributed by CO_2 in all the operations under all the scenarios.

Table 5.8(a): GHG emission attributed by diesel consumption for rice straw production in Sonitpur district under S-I

Operation	**CO_2e emission, tonne**	**Development block**														**Sonitpur total**
		Gab	Bis	Sak	Bag	Beh	Soo	Bih	Pub-c	Ran	Bal	Nad	Bor	Cho	Dhe	
Irrigation	CO_2	75	104	205	239	232	301	310	389	335	381	469	455	575	658	4729
	CO_2e CH_4	0.03	0.04	0.07	0.08	0.08	0.10	0.11	0.13	0.11	0.13	0.16	0.15	0.19	0.22	2
	CO_2e N_2O	1	1	1	2	2	2	2	3	2	3	3	3	4	5	34
	CO_2e indirect	16	22	44	51	49	64	66	83	71	81	100	97	122	140	1004
	Total direct CO_2e	75	105	207	241	234	303	313	392	337	384	473	458	579	663	4764
	Total CO_2e (direct+indirect)	91.12	127.2	250.1	292	283.3	366.8	378.7	474.2	408.4	465.2	572.6	554.7	701.5	802.2	5768
Grand total direct CO_2e		**75**	**105**	**207**	**241**	**234**	**303**	**313**	**392**	**337**	**384**	**473**	**458**	**579**	**663**	**4764**
Grand total indirect CO_2e		**16**	**22**	**44**	**51**	**49**	**64**	**66**	**83**	**71**	**81**	**100**	**97**	**122**	**140**	**1004**
Grand total CO_2e (direct+indirect)		**91**	**127**	**250**	**292**	**283**	**367**	**379**	**474**	**408**	**465**	**573**	**555**	**701**	**802**	**5768**

Note: Gab: Gabharu, Bis: Biswanath, Sak: Sakomatha, Bag: Baghmara, Beh: Behali, Soo: Sootea, Bih: Bihaguri, Pub-c: Pub-choiduar, Ran: Rangapara, Bal: Balipara, Nad: Naduar, Bor: Borchola, Cho: Choiduar, Dhe: Dhekiajuli

Table 5.8(b): GHG emission attributed by diesel consumption for rice straw production in Sonitpur district under S-II

Oper ation	**CO_2e emission, tonne**	**Development block**														**Sonitpur total**
		Gab	Bis	Sak	Bag	Beh	Soo	Bih	Pub-c	Ran	Bal	Nad	Bor	Cho	Dhe	
Land preparation	CO_2	30	42	82	95	93	120	124	155	134	152	187	181	229	262	1886
	CO_2e CH_4	0.01	0.01	0.03	0.03	0.03	0.04	0.04	0.05	0.05	0.05	0.06	0.06	0.08	0.09	0.64
	CO_2e N_2O	0.21	0.30	0.59	0.69	0.67	0.86	0.89	1.11	0.96	1.09	1.34	1.30	1.65	1.88	13.55
	CO_2e indirect	6	9	17	20	20	25	26	33	28	32	40	38	49	56	400
	Total direct CO_2e	30	42	82	96	93	121	125	156	135	153	189	183	231	264	1901
	Total CO_2e (direct+indirect)	36	51	100	116	113	146	151	189	163	186	228	221	280	320	2301
Transplanting	CO_2	3	4	7	9	8	11	11	14	12	14	17	16	21	24	170
	CO_2e CH_4	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.06
	CO_2e N_2O	0.02	0.03	0.05	0.06	0.06	0.08	0.08	0.10	0.09	0.10	0.12	0.12	0.15	0.17	1.22
	CO_2e indirect	1	1	2	2	2	2	2	3	3	3	4	3	4	5	36
	Total direct CO_2e	3	4	7	9	8	11	11	14	12	14	17	16	21	24	171
	Total CO_2e (direct+indirect)	3	5	9	10	10	13	14	17	15	17	21	20	25	29	207
Irrigation	CO_2	75	104	205	239	232	301	310	389	335	381	469	455	575	658	4729
	CO_2e CH_4	0.03	0.04	0.07	0.08	0.08	0.10	0.11	0.13	0.11	0.13	0.16	0.15	0.19	0.22	1.60
	CO_2e N_2O	0.54	0.75	1.47	1.72	1.67	2.16	2.23	2.79	2.40	2.74	3.37	3.27	4.13	4.72	33.96
	CO_2e indirect	16	22	44	51	49	64	66	83	71	81	100	97	122	140	1004
	Total direct CO_2e	75	105	207	241	234	303	313	392	337	384	473	458	579	663	4764
	Total CO_2e (direct+indirect)	91	127	250	292	283	367	379	474	408	465	573	555	701	802	5768
Harvesting	CO_2	9	13	26	30	29	38	39	49	42	48	59	57	72	83	594
	CO_2e CH_4	0.00	0.00	0.01	0.01	0.01	0.01	0.01	0.02	0.01	0.02	0.02	0.02	0.02	0.03	0.20
	CO_2e N_2O	0.07	0.09	0.19	0.22	0.21	0.27	0.28	0.35	0.30	0.34	0.42	0.41	0.52	0.59	4.27
	CO_2e indirect	2	3	5	6	6	8	8	10	9	10	13	12	15	18	126
	Total direct CO_2e	9	13	26	30	29	38	39	49	42	48	59	58	73	83	599
	Total CO_2e (direct+indirect)	11	16	31	37	36	46	48	60	51	58	72	70	88	101	725
Grand total direct CO_2e		**117**	**164**	**322**	**376**	**365**	**473**	**488**	**611**	**527**	**600**	**738**	**715**	**904**	**1034**	**7435**
Grand total indirect CO_2e		**25**	**35**	**68**	**79**	**77**	**100**	**103**	**129**	**111**	**126**	**155**	**151**	**190**	**218**	**1566**
Grand total CO_2e (direct+indirect)		**142**	**198**	**390**	**456**	**442**	**572**	**591**	**740**	**637**	**726**	**894**	**866**	**1095**	**1252**	**9001**

