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A regional case study in India

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Sustainable utilization of biomass resources for decentralized energy generation and climate change mitigation: A regional case study in India

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ABSTRACT

Clean energy transition *via* utilizing biomass resources has been projected as an important climate change mitigation strategy. A vital characteristic of biomass is its localized nature; therefore, bioenergy utilization should follow decentralized planning. Agrarian countries like India can take benefit of its large agricultural biomass waste pool to produce clean renewable energy. However, prior knowledge of spatio-temporal distribution, competing uses, and biomass characteristics are necessary for successful bioenergy planning. This paper assesses biomass resource and its power generation potential at different agro-climatic zone levels in the state of Rajasthan, India considering crop residue biomass (25 different crop residues from 14 crops) and livestock manure (from cattle, buffalo, and poultry). Uncertainties associated with the availability of biomass and the power generation potential are assessed for each agro-climatic zone under different scenarios. Greenhouse gases (GHGs) emissions from biomass-based power generations are also estimated and compared with biomass-equivalent coal power plants. It is observed that the annual biomass power potential of Rajasthan is 3056 MW (2496 MW from crop residues and 560 MW from livestock manure). Scenario analysis suggests that the potential varies from 2445 to 6045 MW under different biomass availability and power plant operating conditions. Annual GHGs emissions due to biomass power generation is 5053 kt CO_2eq. Replacing coal-based power with biomass power would result in annual GHGs savings of 11412 kt CO_2eq. The paper also discusses various carriers and barriers *viz.* logistics, institutional, financial and technical in setting up decentralized bioenergy plants. Outcomes of the present study are expected to assist renewable energy planners in India.

1. Introduction

In order to realize the climate change mitigation goal of the Paris Agreement, the increase in global temperature has to be limited below 2 °C or in a more aggressive plan to 1.5 °C by the end of this century (UNFCCC, 2016). To achieve such goals, complete de-carbonizing the energy sector in less than 50 years and then achieving negative emissions in the latter part of the century is necessary, as indicated in many research findings, including the International Panel on Climate Change (IPCC) (Masson-Delmotte et al., 2018). Such ambitious climate and clean energy goals can be attained by growing the share of renewable energy to around 65% of the global energy supply by 2050 (IRENA, 2018). As of 2018, renewables contributed 13.8% to the global primary energy supply (WBA, 2020). Therefore, accelerated growth in the renewable energy sector is urgent.

Bioenergy is expected to contribute significantly to the global primary energy mix in 2050, among the different renewable energy options, both through electricity and biofuel/biodiesel routes. The biomass sector is of significant importance in diverse contexts as it can, directly and indirectly, impact several Sustainable Development Goals (SDGs), including the SDG 7 - affordable and clean energy, SDG 13 - climate action, SDG 15 - life on land, SDG 8 - decent work and economic growth, and SDG 5 - gender equality (Vijay et al., 2021a). There has been extensive research and development progress on different types of biomass to bioenergy conversion routes (commonly termed as 1st generation, 2nd generation, and 3rd generation biofuels) with mixed

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successes worldwide over the last two decades (Alalwan et al., 2019). Globally, around 637 TWh of electricity, equivalent to 2% of the world's electricity generation, comes from the modern bioenergy routes (Vijay et al., 2021b). The modern bioenergy route is defined as the conversion of biomass into energy using modern technologies such as combustion, gasification, and pyrolysis. Being rich in agricultural biomass, India has also taken several initiatives to harness biomass energy potential (Shrimali and Sen, 2020). The biomass program in India mainly focuses on agro-forestry and agro-industrial residue-based biofuels and power. Together with sugarcane bagasse cogeneration, the biomass power potential of India is 18 GW, and as of 2020, the country has installed nearly 10.2 GW of grid-based biomass power (~11% of the total installed renewable electricity capacity) (MNRE, 2021). In terms of installed biomass electricity capacity, the top five states are Maharashtra (2584 MW), Uttar Pradesh (2117 MW), Karnataka (1887 MW), Tamil Nadu (1012 MW), and Andhra Pradesh (484 MW) (MNRE, 2021).

Biomass is spatio-temporally distributed resource, and local climatic and geographical factors influence its type and availability. Physicochemical properties, residue production ratio, local competing uses (e.g., cooking/heating fuel, animal feed, application as soil organic fertilizer) also impact the net availability of biomass resources for bioenergy generation (Vijay et al., 2015). Prior knowledge of these influencing factors helps augment biomass during the lean feedstock supply period and optimize the supply-chain, reducing logistic cost (Ko et al., 2018). In India, crop residue biomass databases are available at the national level and have estimated the country's annual surplus biomass potential in the range of 150–234 MT, however, local state-level databases are only available for a few states (Hiloidhari et al., 2014; MNRE, 2021; Singh, 2017).

Some state-level biomass assessment studies have estimated the bioenergy (power) potential for the states of Punjab (1464–3172 MW), Haryana (1120 MW), and West Bengal (1197 MW) in India (Chauhan, 2012, 2010; Das and Jash, 2009; Singh et al., 2020; Singh, 2015). However, these studies have only considered the surplus crop residue biomass and not considered the livestock manure, which is a significant source of bioenergy. Moreover, they have not investigated the biomass power-related emissions to evaluate the GHG emission reduction potential at the local state level using surplus biomass. Analysis to understand the possible variations in biomass resource availability, range of biomass-based power potential, resultant emissions, and savings in emissions vis-à-vis fossil power is also lacking in most of the previous state-level studies. Since biomass is especially suitable for local, decentralized applications, region-specific, for example, at the state-level, a readily available database would help decision-makers prioritize investment and plan for long-term sustainability. Investigating such state-level systems can help generate greenhouse gases (GHGs) emission reduction inventory of bioenergy at a local scale. This can promote entrepreneurial activities driven by clean bioenergy and attract international funding through green climate fund (GCF), clean development mechanism (CDM), or other modes.

In view of the above discussion on environment protection as a major objective for switching to bioenergy and the lack of detailed state-level biomass inventories, the present paper discusses agro-climatic zone level biomass resource distribution, power generation potential, GHGs emission reduction potential for the state of Rajasthan, India. Altogether, 25 crop residues available from 14 different crops (Rice, Wheat, Maize, Bajra, Barley, Jowar, Mustard, Sesame, Soybean, Groundnut, Gaur, Gram, Sugarcane, and Cotton) and 3 livestock groups (cattle, buffalo, and poultry) are selected for the study. Rajasthan has been chosen for this study as, until now, it has primarily been considered only for wind and solar-based renewable energy generation. Rajasthan is a unique region with difficult soil conditions, scarce rainfall, under-developed irrigation facilities (over 75% of the cultivated area is rain-fed), and two-third of the state's area under arid/semi-arid climatic profile. Yet, with a diversified cropping pattern and livestock rearing as a significant livelihood source, it efficiently utilizes the water resources to manage the risks associated with dryland agriculture, also presenting the state with a considerable bioenergy potential. The following are the novelties that underpin this study: (i) comprehensive agro-climatic zone level biomass resource database (crop residues and livestock manure) for Rajasthan; and (ii) an assessment of the power generation capacity of various biomass resources, (iii) quantification of GHG emissions reduction utilizing biomass instead of coal as a resource (iv) sensitivity analysis for the considered biomass scenarios (v) Challenges and recommendations for higher adoption of bioenergy in Rajasthan, and a global outlook on the prospects and problems of bioenergy. This study can boost decentralized energy planning in Rajasthan by mapping spatial bioenergy, and GHG emissions profiles as India's current database lacks such a profile of Rajasthan at a local scale covering a wide range of feedstocks. Rajasthan largely has arid/semi-arid regions. Such areas globally represent 41% of the earth's land surface and supports more than 2.5 billion people (32% of the world population) (Gaur and Squires, 2017). Therefore, this work has global relevance as it can assist researchers, energy agencies, policymakers, and project developers to strengthen energy security and mitigate climate change in countries with a strong agricultural economy and significant arid/semi-arid landscapes.