Note: Gab: Gabharu, Bis: Biswanath, Sak: Sakomatha, Bag: Baghmara, Beh: Behali, Soo: Sootea, Bih: Bihaguri, Pub-c: Pub-choiduar, Ran: Rangapara, Bal: Balipara, Nad: Naduar, Bor: Borchola, Cho: Choiduar, Dhe: Dhekiajuli

Table 5.8(c): GHG emission attributed by diesel consumption for rice straw production in Sonitpur district under S-III

Operation	**CO_2e emission, tonne**	**Development block**														**Sonitpur total**
		Gab	Bis	Sak	Bag	Beh	Soo	Bih	Pub-c	Ran	Bal	Nad	Bor	Cho	Dhe	
Land preparation	CO_2	52	73	144	168	163	211	217	272	235	267	329	319	403	461	3312
	CO_2e CH_4	0.02	0.02	0.05	0.06	0.06	0.07	0.07	0.09	0.08	0.09	0.11	0.11	0.14	0.16	1.12
	CO_2e N_2O	0.38	0.52	1.03	1.20	1.17	1.51	1.56	1.96	1.68	1.92	2.36	2.29	2.89	3.31	24
	CO_2e indirect	11	15	30	36	35	45	46	58	50	57	70	68	85	98	703
	Total direct CO_2e	53	74	145	169	164	212	219	274	236	269	331	321	406	464	3337
	Total CO_2e (direct+indirect)	*64*	*89*	*175*	*204*	*198*	*257*	*265*	*332*	*286*	*326*	401	389	491	562	4040
Transplanting	CO_2	15	21	41	48	47	60	62	78	67	77	94	91	116	132	951
	CO_2e CH_4	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.03	0.02	0.03	0.03	0.03	0.04	0.04	0.32
	CO_2e N_2O	0.11	0.15	0.30	0.35	0.34	0.43	0.45	0.56	0.48	0.55	0.68	0.66	0.83	0.95	6.83
	CO_2e indirect	3	4	9	10	10	13	13	17	14	16	20	19	25	28	202
	Total direct CO_2e	15	21	42	48	47	61	63	79	68	77	95	92	117	133	958
	Total CO_2e (direct+indirect)	18	26	50	59	57	74	76	95	82	94	115	112	141	161	1160
Irrigation	CO_2	75	104	205	239	232	301	310	389	335	381	469	455	575	658	4729
	CO_2e CH_4	0.03	0.04	0.07	0.08	0.08	0.10	0.11	0.13	0.11	0.13	0.16	0.15	0.19	0.22	1.60
	CO_2e N_2O	0.54	0.75	1.47	1.72	1.67	2.16	2.23	2.79	2.40	2.74	3.37	3.27	4.13	4.72	34
	CO_2e indirect	16	22	44	51	49	64	66	83	71	81	100	97	122	140	1004
	Total direct CO_2e	75	105	207	241	234	303	313	392	337	384	473	458	579	663	4764
	Total CO_2e (direct+indirect)	91	127	250	292	283	367	379	474	408	465	573	555	701	802	5768
Harvesting	CO_2	24	34	67	78	76	98	102	127	110	125	154	149	188	215	1548
	CO_2e CH_4	0.01	0.01	0.02	0.03	0.03	0.03	0.03	0.04	0.04	0.04	0.05	0.05	0.06	0.07	0.52
	CO_2e N_2O	0.18	0.25	0.48	0.56	0.55	0.71	0.73	0.91	0.79	0.90	1.10	1.07	1.35	1.55	11.12
	CO_2e indirect	5	7	14	17	16	21	22	27	23	27	33	32	40	46	329
	Total direct CO_2e	25	34	68	79	77	99	102	128	110	126	155	150	190	217	1560
	Total CO_2e (direct+indirect)	30	42	82	96	93	120	124	155	134	152	187	182	230	263	1889
Grand total direct CO_2e		**168**	**234**	**460**	**538**	**522**	**675**	**697**	**873**	**752**	**857**	**1054**	**1021**	**1292**	**1477**	**10620**
Grand total indirect CO_2e		**35**	**49**	**97**	**113**	**110**	**142**	**147**	**184**	**158**	**180**	**222**	**215**	**272**	**311**	**2237**
Grand total CO_2e (direct+indirect)		**203**	**283**	**557**	**651**	**631**	**817**	**844**	**1057**	**910**	**1037**	**1276**	**1236**	**1564**	**1788**	**12856**

Note: Gab: Gabharu, Bis: Biswanath, Sak: Sakomatha, Bag: Baghmara, Beh: Behali, Soo: Sootea, Bih: Bihaguri, Pub-c: Pub-choiduar, Ran: Rangapara, Bal: Balipara, Nad: Naduar, Bor: Borchola, Cho: Choiduar, Dhe: Dhekiajuli

Table 5.8(d): GHG emission attributed by diesel consumption for rice straw production in Sonitpur district under S-IV

Operation	**GHG emission, tonne**	**Development block**														Sonitpur total
		Gab	Bis	Sak	Bag	Beh	Soo	Bih	Pub-C	Ran	Bal	Nad	Bor	Cho	Dhe	
Land preparation	CO_2	47	66	130	152	147	191	197	246	212	242	298	288	365	417	2998
	CO_2e CH_4	0.02	0.02	0.04	0.05	0.05	0.06	0.07	0.08	0.07	0.08	0.10	0.10	0.12	0.14	1.01
	CO_2e N_2O	0.34	0.47	0.93	1.09	1.06	1.37	1.41	1.77	1.52	1.74	2.14	2.07	2.62	2.99	22
	CO_2e indirect	10	14	28	32	31	40	42	52	45	51	63	61	77	88	636
	Total direct CO_2e	48	67	131	153	148	192	198	248	214	244	300	290	367	420	3021
	Total CO_2e (direct+indirect)	58	81	159	185	180	233	240	301	259	295	363	352	445	509	3657
Transplanting	CO_2	15	21	41	48	47	60	62	78	67	77	94	91	116	132	951
	CO_2e CH_4	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.03	0.02	0.03	0.03	0.03	0.04	0.04	0.32
	CO_2e N_2O	0.11	0.15	0.30	0.35	0.34	0.43	0.45	0.56	0.48	0.55	0.68	0.66	0.83	0.95	6.83
	CO_2e indirect	3	4	9	10	10	13	13	17	14	16	20	19	25	28	202
	Total direct CO_2e	15	21	42	48	47	61	63	79	68	77	95	92	117	133	958
	Total CO_2e (direct+indirect)	18	26	50	59	57	74	76	95	82	94	115	112	141	161	1160
Irrigation	CO_2	75	104	205	239	232	301	310	389	335	381	469	455	575	658	4729
	CO_2e CH_4	0.03	0.04	0.07	0.08	0.08	0.10	0.11	0.13	0.11	0.13	0.16	0.15	0.19	0.22	1.60
	CO_2e N_2O	0.54	0.75	1.47	1.72	1.67	2.16	2.23	2.79	2.40	2.74	3.37	3.27	4.13	4.72	34
	CO_2e indirect	16	22	44	51	49	64	66	83	71	81	100	97	122	140	1004
	Total direct CO_2e	75	105	207	241	234	303	313	392	337	384	473	458	579	663	4764
	Total CO_2e (direct+indirect)	91	127	250	292	283	367	379	474	408	465	573	555	701	802	5768
Harvesting	CO_2	39	54	107	125	121	157	162	203	174	199	245	237	300	343	2463
	CO_2e CH_4	0.01	0.02	0.04	0.04	0.04	0.05	0.05	0.07	0.06	0.07	0.08	0.08	0.10	0.12	0.83
	CO_2e N_2O	0.28	0.39	0.77	0.90	0.87	1.12	1.16	1.45	1.25	1.43	1.76	1.70	2.15	2.46	18
	CO_2e indirect	8	12	23	26	26	33	34	43	37	42	52	50	64	73	523
	Total direct CO_2e	39	55	108	126	122	158	163	204	176	200	246	239	302	345	2482
	Total CO_2e (direct+indirect)	47	66	130	152	148	191	197	247	213	242	298	289	365	418	3005
Grand total direct CO_2e		**177**	**247**	**487**	**568**	**551**	**714**	**737**	**923**	**795**	**905**	**1114**	**1079**	**1365**	**1561**	**11225**
Grand total indirect CO_2e		**37**	**52**	**103**	**120**	**116**	**150**	**155**	**194**	**167**	**191**	**235**	**227**	**288**	**329**	**2364**
Grand total CO_2e (direct+indirect)		**215**	**300**	**589**	**688**	**667**	**864**	**892**	**1117**	**962**	**1096**	**1349**	**1307**	**1653**	**1890**	**13589**

Note: Gab: Gabharu, Bis: Biswanath, Sak: Sakomatha, Bag: Baghmara, Beh: Behali, Soo: Sootea, Bih: Bihaguri, Pub-c: Pub-choiduar, Ran: Rangapara, Bal: Balipara, Nad: Naduar, Bor: Borchola, Cho: Choiduar, Dhe: Dhekiajuli

5.4.8. GHG emission attributed by fertiliser consumption

Fertiliser demand and fertiliser application related GHG emission in the study area is presented in Table 5.9. Overall, fertiliser demand for rice cultivation in Sonitpur district is estimated to be 7747 tonne on annual basis. At block level, the lowest (122 tonne) and the highest (1077 tonne) amount of fertiliser demand are observed in Gabharu and Dhekiajuli, respectively (Table 5.9).

On the other hand, CO_2e N_2O emission attributed by fertiliser application in the district is estimated to be 8542 tonne (Table 5.9). At block level, the emission varies from the lowest in Gabharu (135 tonne CO_2e N_2O) to the highest in Dhekiajuli (1188 tonne CO_2e N_2O).

Table 5.9: GHG emission attributed by fertiliser consumption for rice straw production in Sonitpur district

Development block	Fertiliser demand, tonne	CO_2e N_2O emission, tonne
Gabharu	122	135
Biswanath	171	188
Sakomatha	336	370
Behali	380	420
Baghmara	392	432
Sootea	493	543
Bihaguri	509	561
Rangapara	549	605
Balipara	625	689
Pub-choiduar	637	702
Borchola	745	821
Naduar	769	848
Choiduar	942	1039
Dhekiajuli	1077	1188
Sonitpur total	**7747**	**8542**

5.4.9. GHG emission attributed by pesticide consumption

District and development block wise pesticide application related CO_2e GHG emission in the study area presented in Table 5.10. Overall, emission due to pesticide application in Sonitpur district is estimated to be 139 tonne CO_2e. At block level, the lowest and the highest emission are observed in Gabharu (2 tonne CO_2e) and Dhekiajuli (19 tonne CO_2e) as shown in Table 5.10.