2. Methods

2.1. Study area at a glance: Rajasthan

Rajasthan is India's largest state, with a geographical area of 34.22 Mha, accounting for 10.41% of the country's total geographical area (DES, 2021). It is administratively divided into 33 districts and has a population of 68.55 million, with 75% of the population residing in rural areas (DES, 2021). Rajasthan state's current installed electricity capacity is 21835 MW, dominated by a coal-based electricity share of 12782 MW. The state's per-capita electricity consumption is 1282 kWh, around one-third of the global average of about 3500 kWh (Ministry of Power, 2019). Amongst renewables, solar contributes the highest installed electricity capacity (5002 MW), followed by wind (4337 MW) (DES, 2021). The current installed capacity from biomass is only 121.3 MW against an estimated potential of 1140 MW (MNRE, 2021). This estimated potential by the Ministry of New and Renewable Energy (MNRE), Government of India, is more than two decades old and has not been re-evaluated or updated, justifying the need for the current work.

The agriculture and allied sector contribute 25.2% to Rajasthan's Gross State Domestic Product (GSDP), well above the national average of 14.6% (DES, 2020). Around 52% of the state's geographical area is under agriculture, with more than 60% population dependent on it for livelihood. Despite the agro-climatic adversities in Rajasthan, it ranks high in India for the production of mustard, bajra (pearl millet), guar (cluster bean), pulses, soybean, maize, and wheat crops (Swain et al., 2012). Due to rainfall scarcity, the share of power-driven tube-wells for irrigation is high. Agriculture accounts for 39.2% of Rajasthan's total electricity consumption, much higher than agriculture's share (20.98%) in India's electricity consumption (Swain et al., 2012). Moreover, due to the challenging geography, harsh agro-climatic conditions, and uncertain rain-fed agriculture, the significance of animal husbandry as an economic activity in Rajasthan has increased with a 13% contribution towards GSDP. Rajasthan has the second-highest livestock population (57.73 million), with 13.32 million cattle, 12.97 million buffaloes, and 8.02 million poultry accounting for 6.89% cattle, 11.94% buffaloes, and 81.31% camel population of the country (19th Livestock Census, 2014). Thus, tapping the crop residual and livestock manure biomass for energy generation in Rajasthan is essential for sustainable and eco-friendly economic growth.

2.2. Estimation of biomass resource availability and power generation capacity

All the 33 districts of Rajasthan have been assessed for crop production, considering the data of three years from 2014–15 to 2016–17 (DOA, 2018, 2017, 2016) to minimize the yearly fluctuation in crop production. In terms of agriculture, the state is divided into ten agro-climatic regions, each with two to five districts. The analysis in this study is based on the agro-climatic zone-wise distribution of districts (See supplementary file for details). Overall, 14 crops and their 25 residues have been considered for each zone. Factors such as crop residue ratio (CRR), lower heating value (LHV), surplus fraction, as given in Table 2, and biomass to energy conversion efficiency are considered while estimating biomass power potential. For crop residual biomass, combustion technology, which is the most matured and widely used bioenergy technology for biomass with moisture content less than 50% is selected (Malico et al., 2019). For livestock manure, three categories, namely, cattle, buffalo, and poultry, have been considered. For manure biomass, biogas production, and then biogas to power conversion through IC engine is considered for the analysis (Kapoor et al., 2020). Factors influencing manure-based power potential, for example, manure yield, collection efficiency, methane fraction, and heating value of methane, are collected from standard literature as presented in Table 2 and used for the present analysis. Table 1 explains the technique in depth. For each region, the biomass resource density (tonnes/km^2), biomass power density (kW/km^2), and per-capita capacity (kWh/capita) is assessed (See supplementary file for details). Furthermore, the data created by the various models was used to create geo-spatial distribution maps of biomass and power potential for each agro-climatic zone in Rajasthan using a Geographical Information System (GIS) environment. All the biomass related information is fed into the attribute table of the GIS maps for query, visualization, analysis and future update.

2.3. GHG emissions estimation from biomass and fossil-based electricity production

Land preparation, crop production, animal husbandry, biomass harvest, storage, and transport, as well as feedstock pre-processing, are all required to produce electricity from biomass resources. Increasing crop production also escalates the usage of nitrogenous fertilizers that further results in nitrous oxide (N_2O) emissions, which is a significant source of GHG (~300 times higher Global Warming Potential than CO_2) (Singh and Gu, 2010). All such activities require energy, machinery/mechanized inputs, and materials in different forms, leading to emissions. The environmental impact of various types of bioenergy (electricity, heat, transportation fuel) generation varies depending upon feedstock types, production process and conversion technology. GHG emissions and other environmental impacts (e.g., eutrophication, acidification, ecotoxicity) of bioenergy are much lower than the fossil alternatives, according to life cycle assessment (LCA) studies (Arteaga-Pérez et al., 2015). It is difficult to acquire accurate emission estimations due to a lack of region-specific inventory data. The IPCC has generated a database of life cycle GHGs emissions from bioenergy considering several feedstocks (e.g., crop residues, forest residues) (Iordan et al., 2016; Spath et al., 1999). As a result, the IPCC's life cycle emissions database is used to analyze GHG emissions from biomass-based power generation in the study area. Since the IPCC emission database is available in the CO_2eq unit, therefore other literature (Hiloidhari et al., 2019; Oreggioni et al., 2017) are also consulted to estimate individual GHGs-wise (CO_2, CH_4, N_2O) emissions (Table 3) as given below:

$$E(i) = \sum_{i=0}^{n} BP(j, i) \times Ef(i) \times 10^{-3}$$

Here, $E_{(i)}$ is total GHG emissions from biomass power in the *i*th

Table 1
Models for assessing the biomass resource and power potential.

Model	Parameters	Description
Crop Residue **Model 1** $CRBP = \sum_{i=1}^{n} CP(i) \times CRR(i)$ **Model 2** $SCRBP = \sum_{i=1}^{n} CP(i) \times CRR(i) \times SRF(i)$ **Model 3** $BMPP = \frac{\sum_{i=1}^{n} CP(i) \times CRR(i) \times SRF(i) \times LHV(i) \times \eta_{conv.}}{T \times 3.6}$	CRBP - Crop Residue Biomass Potential, tonnes; SCRBP -Surplus Crop Residue Biomass Potential, tonnes; BMPP - Biomass Power Potential, MW; CP(i) - Annual Crop Production, tonnes; CRR(i) - Crop Residue Ratio; SRF(i) - Surplus Residue Factor; LHV(i) - Lower Heating Value, MJ/ton; η_{conv}- Conversion efficiency; T - Annual operating duration of power plant, Hours; Here, i represents individual crop residue and all the estimations are done zone-wise.	*Model (1)* determines annual gross crop residual biomass potential for a given area. *Model (2)* estimates surplus crop residue biomass potential out of the total crop residual biomass, particularly available for energy production in a given area. It considers SRF for a given crop, i.e., amount of residue available for power generation, after accounting for competing uses (e.g., animal feed, fertilizer) (Hiloidhari et al., 2014). *Model (3)* is used to evaluate power generation potential from surplus biomass. It considers the LHV of each crop residue and the conversion efficiency of 25% (McKendry, 2002). The selection of appropriate technology is defined by the biomass availability, conversion efficiency and energy requirements of a region. *Note:* CRR, SRF, and LHV values for different crops are used from previous investigations, as shown in Table 2 (Hiloidhari et al., 2014). CP is collected from the