Table 5.10: GHG emission attributed by pesticide consumption for rice straw production in Sonitpur district

Development block	**CO_2e emission, tonne**
Gabharu	2
Biswanath	3
Sakomatha	6
Behali	7
Baghmara	7
Sootea	9
Bihaguri	9
Rangapara	10
Balipara	11
Pub-choiduar	11
Borchola	13
Naduar	14
Choiduar	17
Dhekiajuli	19
Sonitpur total	139

5.4.10. GHG emission attributed by diesel used for rice straw collection and transportation

Results of GHG emission attributed by diesel in tractor for collection and transportation (by tractor) of residue are presented in Table 5.11. Overall at district level, 111272 tonne of rice straw need to be transported.

Grand total GHG emission (direct and indirect) in Sonitpur district is estimated to be 1324 tonne CO_2e (direct 1093 tonne and indirect 230 tonne). Development blocks level emission variation ranges from the lowest of 21 tonne CO_2e in Gabharu to the highest of 152 tonne CO_2e in Dhekiajuli. GHG species wise, the highest emission is contributed by CO_2 and the lowest by CH_4 as shown in Table 5.11.

Table 5.11: GHG emission attributed by diesel used for rice straw collection and transportation

Development block	Amount of straw to be transported, tonne	Diesel energy demand, GJ	Emission, tonne					
			CO_2	CO_2e CH_4	CO_2e N_2O	CO_2e indirect	CO_2e direct	Total CO_2e (direct+indirect)
Gabharu	1758	233	17	0.006	0.123	4	17	21
Biswanath	2453	325	24	0.008	0.172	5	24	29
Sakomatha	4824	639	47	0.016	0.338	10	47	57
Behali	5465	723	53	0.018	0.383	11	54	65
Baghmara	5633	746	55	0.019	0.394	12	55	67
Sootea	7076	937	69	0.023	0.496	15	70	84
Bihaguri	7306	967	71	0.024	0.512	15	72	87
Rangapara	7880	1043	77	0.026	0.552	16	77	94
Balipara	8975	1188	88	0.030	0.629	19	88	107
Pub-choiduar	9149	1211	89	0.030	0.641	19	90	109
Borchola	10700	1416	104	0.035	0.749	22	105	127
Naduar	11046	1462	108	0.036	0.774	23	109	131
Choiduar	13533	1791	132	0.045	0.948	28	133	161
Dhekiajuli	15476	2048	151	0.051	1.084	32	152	184
Sonitpur total	**111272**	**14729**	**1085**	**0.367**	**7.793**	**230**	**1093**	**1324**

5.4.11. GHG emission attributed by rice straw combustion for power generation

Combustion of rice straw for power generation also releases GHG, more particularly CO_2, CH_4 and N_2O. A trace of amount other atmospheric pollutants such as SO_x, CO, particulate matter (PM) are also released into the atmosphere. However, emission estimation of these pollutants is out of scope of the present research work.

Overall in Sonitpur district, 121742 tonne CO_2e GHG is emitted into the atmosphere due to the combustion of 112594 tonne rice straw as presented in Table 5.12. GHG species wise, the highest emission is contributed by CO_2 (120926 tonne), and the lowest is by CH_4 (816 tonne CO_2e). At development block level, the lowest emission is estimated to be in Gabharu (1747 tonne CO_2e), and the highest in Dhekiajuli (19168 tonne CO_2e) as shown in Table 5.12.

Table 5.12: GHG emission attributed by rice straw combustion for power generation

Development block	Net rice straw, tonne	CO_2 emission, tonne	CO_2e CH_4 emission, tonne	CO_2e N_2O emission, tonne	Net CO_2e emission, tonne
Gabharu	1591	1709	12	19	1747
Biswanath	2203	2366	16	26	2425
Sakomatha	3628	3896	26	43	4008
Baghmara	7136	7664	52	85	7785
Behali	5764	6191	42	69	6305
Sootea	6096	6547	44	73	6694
Bihaguri	8594	9230	62	102	9387
Pub-choiduar	7970	8560	58	95	8711
Rangapara	7845	8426	57	94	8630
Balipara	12372	13288	90	147	13476
Naduar	8249	8859	60	98	9066
Borchola	12293	13203	89	147	13439
Choiduar	12367	13282	90	147	13568
Dhekiajuli	16486	17706	120	197	19168
Sonitpur total	**112594**	**120926**	**816**	**1342**	**121742**

5.4.12. GHG emission attributed by diesel used for coal transportation

Diesel energy demand and associated GHG emission from coal transportation is presented in Table 5.13. Overall, in Sonitpur district, 75566 tonne of straw equivalent coal (~1738028 GJ) would be required for transportation in order to generate straw equivalent power (*i.e.* 11 MW). This will demand 62803 GJ of diesel energy at district level.

In terms of emission, net CO_2e GHG emission in Sonitpur district due to transportation is estimated to be 5643 tonne (4662 tonne CO_2e direct and 982 CO_2e indirect emissions). At development block level, net CO_2e emission varies from the lowest of 80 tonne in Gabharu to the highest of 826 tonne in Dhekiajuli as shown in Table 5.13. GHG species wise, the highest emission is contributed by CO_2, followed by N_2O and CH_4.

Table 5.13: GHG emission attributed by diesel used for coal transportation

Development block	Straw eq. coal demand, tonne	Coal energy, GJ	Diesel energy, GJ	Emission, tonne					
				CO_2	CO_2e CH_4	CO_2e N_2O	CO_2e indirect	Net direct CO_2e	Net CO_2e
Gabharu	1068	24559	887	65	0.02	0.47	14	66	80
Biswanath	1479	34006	1229	91	0.03	0.65	19	91	110
Sakomatha	2435	56003	2024	149	0.05	1.07	32	150	182
Behali	3868	88974	3215	237	0.08	1.70	50	239	289
Sootea	4091	94099	3400	250	0.08	1.80	53	252	306
Baghmara	4789	110153	3980	293	0.10	2.11	62	295	358
Rangapara	5265	121097	4376	322	0.11	2.32	68	325	393
Pub-Choiduar	5349	123027	4446	328	0.11	2.35	70	330	399
Naduar	5536	127334	4601	339	0.11	2.43	72	342	413
Bihaguri	5768	132659	4794	353	0.12	2.54	75	356	431
Borchola	8250	189758	6857	505	0.17	3.63	107	509	616
Choiduar	8300	190900	6898	508	0.17	3.65	108	512	620
Balipara	8303	190977	6901	508	0.17	3.65	108	512	620
Dhekiajuli	11064	254482	9196	677	0.23	4.87	144	683	826
Sonitpur	**75566**	**1738028**	**62803**	**4627**	**1.57**	**33.23**	**982**	**4662**	**5643**

5.4.13. GHG emission attributed by coal combustion for power generation

Results of district and development wise level GHG emission due to coal combustion for power generation is presented in Table 5.14. As mentioned earlier, emission factor for CO_2, CH_4 and N_2O are taken as 2.238 kg kg^{-1} coal, 0.0004 kg kg^{-1} coal and 0.0195 kg kg^{-1} coal, respectively [DEFRA]. In Sonitpur district, net CO_2e GHG emission (direct and indirect) is estimated to be 198551 tonne (170621 tonne CO_2e direct and 27929 tonne CO_2e indirect). Net emission at development block level is observed to be the lowest in Gabharu (2806 tonne CO_2e) and the highest in Dhekiajuli (29072 tonne CO_2e) as shown in Table 5.14.

Table 5.14: GHG emission attributed by coal combustion for power generation

Development block	Straw eq. coal demand, tonne	Coal energy, GJ	Emission, tonne					
			CO_2	CO_2e CH_4	CO_2e N_2O	CO_2e direct	CO_2e indirect	Net CO_2e
Gabharu	1068	24559	2390	0.43	21	2411	395	2806
Biswanath	1479	34006	3309	0.59	29	3338	546	3885
Sakomatha	2435	56003	5449	0.97	47	5498	900	6398
Behali	3868	88974	8658	1.55	75	8735	1430	10164
Sootea	4091	94099	9156	1.64	80	9238	1512	10750
Baghmara	4789	110153	10718	1.92	93	10814	1770	12584
Rangapara	5265	121097	11783	2.11	103	11888	1946	13834
Pub-Choiduar	5349	123027	11971	2.14	104	120.77	1977	14054
Naduar	5536	127334	12390	2.21	108	12500	2046	14546
Bihaguri	5768	132659	12908	2.31	112	13023	2132	15155
Borchola	8250	189758	18464	3.30	161	18628	3049	21678
Choiduar	8300	190900	18575	3.32	162	18741	3068	21808
Balipara	8303	190977	18583	3.32	162	18748	3069	21817
Dhekiajuli	11064	254482	24762	4.43	216	24982	4089	29072
Sonitpur total	**75566**	**1738028**	**169118**	**30.23**	**1474**	**170621**	**27929**	**198551**

5.5. Comparison of GHG emission between rice straw biomass power plant and coal power plant

Scenario wise GHG emission performance between rice straw biomass power plant and coal fired power plant is presented in Table 5.15. In the all scenarios, life cycle GHG emission (rice cultivation, rice straw transportation & collection and conversion in power plant) is less than coal fired power plant, if we allocate 40% of emission to rice straw production. Even if we allocate 100% emission to rice straw power, still net emission is less than coal power plant for all the scenarios.

Compared to the 204194 tonne CO_2e emission from coal power plant, emissions (tonne CO_2e) under the four rice straw biomass power scenarios in Sonitpur district are: (i) S-I: 138849, (ii) S-II: 142125, (iii) S-III: 146091 and (iv) S-IV: 146996.

The practices of rice crop production and level of mechanisation influence the GHG emission while considering the rice residue as potential feedstock. About 6% increase in CO_2e GHG emission is results from the rice straw considered in mechanised methods of rice cultivation (1.53 kg of CO_2e kWh^{-1}) compared with the traditional method (bullock and animal powered) of rice cultivation (1.44 kg of CO_2e kWh^{-1}).

Substantial amount of emission reduction (about 47%) is possible in rice residue based decentralised power generation (even with the highly mechanised crop cultivation) compared with conventional coal based centralised power generation (2.12 kg of CO_2e kWh^{-1}).

Similar findings have also been reported in literature. For example, Safie et al., 2014 [21] reported the life cycle CO_2e GHG emission from rice straw power as 0.85 kg CO_2e kWh^{-1} for Malaysia. In case of wheat straw and *Brassica carinata* fired power plant, CO_2e GHG emission are 1.076 CO_2e kWh^{-1} and 1.086 CO_2e kWh^{-1}, respectively [21]. In coal fired power plant, CO_2 emission is reported as 1.21 kg kWh^{-1}. The higher emission from coal fired power estimated in the present study, could be due to low heat content of coal and long transport distance from coal mine to coal power plant.

It is also reported that open field burning of one tonne of rice straw emits of 1.52 tonne CO_2e GHG [21]. From the present LCA based rice straw power generation study, it is observed that burning of one tonne of straw for power production under S-I, S-II, S-III and S-IV would release 1.23, 1.26, 1.30 and 1.31 tonne CO_2e GHG, respectively. On the other hand, considering all the life cycle stages, burning of one tonne of coal for power production would release 2.70 tonne CO_2e GHG,.