(*continued on next page*)

Table 1 (*continued*)

Model	Parameters	Description
		Department of Agriculture (DOA, 2018, 2017, 2016). The annual operating time of a biomass power plant is considered as 6570 h.
Livestock Manure **Model 4** $BGP = \frac{\sum_{i=1}^{n} P(i) \times Y(i) \times \eta_{coll.}(i)}{A(i)}$ **Model 5** $BGPP = \frac{\sum_{i=1}^{n} P(i) \times Y(i) \times \eta_{coll.}(i) \times M \times LHV \times \eta_{conv.}}{T \times 3.6 \times A(i) \times 1000}$	BGP - Annual Biogas Generation Potential from manure, m^3; BGPP - Annual Biogas Power Potential, MW; *P(i)* - Livestock population; Y(i) - Manure yield, kg/animal/year; $\eta_{coll.}$ *(i)* - Manure collection efficiency; M - Methane (CH_4) content in biogas; LHV - Lower Heating Value of CH_4, MJ/m^3; $\eta_{conv.}$ - Conversion efficiency; T - Annual operating duration of power plant, Hours; A(i) - Amount of manure required per m^3 of biogas production, kg; Here, i represents the livestock category, and all estimations are done zone-wise.	*Model (4)* estimates biogas generation potential from livestock manure in a given area. District livestock population (cattle, buffalo, and poultry) data is collected from the Livestock Census of India and classified into agro-climatic zones as specified ("19th Livestock Census," 2014). Per day manure yield per animal is taken as 10 kg/d, 15 kg/d, and 0.18 kg/d for cattle, buffalo, and poultry, respectively (Harsdorff, 2014). Manure collection efficiency for energy purposes has been taken as 50% for cattle and buffalo and 75% for poultry (Rahman and Paatero, 2012). The average manure required for each livestock category to produce 1 m^3 of biogas is 25 kg for cattle/buffalo and 5 kg for poultry (Sharma and Samar, 2016). *Model (5)* determines biogas power potential from the collectible manure biomass in a given zone. Methane content in biogas, LHV of methane, and net conversion efficiency (biofuel to power) are taken as 0.6, 35.78 MJ/m^3, and 25%, respectively (Brahma et al., 2016). *Note:* Annual operating time of biogas-based power plant is considered as 6570 h.

region, kg/yr; $BP_{(j,i)}$ is power generation from a specific type of feedstock (*j*) in *i*th region, kWh/yr; *Ef* is emission factor, g/kWh.

The biomass power (BP) potential is estimated according to the equations given in Table 1. All the three major GHGs *viz.* CO_2, CH_4, and N_2O are considered for analysis, and their individual emission factors (Ef) are given in Table 3 (Hiloidhari et al., 2019; Iordan et al., 2016; Oreggioni et al., 2017; Spath et al., 1999). The GHGs emissions from biomass-based power are also compared with equivalent coal-based power emissions using the factors presented in Table 3 (Spath et al., 1999).

2.4. Sensitivity analysis

Net biomass availability of a region and type can significantly impact the power generation potential. Differences in the calorific value of different biomass residues can also affect the results. It is difficult to individually evaluate the effect of each parameter. Two crucial factors affecting the final power generation potential are net biomass availability and the conversion efficiency of the power plant. Literature suggests that biomass power plants' net conversion efficiency may vary from 20 to 40% (Kumar et al., 2015).

A sensitivity analysis was performed in the present study to determine the variance in outcomes, using three scenarios (standard, low, and high biomass availability) with nine possible cases considering different conversion efficiencies, as shown in Table 4.

3. Results and discussion

The availability of gross and surplus biomass (crop residues and livestock manure) in all of Rajasthan's 10 agro-climatic areas, and their power generation capacity and associated potential GHG emissions, are addressed.

3.1. Distribution of biomass resources and their availability

Annual biomass potential (crop residues on a dry basis and livestock manure on a wet basis) in Rajasthan is estimated to be 149.81 mt with 120.2 mt contributions from livestock manure and 29.6 mt crop residues. Since it serves multiple utilization options, such as animal feed, animal bedding, thatching, domestic fuel, and fertilizer, the total residual biomass generated cannot be used entirely for energy production (Hiloidhari et al., 2014). Surplus biomass availability for energy generation is also driven by the threshing and harvesting practices (manual and mechanized) followed in the region apart from the competing uses

Table 2
Characteristics of the selected crops and crop calendar.

Crop Category	Surplus residue factor (SRF)	Crop Name	Type of Residue	Crop residue ratio (CRR) (kg/kg)	LHV (MJ/kg)	Crop Sowing Period	Crop Harvest Period
Cereals	0.29	Rice	Straw	1.5	15.54	Jun–Jul	Oct–Nov
			Husk	0.2	15.54		
		Wheat	Stalk	1.5	17.15	Nov–Dec	Mar–May
			Pod	0.3	17.39		
		Maize	Cob	0.3	17.39	Jun–Jul	Oct–Nov
			Stalk	2	16.67		
		Bajra	Cob	0.33	17.39	Jun–Jul	Sep–Oct
			Husk	0.3	17.48		
			Stalk	2	18.16		
		Barley	Straw	1.3	18.16	Nov–Dec	Mar–May
		Jowar	Cob	0.5	17.39	Jun–Jul	Oct–Nov
			Husk	0.2	17.48		
			Stalk	1.7	18.16		
Oilseeds	0.18	Mustard	Stalk	1.8	17	Sep–Oct	Feb–Mar
		Sesame	Stalk	1.2	14.35	Jun–Jul	Oct–Nov
		Soybean	Stalk	1.7	16.99	Jun–Jul	Sep–Oct
		Groundnut	Shell	0.3	15.56	Jun–Jul	Oct–Nov
			Stalk	2	14.4		
Pulses	0.23	Gaur	Stalk	2	16.02	Jul–Aug	Oct–Nov
		Gram	Stalk	1.1	16.02	Aug–Dec	Mar–Apr
Sugarcane	0.4	Sugarcane	Bagasse	0.33	20	Mar–Apr	Dec–Mar
			Top and leaves	0.05	20		
Cotton	0.1	Cotton	Stalk	3.8	17.4	Apr–May	Nov–Dec
			Husk	1.1	16.7		
			Boll Shell	1.1	18.3		

Table 3
GHG emissions factors for biomass and coal-based power generation.

Source	CO_2 (g/kWh)	CH_4 (g/kWh)	N_2O (g/kWh)
Animal Manure	86.00	4.35	0.380
Crop Biomass	224.94	0.047	0.012
Coal	803.76	0.44	0.0037
Global Warming Potential (GWP)	1	34	298

Table 4
Different scenarios for sensitivity analysis.

Selected cases	Surplus residue factor (SRF) for crops, %	Manure collection efficiency ($\eta_{coll.}$), %	Conversion efficiency, %
Std1.20%	Crop category wise (10–40)[a]	50,50,75	20
Base Case	Crop category wise (10–40)[a]	50,50,75	25
Std1.30%	Crop category wise (10–40)[a]	50,50,75	30
L1.20%	25	25, 25, 50	20
L2.25%	25	25, 25, 50	25
L3.30%	25	25, 25, 50	30
H1.20%	50	50, 50, 75	20
H2.25%	50	50, 50, 75	25
H3.30%	50	50, 50, 75	30

[a] as given in Table 2.