5.6. Summary

The lifecycle GHG emission for decentralised electrical power generation are successfully modelled in spatial scale and becomes useful for assessment for the case of Sonitpur district. Two options of fuel *viz.*, (i) distributed surplus rice straw and (ii) centralised coal, are compared for GHG emission performance using the developed model. The practices of rice crop production and level of mechanisation influence the GHG emission while considering the rice residue as feedstock. About 6% increase in CO_2e GHG emission is resulted from the rice straw considered in mechanised methods of rice cultivation (1.53 kg of CO_2e kWh^{-1}) compared with the traditional method (bullock and animal powered) of rice cultivation (1.44 kg of CO_2e kWh^{-1}). Substantial amount of emission reduction (about 47%) is possible in rice residue based decentralised power generation (even with the highly mechanised crop cultivation) compared with conventional coal based centralised power generation (2.12 kg of CO_2e kWh^{-1}).

Table 5.15: Comparison of GHG emission between rice straw biomass power and coal fired power

Scenario	Emission categories	Ga	Bis	Sak	Bag	Beh	Soo	Bih	Pub-C	Ran	Bal	Nad	Bor	Cho	Dhe	Sonitpur total
S-I	Rice straw power emission, tonne	2014	2802	4739	8620	7150	7764	10497	9977	9922	14853	10704	15095	15619	21757	138849
S-II		2066	2874	4881	8786	7311	7972	10712	10246	10154	15118	11029	15410	16018	22212	142125
S-III		2129	2962	5053	8987	7506	8224	10972	10572	10435	15437	11423	15792	16500	22764	146091
S-IV		2143	2982	5093	9033	7551	8282	11032	10647	10499	15510	11512	15879	16610	22890	146996
Coal power emission, tonne		2885	3995	6580	10453	11055	12941	14227	14454	14960	15586	22294	22428	22437	29898	204194

Note: Gab: Gabharu, Bis: Biswanath, Sak: Sakomatha, Bag: Baghmara, Beh: Behali, Soo: Sootea, Bih: Bihaguri, Pub-c: Pub-choiduar, Ran: Rangapara, Bal: Balipara, Nad: Naduar, Bor: Borchola, Cho: Choiduar, Dhe: Dhekiajuli

REFERENCES

[1] Fargione, J., et al. Land clearing and the biofuel carbon debt, *Science* **319**, 1235--1238, 2008.

[2] Lapola, D.M., et al. Indirect land-use changes can overcome carbon savings from biofuels in Brasil, *Proc Natl Acad Sci* **107**, 3388--3393, 2010.

[3] Searchinger, T., et al. Use of U.S. croplands for biofuels increases greenhouse Gases through emissions from land-use change, *Science* **319**, 1238--1240, 2008.

[4] Danielsen, F., et al. Biofuel plantations on forested lands: Double jeopardy for biodiversity and climate, *Conserv Biol* **23**, 348--358, 2009.

[5] Hill, J., et al. Climate change and health costs of air emissions from biofuels and gasoline, *Proc Natl Acad Sci* **106**, 2077--2082, 2009.

[6] Gnansounou, E., et al. Life cycle assessment of biofuels: Energy and greenhouse gas balances, *Bioresour Technol* **100**, 4919--4930, 2009.

[7] Shafiea, S.M., et al. Life cycle assessment of rice straw-based power generation in Malaysia, *Energy* **70**, 401--410, 2014.

[8] Silalertruksa, T., & Gheewala, S.H. A comparative LCA of rice straw utilisation for fuels and fertiliser in Thailand, *Bioresour Technol* **150**, 412--419, 2013.

[9] Shie, J.L., et al. Scenario comparisons of gasification technology using energy life cycle assessment for bioenergy recovery from rice straw in Taiwan, *Energy Convers Manage* **87**, 156--163, 2014.

[10] Sanscartier, D., et al. Life cycle greenhouse gas emissions of electricity generation from corn cobs in Ontario, Canada, *Biofuels, Bioprod Biorefin* **8**, 568--578, 2014.

[11] Yang, J., & Chen, B. Global warming impact assessment of a crop residue gasification project-A dynamic LCA perspective, *Appl Energ* **122**, 269--79, 2014.

[12] Baruah, D.C., & Bora, G.C. Energy demand forecast for mechanised agriculture in rural India, *Energy Policy* **36,** 2628--2636, 2008.

[13] Baruah, D.C., et al. Present status and future demand for energy for bullock-operated paddy-farms in Assam (India), *Appl Energ* **79**, 145--157, 2004.

[14] Walsh, C. A comparison of carbon dioxide emissions associated with motorised transport modes and cycling in Ireland, *Transportation Research Part D* **13**, 392--399, 2008.

[15] Maraseni, T.N., et al. Greenhouse gas emissions from rice farming inputs: a cross-country assessment, *J Agric Sci* **147**, 117--126, 2009.

[16] Pathak, H., et al. Emission of nitrous oxide from soil in rice-wheat systems of Indo-Gangetic plains of India. *J Environ Monitoring Assessment* *77*(2), 163--178, 2002.

[17] Heimpel, G.E., et al. Environmental consequences of invasive species: Greenhouse gas emissions of insecticide use and the role of biological control in reducing emissions. *Plos One* **8**, e72293, 2013.

[18] Department of Energy and Climate Change (DECC) and the Department for Environment, Food and Rural Affairs (DEFRA), *2012 Guidelines to Defra/DECC's GHG Conversion Factors for Company Reporting*, 2012.

[19] United States Environmental protection Agency. http://www.epa.gov/climateleadership/documents/emission-factors.pdf. (accessed 12/6/2014).

[20] The Intergovernmental Panel on Climate Change. *IPCC Fourth Assessment Report: Climate Change 2007*, http://www.ipcc.ch/publications_and_data/ar4/wg1/en/ch2s2-10-2.html. (accessed 02/01/2013).

[21] Shafie, S.M., et al. Life cycle assessment of rice straw-based power generation in Malaysia, *Energy* **70**, 401--410, 2014.