(Trivedi et al., 2017). Similarly, all the manure produced by livestock is difficult to collect and use. Manure produced during grazing, agricultural operations and rural transport cannot be collected. Hence, manure's collection feasibility is higher when stall-fed or particularly reared for milk production. In general, with higher competitive uses of biomass residues, their availability for energy generation decreases. Considering all these factors, surplus biomass potential for energy generation in Rajasthan has been estimated to be 75.48 mt. Zone-wise variation in the total biomass potential and the surplus biomass available is shown in Fig. 1 (See supplementary file for detail). The contribution of the livestock manure towards surplus biomass potential is 60.23 mt, and crop residues are 15.25 mt. It is crucial to understand that the moisture content of livestock manure is much higher (80%) on a wet weight basis, which is the primary explanation for its higher surplus quantity than crop residues. Zone-wise variation in surplus crop residue biomass is 690–2652 kt (kilo tonne), and for collectible livestock manure, it is 3895–9547 kt. It is observed that Bharatpur zone has the maximum surplus biomass potential for both crop residues and livestock manure, and Jalore zone has the minimum surplus crop residues. In contrast, Ganganagar zone has the minimum surplus collectible livestock manure. Udaipur zone with a hilly terrain is a special case with high livestock population and lower agricultural production, resulting in 50% of its power potential from livestock manure alone.

Among the surplus crop residues, wheat (5.45 mt) has the largest contribution, followed by bajra (3.80 mt), maize (1.15 mt), and mustard (1.1 mt). Details of crop-wise surplus residue contribution are given in the supplementary file. These crops require comparatively less water to grow, and the production results are in line with Rajasthan's agro-climatic zones arid/semi-arid characteristics. Crops contributing minimum to surplus crop residues are Sugarcane (0.061 mt) and Rice (0.14 mt), which are water-intensive crops and grow mainly in humid and well-irrigated agro-climatic zones of Rajasthan. Similar to spatial variations (Fig. 1), temporal variations also exist in the crop residues that need to be considered to better assess the current biomass demand-supply scenario of a zone for enhancing the output of a biomass power plant. Table 2 shows the crop calendar of the selected crops in Rajasthan ("Crop Calender," 2011).

3.2. *Power generation potential from biomass*

The annual primary energy potential of Rajasthan from surplus biomass 443 PJ, i.e., 1.8% of India's primary energy consumption (24,800 PJ) in 2013 (Hiloidhari et al., 2019). The power potential of biomass (from crops and manure) depends on the selection of energy conversion technologies. Biomass is converted to energy usually *via* two main technological routes *viz.*, thermo-chemical and bio-chemical. For power generation from biomass, many conversion technologies have been successfully demonstrated, including combustion, pyrolysis, gasification, and biomethanation (Kumar et al., 2015). Direct combustion for steam production is a matured and widely used technology suitable

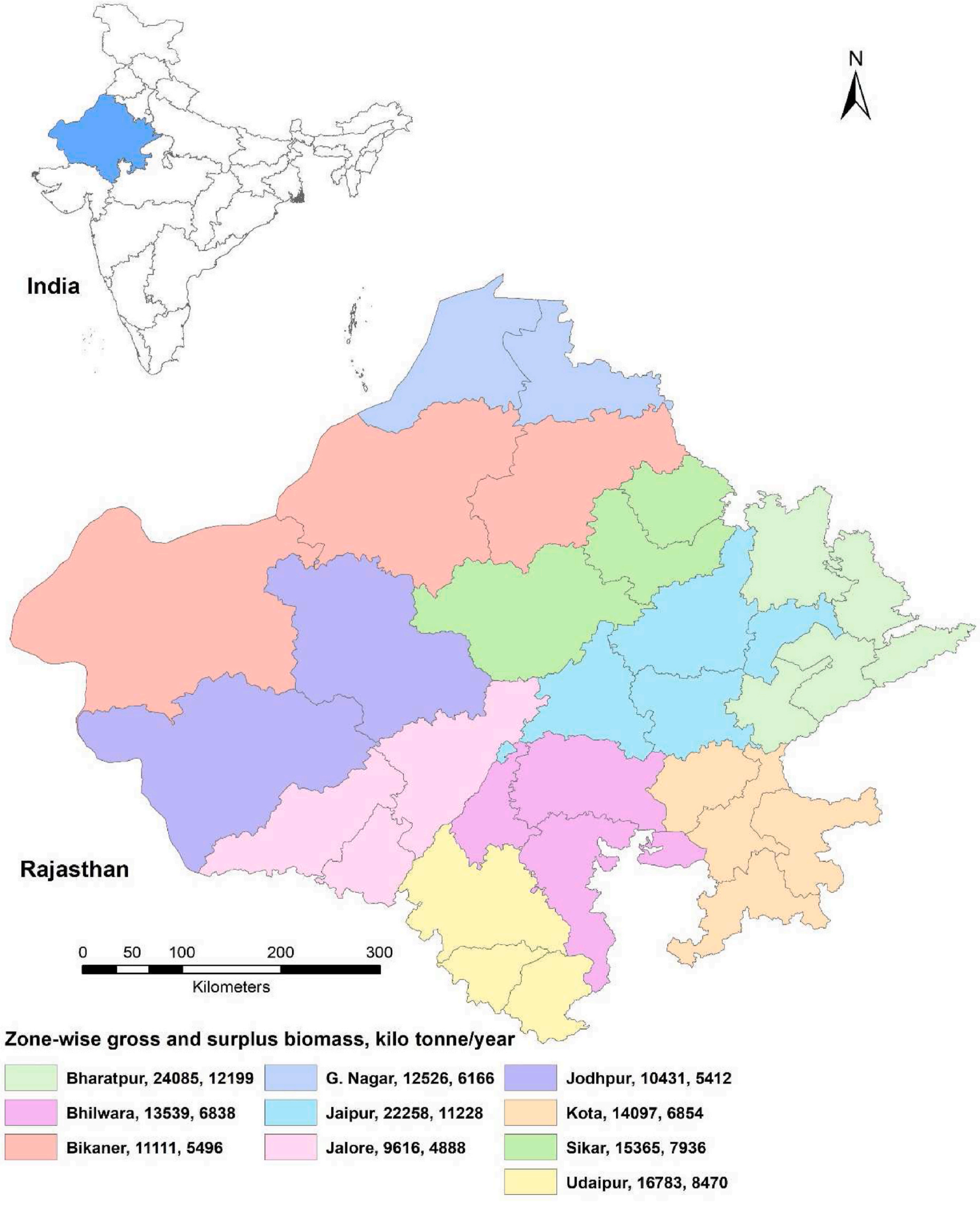

Fig. 1. Zone-wise annual gross and surplus biomass resource potential of Rajasthan, India.

for loose biomass, having a net conversion efficiency of 20–40% (Demirbaş, 2001; McKendry, 2002; Singh, 2016).