CHAPTER 6

SUMMARY AND CONCLUSIONS

CHAPTER 6

SUMMARY AND CONCLUSIONS

The works of this PhD research is summarised in this Chapter as below.

6.1. Energy concern: global, national and regional perspective

Energy is the prime requirement for the growth and development of human society. The intensity of energy use has determinant influence on development of a region. Until now, major share of global energy need is fulfilled through fossil energy resources and this could continue for some more time. However, the fossil energy resources are diminishing at an alarming rate and they are also the major cause of global climate change. Therefore, all nations of the world are giving substantial importance to renewable and clean sources of energy. India, a major global economy, is also facing serious energy crisis. To maintain India's economic growth rate and achieve energy needs of every citizen, energy security and energy sustainability are major concerns for India. Fossil energy sources of the country are inadequate to meet its domestic energy need and therefore the country fairly dependent on foreign energy imports. More than 80% of the oil demand of India is met through foreign imports. Realising the limitations of fossil energy in India, the Government of India has attempted to harness renewable energy resources by implementing various policies, schemes and projects.

Assam is one of the 29 states of India situated in the North-Eastern part. Like many parts of India, there is a serious imbalance of energy supply-demand in Assam. Chronically deficient electrical power supply is considered as one of the major bottlenecks for development in the state of Assam. With the limitations of the traditional sources of energy, it is imperative to promote appropriate sources of renewable energy. The state of Assam is an agriculturally dominating region where about 70% population relies on crop production. Further, rice based cropping system is followed in all the districts of this region. Thus, prospect of surplus rice residue as a source of decentralised renewable energy generation has been matter of investigation of the present investigation.

6.2. Crop residue for energy: Research issues

Biomass, solar, wind and small hydro are the major sources of renewable energy in India. Biomass resources are almost uniformly distributed all over India. Among the various sources of biomass resources, India generates a large amount of agricultural residue biomass. Uses of agricultural residues including rice straw for renewable heat and power generation have been reported from many parts of the world including India. Agricultural residue has prospect as a resource for decentralised power generation in many power deficient regions including in Assam. Soundness of power generation technology, appropriateness of feedstock (crop residue characteristics), precise and reliable assessment of feedstock (supply ensured) and prediction of environmental consequences are some of the major pre-requisites for planning and promoting crop residue based power generation. Considering the rice residue based power generation, technological soundness and feedstock characterisation have already been almost resolved. However, the issues of assessment and prediction of GHG emission are found unattended and therefore considered for the present investigation as highlighted below.

6.2.1. Precise assessment of surplus crop residue biomass

Crop residues are distributed resource with spatio-temporal variation in its availability. Furthermore, its competing uses also vary geographically. Traditional methods of assessment using survey and secondary data are not adequate to precisely estimate agricultural residue of a region. This is one of the barriers in implementation of agricultural residue based renewable energy programme. Remote sensing (RS) and Geographic Information System (GIS) is a spatial technique to assess and monitor earth resources. The use of RSGIS in renewable energy assessment has been gaining wider attention all over the world. RSGIS can provide precise information of biomass resource strength even at a very small scale. In addition, the generated information can be retrieved and updated at user will. There are many successful examples of RSGIS uses in the assessment of forest biomass, agricultural residue biomass *etc*. Furthermore, RSGIS have been also used to design biomass power plant, select optimal power plant location and identifying cost effective biomass transportation network.

6.2.2. Green house gas emission assessment for crop residue biomass based power generation

Unsustainable exploitation of biomass resources may even release more GHG (greenhouse gas) than its fossil counterpart and jeopardise many ecosystem functions. For example, bioenergy feedstocks production from natural forests or grasslands may not be justified option because these are already natural CO_2 sink. Rice straw, a by-product of rice crop production system, is a potential feedstock for power generation. Large amount of rice straw is available in Assam, indicating prospect for power generation. However, assessment of net GHG balance of such rice straw power generation from a life cycle prospective is important. Although Life Cycle Assessment (LCA) has been widely used to assess GHG balance of biomass power projects in many parts of the world, but in India biomass energy LCA studies are very limited.

6.3 Research objectives, tools, approaches and outcomes

6.3.1. Research objectives

Considering (i) potential of rice straw as a distributed energy resource for decentralised power, (ii) usefulness of spatial tools in biomass resource assessment, and (iii) importance of assessing GHG emission from rice straw based biomass power, the present research is conducted in Sonitpur district of Assam, India with three specific objectives, *viz*., (1) to develop a spatial tool for biomass resource assessment, (2) to assess rice straw residue biomass availability for decentralised energy generation, (3) to assess GHG emission performance of biomass energy generation from rice straw using life cycle assessment (LCA) technique. Standard procedures are followed to achieve the objectives as highlighted below.

6.3.2. Tools and approaches: Spatial model for crop residue assessment

A Remote sensing (RS) and Geographic Information System (GIS) based spatial model is developed to assess distribution and availability of crop residues in Sonitpur district. A variety of inputs (both spatial and non-spatial) are used to run and generate output from the spatial model. The output of this modelling tool in the form of spatial maps and attribute tables are further used with mathematical models to quantify rice straw residue availability and subsequently biomass energy potential. This is done at three pre-set spatial levels, *viz.* (i) district (highest level of administrative unit within the province), (ii) development block (administrative units for decentralised governance) and (iii) village (smallest recognised administrative unit).