Rajasthan's gross estimated biomass power potential is estimated to be 3056 MW (base case using the methodology and biomass characteristics presented in Tables 1 and 2), which is roughly 14% of the state's current installed electricity capacity (21835 MW). The share of surplus crop residues and livestock manure in the gross estimated power potential is 2496 MW and 560 MW. Zone-wise variation in biomass power potential is presented in Fig. 2, and it ranges from a minimum of 153 MW for Jalore to a maximum of 527 MW for Bharatpur zone. Zone-wise share of surplus crop and surplus manure towards biomass power potential is shown in the supplementary file. The share of crop residues towards power potential is estimated to be 2496 MW. Among the crops, wheat (891 MW), bajra (650 MW), and maize (183 MW) together contribute 70% of the power from crop residual biomass, whereas the share of rice (20.7 MW), sugarcane (9.05 MW) and sesame (4.1 MW) is less than 2%, in accordance with their biomass availability. Biomass power potential from livestock manure is 560 MW, with a zone-wise variation of 35.7 MW for Ganganagar (Minimum) to 89.8 MW for Jaipur zone (Maximum). Current biomass-based power installation of 121

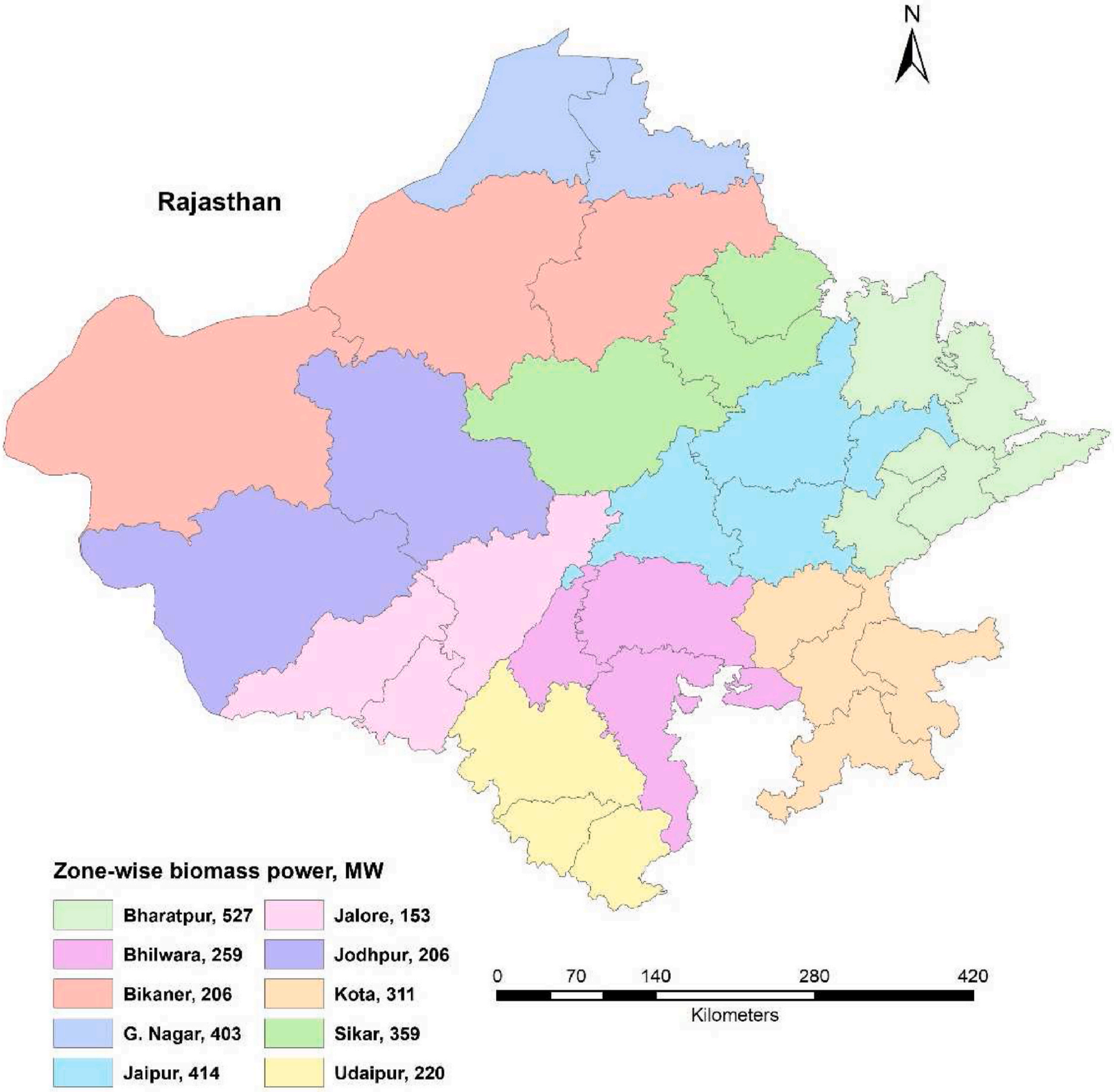

Fig. 2. Zone-wise annual biomass power potential in Rajasthan, India.

MW leaves significant biomass potential (>95%) left to be harvested in the state. Decentralized biomass power production can also help reduce the significantly high aggregate technical and commercial losses of 27.78% in the state (UDAY, 2021).

The current estimate of Rajasthan's biomass power capacity varies from the 1140 MW estimate made by IISc for MNRE in the Biomass Resource Atlas of India (BRAI) report ("BRAI," 2004). The differences could not be verified, but it is to be noted that the BRAI estimates are a decade old (for 2000–2004). Moreover, the atlas estimates do not consider the biomass power potential from livestock manure.

Further, as an alternative to electricity, the biogas from livestock manure can also be used as a cooking fuel (Vijay et al., 2020b). The livestock manure-based biogas potential for cooking has been estimated in terms of LPG cylinder replacement potential. Zone-wise LPG Cylinder replacement potential for cooking energy from livestock manure biogas is presented in a supplementary file. The calorific values of biogas was taken 19.71 MJ/kg and for LPG as 45.2 MJ/kg, making one cum biogas equivalent to 0.43 kg of LPG ("Calorific Value," n.d.; Rahman and Paatero, 2012). A non-commercial LPG cylinder in India can carry 14.2 kg LPG. The biogas potential in Rajasthan is calculated to be 2474 million m^3. Using the determined conversion factor, it is estimated that there is a potential of replacing 74.87 million LPG cylinders (10632 kt LPG) in Rajasthan. Similar to electricity potential, Jaipur zone (12 million cylinders) has the highest LPG cylinder replacement potential from biogas, followed by Bharatpur (11.7 million) and Udaipur (9.4 million) zones due to higher availability of manure in these areas and Jodhpur (5.4 million), Jalore (5.1 million) and Ganganagar (4.8 million) zones have the least potential for using biogas as cooking fuel.

Thus, the outcomes suggest that the livestock manure used for cooking applications or composting should be anaerobically digested for biogas production. This will help save energy wastage as the useful energy obtained from AD is comparatively higher. Further, the digestate produced as a by-product in AD is nutrient-rich organic manure that can improve soil fertility and crop yield (Vijay et al., 2020a).

3.3. *Biomass resource and power densities and per capita availability*

The zone-wise data for population and geographical area were collected from the Indian Census statistics (Census of India, 2011). The biomass distribution of the zones, as shown in Fig. 3 indicate that the

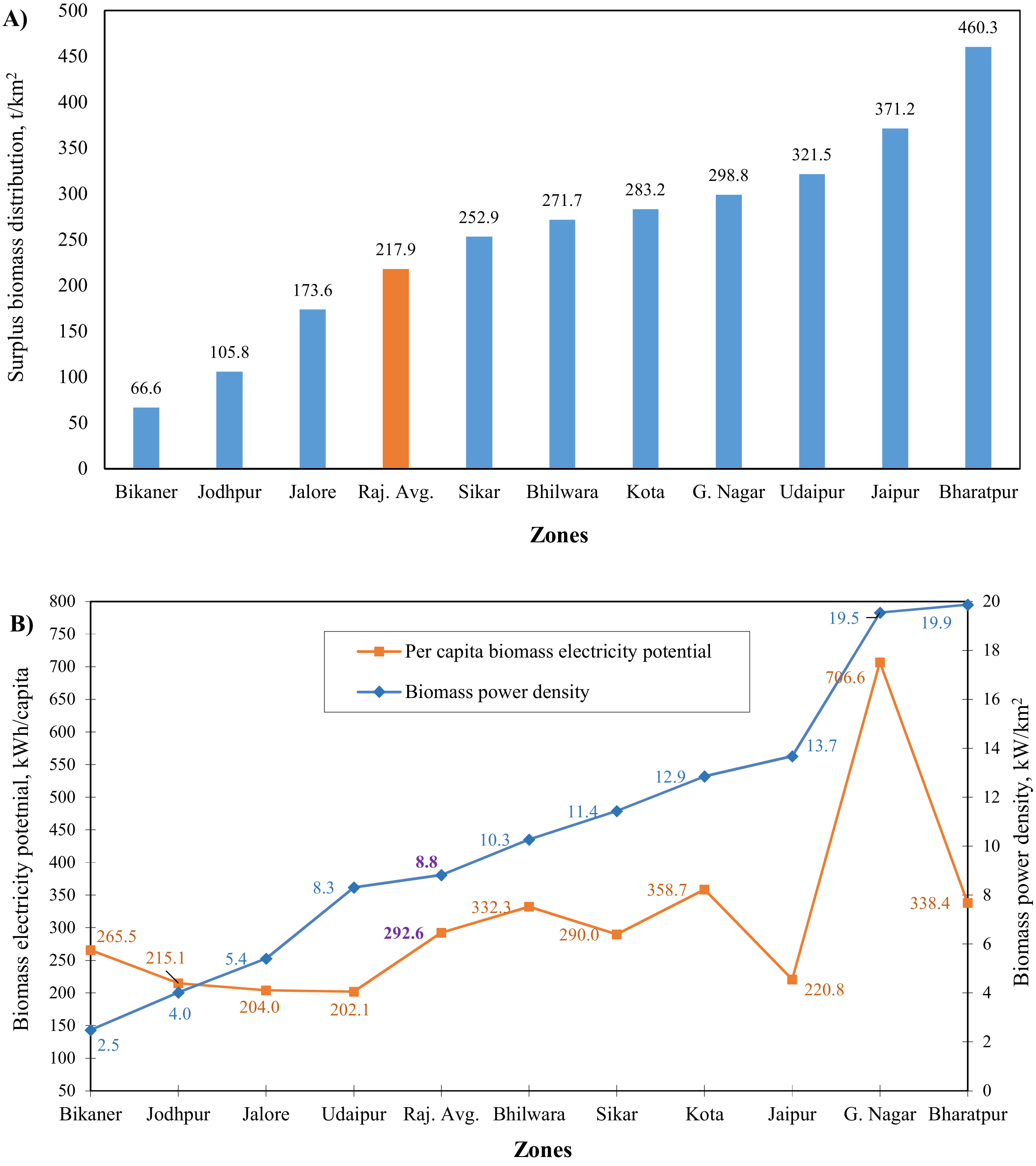

Fig. 3. (A)Zone-wise surplus biomass distribution (t/km^2). (B). Zone-wise per-capita biomass electricity potential (kWh/capita) and biomass power density (kW/km^2).

values range from 66.58 t/km^2 for Bikaner zone (having largest area and lesser agricultural production being a hyper arid partially irrigated zone) to 460.31 t/km^2 for the agriculturally rich Bharatpur zone (belonging to flood-prone eastern plain with good availability of groundwater and irrigation facilities). Accordingly, the electricity potential per unit area is found to be highest for the Bharatpur zone (19.87 kW/km^2) followed by the Ganganagar zone (19.54 kw/km^2) and the lowest for the Bikaner zone (2.49 kW/km^2). The electricity potential per capita is found to be highest for the Ganganagar zone (706.6 kWh/capita) belonging to irrigated northwestern plains on account of its small area, low population, and high agricultural production. Electricity potential is lowest for the Udaipur zone (202.11 kWh) on account of its small area, low agricultural production, and high population. The average surplus biomass distribution and biomass-based electricity potential (per unit area, per capita) for the state of Rajasthan are found to be 217.95 t/km^2, 292.59 kWh/capita and 8.82 kW/km^2, respectively.

These metrics illustrate the essence of biomass resources (feedstocks for bioenergy) distribution over a geographical area. The cost, location, infrastructure, and land requirements for establishing a bioenergy plant can be determined by comparing biomass distribution and energy per unit area and capita across different zones. These studies are essential in making market development recommendations that will expand the use of bioenergy as a substitute or alternative to fossil fuels.

3.4. GHG emissions from biomass resource-based power generation

Fig. 4 depicts zone-by-zone variance in GHG emissions from biomass resource-based power (in terms of CO_2eq and individual GHGs). It is estimated that generating power from biomass will annually lead to CO_2 (4005 kt), CH_4 (16.80 kt), and N_2O (1.60 kt) emissions. CO_{2eq} emissions are calculated by aggregating the CO_2, $CH_{4,}$ and N_2O emissions after accounting for their GWP values. Since the GWP of CH_4 and N_2O is significantly higher than that of CO_2, the gross CO_2eq emissions from biomass power were found to be 5053 kt. It is observed that the share of CO_2, CH_4, and N_2O in the CO_2eq emissions are 79.26%, 11.30%, and 9.42%, respectively. It is important to note that emissions from crop residue-based power account for 74.67 percent of total CO_2eq emissions, while emissions from manure-based power account for 25.32 percent. It is observed that CO_2eq emissions for crop-based power are minimum for the Jalore zone and maximum for the Bharatpur zone. Similarly, the