6.3.3. Tools and approaches for GHG emission assessment

Greenhouse gas (GHG) emission performance of rice straw based biomass power is assessed from LCA prospective. Three major GHGs *viz.* CO_2, CH_4 and N_2O are considered while evaluating the emission performance. The GHG emission is estimated throughout the life cycle stages of rice straw based biomass power, *i.e.* (a) rice crop cultivation, (b) straw residue collection and transportation, and (c) straw residue conversion in biomass conversion plant to generate power. The GHG emission performance is also compared with an assumed coal fired power plant (having equivalent power generation capacity in comparison with rice straw based power plant). Spatial mathematical tools are proposed incorporating specific system parameters to estimate the emission from (i) crop residue based power generation and (ii) coal based power generation.

Considering the variation of rice crop cultivation practices prevailing in Sonitpur district of Assam, four different rice cultivation scenarios, *viz.* (i) scenario-I, (ii) scenario-II, (iii) scenario-III, and (iii) scenario-IV are designed for evaluation. While scenario-I is business as usual scenario, the other scenarios are mechanised scenarios with improved technological packages and with variations in mechanisation levels.

6.3.4. Summary of outcomes of the present research work

- Spatial model developed for assessment of surplus crop residue at user-defined spatial levels are found useful for planning rice residue based electricity generation programme in Sonitpur District of Assam. Thus, the present research successfully demonstrated the applicability of the spatial tool for a representative agricultural rural region of India enabling to precisely estimate the resource as well as its equivalent power potential up to the smallest administrative unit (village).

- Annual rice straw residue potential for renewable energy generation in the district is 0.11 million tonne (1733948 GJ), equivalent to 11 MW continuous electrical power. This is considered significant considering the prevailing crisis for electrical power in the region.

- Straw residue availability among the 14 development blocks varies from the lowest of 1591 tonne (equivalent to about 0.61 MW continuous electrical power in *Gabharu* development block) to the highest of 16468 tonne (equivalent to about 1.61 MW continuous electrical power in *Dekiajuli* development block).

- Among the 1615 villages of the district, 831 villages have net rice straw residue potential less than 100 tonnes per annum and the rest 380 villages have net straw residue potential higher than 100 tonne per annum. Rice straw residue alone can support more than 10 kW continuous electrical power generation in each of the 667 villages in the Sonitpur district. Further, 8 villages each are potential for more than 50 kW at individual village level, out of these 667 villages.

- The lifecycle GHG emission for decentralised electrical power generation are successfully modelled in spatial scale and becomes useful for assessment for the case of Sonitpur district. Two options of fuel *viz.*, (i) distributed surplus rice straw and (ii) centralised coal, are compared for GHG emission performance using the developed model.

- The model provides the GHG emission attribution from distinct phases of power generation *viz.*, (i) production of rice straw in the field, (ii) collection and transportation of rice straw and (iii) conversion as fuel in power plant. The highest share is attributed by the conversion phase of power generation while the lowest is attributed to the transportation of the residue from field to the plant.

- The practices of rice crop production and level of mechanisation influence the GHG emission while considering the rice residue as potential feedstock. About 6% increase in CO_2 equivalent GHG emission is resulted from the rice straw considered in mechanised methods of rice cultivation (1.53 kg of CO_2 equivalent kWh^{-1}) compared with the traditional method (bullock and animal powered) of rice cultivation (1.44 kg of CO_2 equivalent kWh^{-1}) .

- Substantial amount of emission reduction (about 47%) is possible in rice residue based decentralised power generation (even with the highly mechanised crop cultivation) compared with conventional coal based centralised power generation (2.12 kg of CO_2 equivalent kWh^{-1}).

6.4. Conclusions

- The spatial models (crop residue and GHG emission assessments) and outcomes of the present investigation would assist decision makers to plan decentralised crop residue based biomass power plant for power crisis driven rural India.

- Surplus rice straw residue is found as potential feedstock for decentralised power generation in Sonitpur district of Assam (India) from both abundance and GHG emission performance.

- The spatially distributed power generation potential from crop residue fuelled electricity along with potential GHG emission are assessed at district, development block and village level in Sonitpur district of Assam (India). However, for long term sustainability of the proposed decentralised biomass power generation in the district, other relevant issues such as (i) electricity demand assessment and (ii) agro-economic and social consideration pertaining to rice straw utilisation for power generation requires further investigation and therefore suggested for future work.

LIST OF PUBLICATIONS

1. Hiloidhari, M., & Baruah, D.C. GIS mapping of rice straw residue for bioenergy purpose in a rural area of Assam, India, *Biomass Bioenerg* **71**, 125--133, 2014.
2. Hiloidhari, M. et al. Bioenergy potential from crop residue biomass in India, *Renew Sustain Energ Rev* **32**, 504--512, 2014.
3. Sahu, B.K., et al. Global development in wind power with special focus on the top five countries, *Renew Sustain Energ Rev* **19**, 348--359, 2013.
4. Hiloidhari, M., et al. GIS based assessment of rice (*Oryza sativa*) straw biomass as an alternative fuel for tea (*Camellia sinensis* L.) drying in Sonitpur district of Assam, India, *Biomass Bioenerg* **44**, 160--167, 2012.
5. Hazarika, S., et al. Improving distribution efficiency of electrical network using geo-electrical options: a case study in a rural area of Assam (India), *Energy Efficiency* **5**, 519--530, 2012.
6. Hiloidhari, M., & Baruah, D.C. Crop residue biomass for decentralized electrical power generation in rural areas (part 1): Investigation of spatial availability, *Renew Sustain Energ Rev* **15**, 1885--1892, 2011.
7. Hiloidhari, M., & Baruah, D.C. Rice straw residue biomass potential for decentralized electricity generation: a GIS based study in Lakhimpur district of Assam, India, *Energ Sustain Dev* **15**, 214--222, 2011.
8. Baruah, D.C. & Hiloidhari, M. Adequacy of crop residue biomass as renewable energy for tea drying in Assam: A spatial assessment, *J Agric Engg* **46** (1), 43--50, 2009.