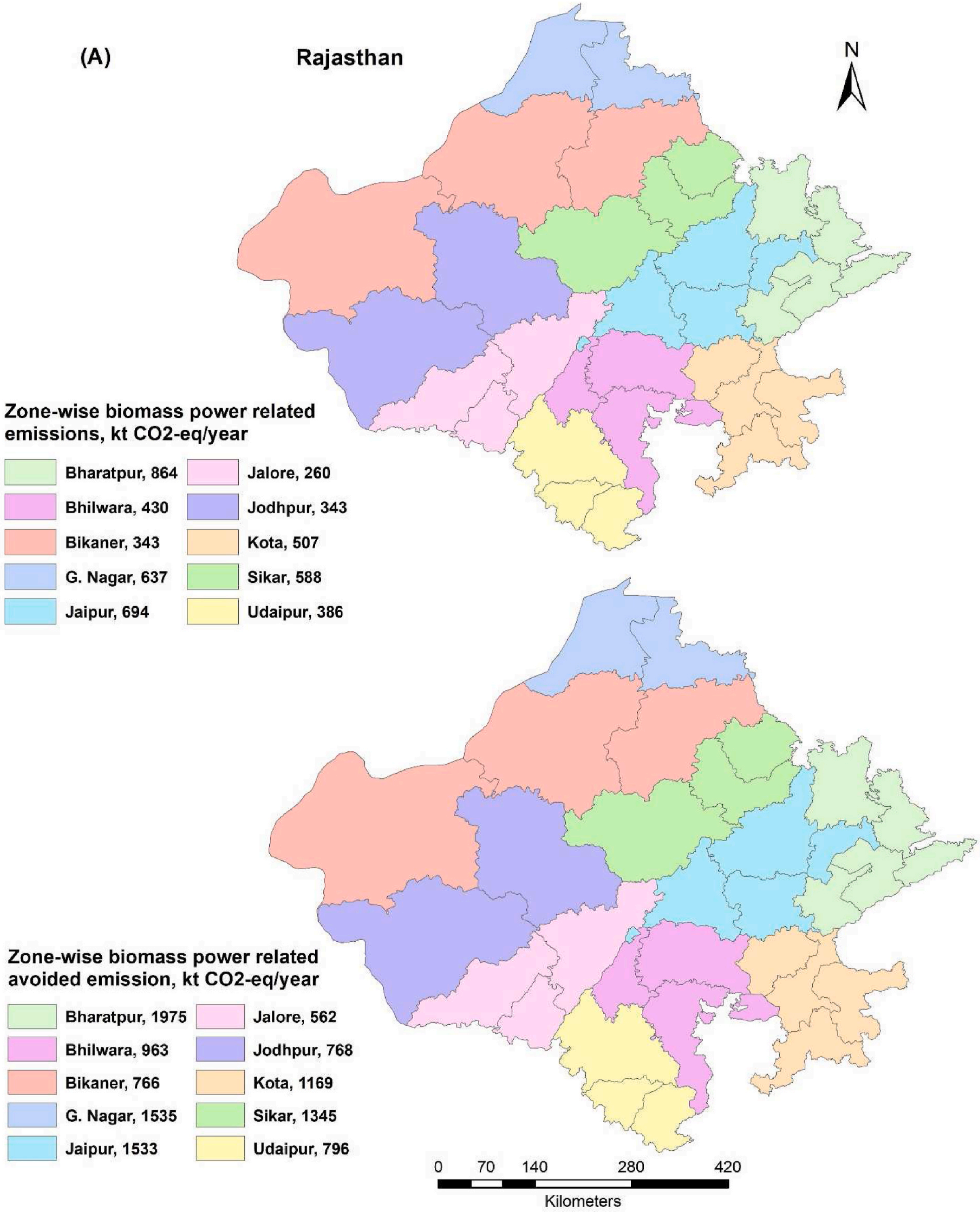

Fig. 4. (A)CO_2eq GHG emissions from total biomass (crop and manure) dependent power generation in Rajasthan, as well as emissions avoided/saved by replacing coal with biomass. **(B).** Zone-wise emissions (CO_2, CH_4, and N_2O) from total biomass (crop and manure).

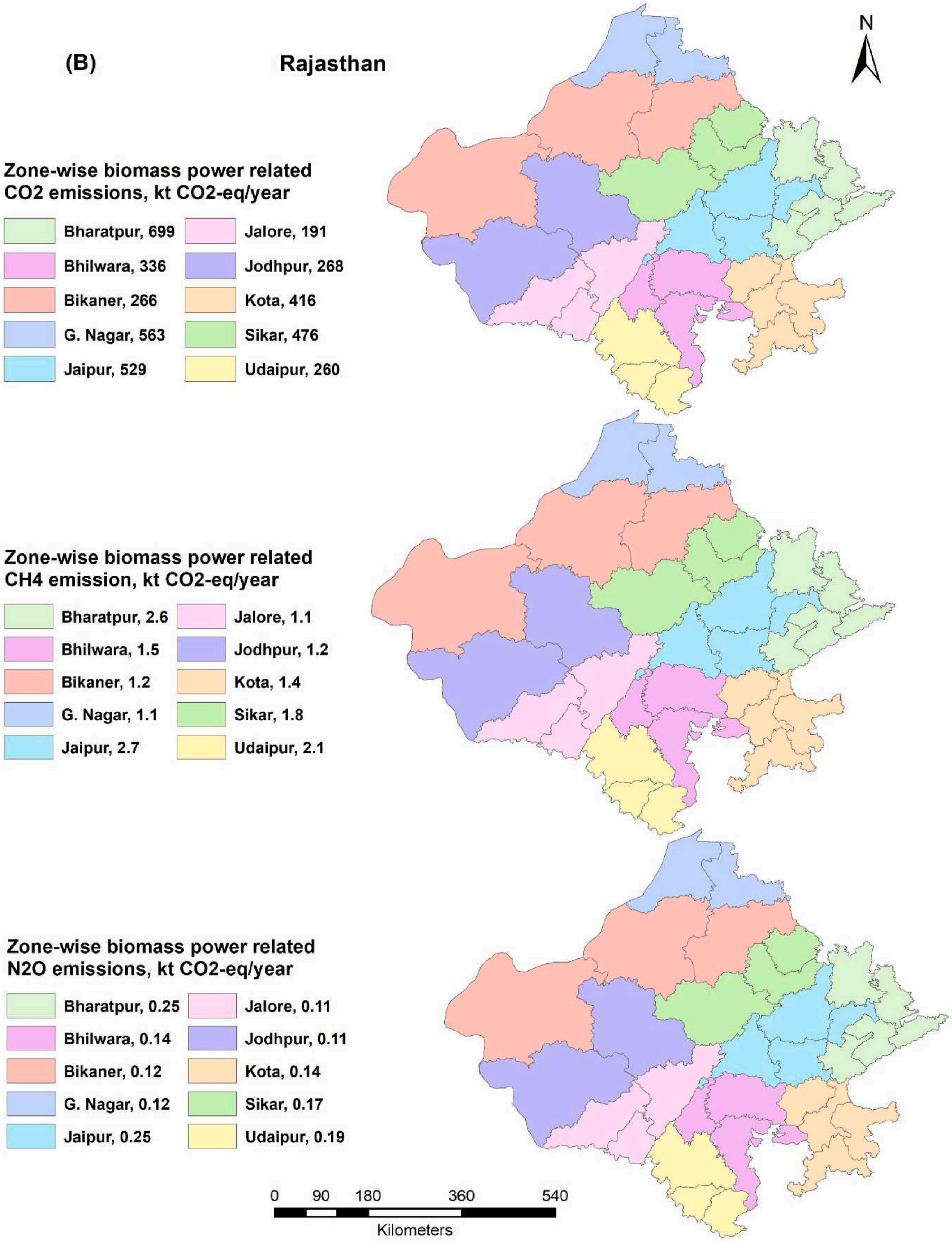

Fig. 4. (*continued*).

CO_2eq emissions for livestock manure-based power are minimum for the Ganganagar zone and maximum for the Jaipur zone.

A comparison of emissions has been made between biomass power and power from coal. It is estimated that when coal is used to generate power equivalent to the biomass power potential in the state (i.e. 3056 MW), then annually, 16465 kt CO_2eq emissions are generated. Thus, by utilizing biomass for power generation in the state, more than 69 percent of GHG emissions (11412 kt CO_2eq) can be preserved or avoided. Moreover, using biomass will also reduce particulate matter emissions due to open-field burning of the crop residues (Bhatt et al., 2016).

3.5. *Sensitivity analysis*

The potential for biomass power generation and subsequent emissions will differ greatly depending on the availability of biomass resources, their characteristics, and energy conversion mechanisms. As a result, a sensitivity analysis is performed using these input parameters, and the results are analyzed below:

3.5.1. *Variance in the availability of biomass resources for the considered scenarios*

The current study considers three different biomass availability scenarios with three different conversion efficiencies, as shown in Table 4. According to Fig. 5, the excess biomass (crop residues and manure) capacity ranges from 45.95 mt for low biomass availability to 121.76 mt for high biomass availability. Surplus crop residues are found to be in the range of 15.25 mt–31.52 mt, and the available livestock manure can range from 30.18 mt to 90.23 mt.

3.5.2. *Variance in efficiency of biomass to power conversion for the considered scenarios*

Table 4 shows the biomass power capacity of crop residues and livestock manure using three conservative conversion efficiencies ranging from 20 to 30%. It is observed from Fig. 5 that the biomass power production potential will significantly vary for the different considered scenarios, and it will increase with the rise in surplus biomass availability and also by adopting more efficient technologies for biomass conversion. The assessed total power potential from crop residues and livestock manure varies from 2285 MW (low biomass collection and low

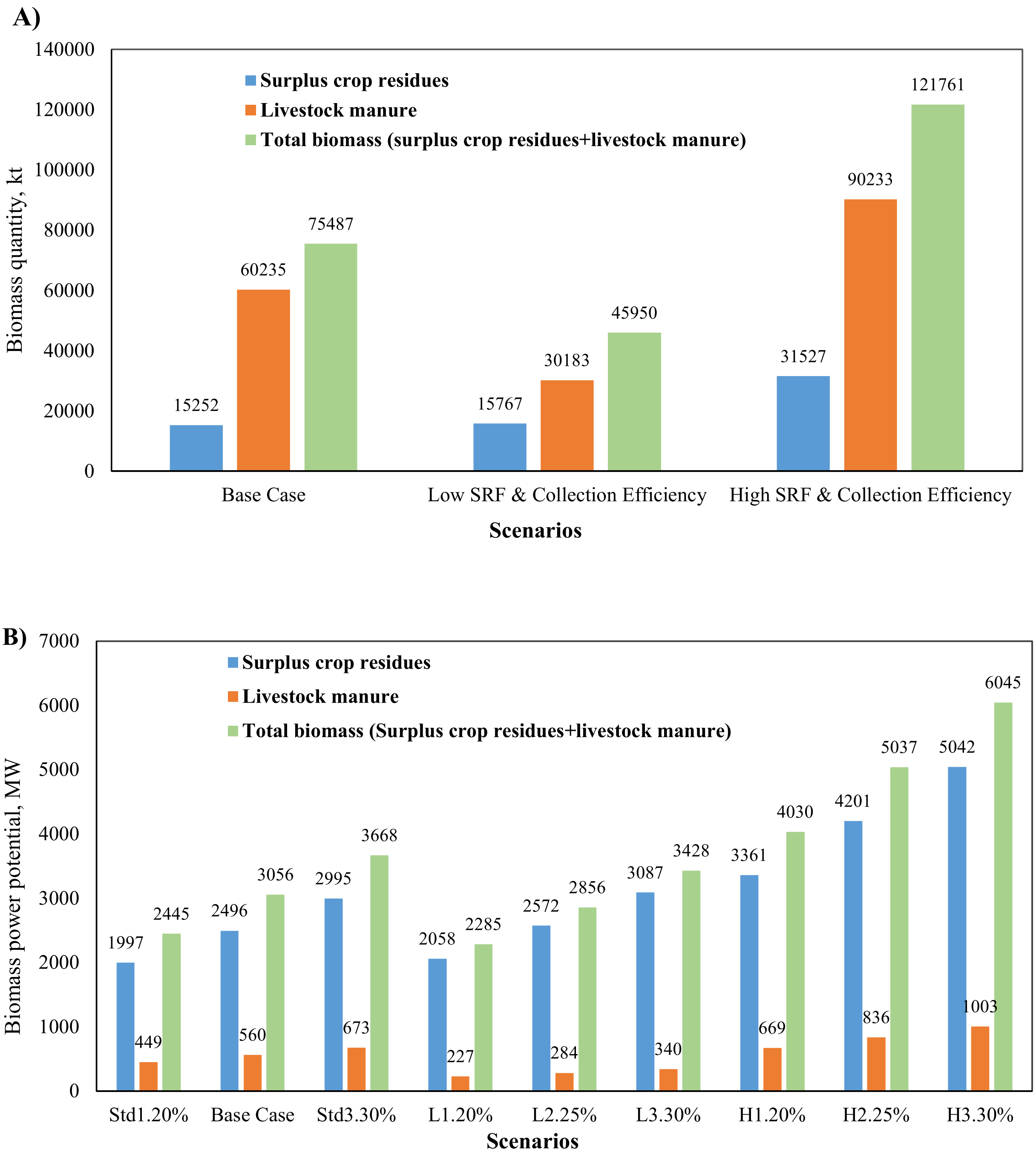

Fig. 5. (A). Annual surplus biomass availability, and **(B).** The biomass power potential for the different scenarios considered in Rajasthan.

efficiency of conversion case) to 6045 MW (high biomass collection and high efficiency of conversion case). The maximum biomass power potential (6045 MW) as obtained from the analysis is 49.44% greater than the base case (3056 MW), and if it can be realized then its share in the installed electricity capacity of Rajasthan would be more than 30%. It is found that the crop residues-based power potential ranges from 1997 MW to 5042 MW. Similarly, the livestock manure-based power potential ranges from 227 MW to 1003 MW for the considered cases.

3.5.3. *Variance in GHG emissions for the considered scenarios*

The amount of GHGs emissions is the direct result of the amount of power generation. Feedstock properties, conversion routes, and their efficiency impacts the emissions intensity. In the case of biomass, most of the emissions are associated with crop cultivation activities (irrigation, fertilizer, and agro-chemical applications). In fact, nitrogen fertilizer application is a major drawback of biomass fuel, and associated N_2O emissions can negate the emissions saving benefits of biomass (Crutzen et al., 2008) The emissions during biomass conversion phase, on the other hand, can be considered carbon-neutral, if the feedstock is obtained from annual energy crops or agricultural crop residues. Thus, most of the biomass energy emissions are linked to the crop cultivation phase, while in the coal-based power, highest share of emissions is from the combustion phase.

Emissions from biomass power plants can differ considerably as their share of overall power output rises due to the different biomass supply and power capacity for the scenarios considered. According to the current study, total CO_2eq emissions for biomass power will range from 3.6 mt (Case: low biomass collection and low conversion efficiency - L1.20%) to 9.9 mt (Case: high biomass collection and high conversion efficiency - H3.30%), as shown in Fig. 6. Under the scenarios considered, 8.7 mt–22.7 mt CO_2eq emissions can be prevented by using biomass in place of coal for power generation.

To increase biomass availability for higher power generation and thus reduce GHG emissions, it is important to recognize the barriers to bioenergy penetration and, as a result, work on supporting technologies and policies, as discussed below.

3.6. *Challenges and recommendations for efficient implementation of bioenergy technologies*

3.6.1. *Biomass availability, logistics, and treatment*

The availability of crop residues is seasonal as different crop residues are available in different seasons and in different quantities, depending on the cropping pattern, harvesting practices, and competing biomass uses in a region (Hiloidhari et al., 2014). Surplus residues are sometimes thrown away or left for open composting which results in poor quality compost due to slow and partial degradation or even burnt in many areas to save farmers time, labour and money (Gupta et al., 2004). The livestock manure is available every day, however, the collectible manure may vary during rainfall and grazing period, as the collection becomes challenging. These factors lead to wide variability in biomass availability. It can be increased by farming of energy crops such as Bamboo, Napier grass, etc. on wastelands. Annual updating of variation in biomass availability and spatial factors such as CRR, SRF, and LHV in government statistics using the recent geospatial technologies should be conducted to optimize biomass management planning energy production. Spatial variations in these factors could not be accounted in this study, which is a limitation of this study.

Logistics operations of biomass (collection, handling, storage and transport) and associated costs are among the biggest challenges faced in implementing bioenergy programs (Liu et al., 2016). The collection of biomass needs to be interlinked with harvesting processes and favorable mechanisms for incentivizing the farmers should be developed so that they avoid burning residues and offer it for energy generation. Further, the energy generation sites need to be established in proximity to the site where biomass is generated to minimalize the transport cost, which constitutes major share of the supply chain. The low density of crop residues poses further logistics problems. Biomass densification can help improve logistics. Development of storage systems that can store the biomass residues without any quality degradation is required since the

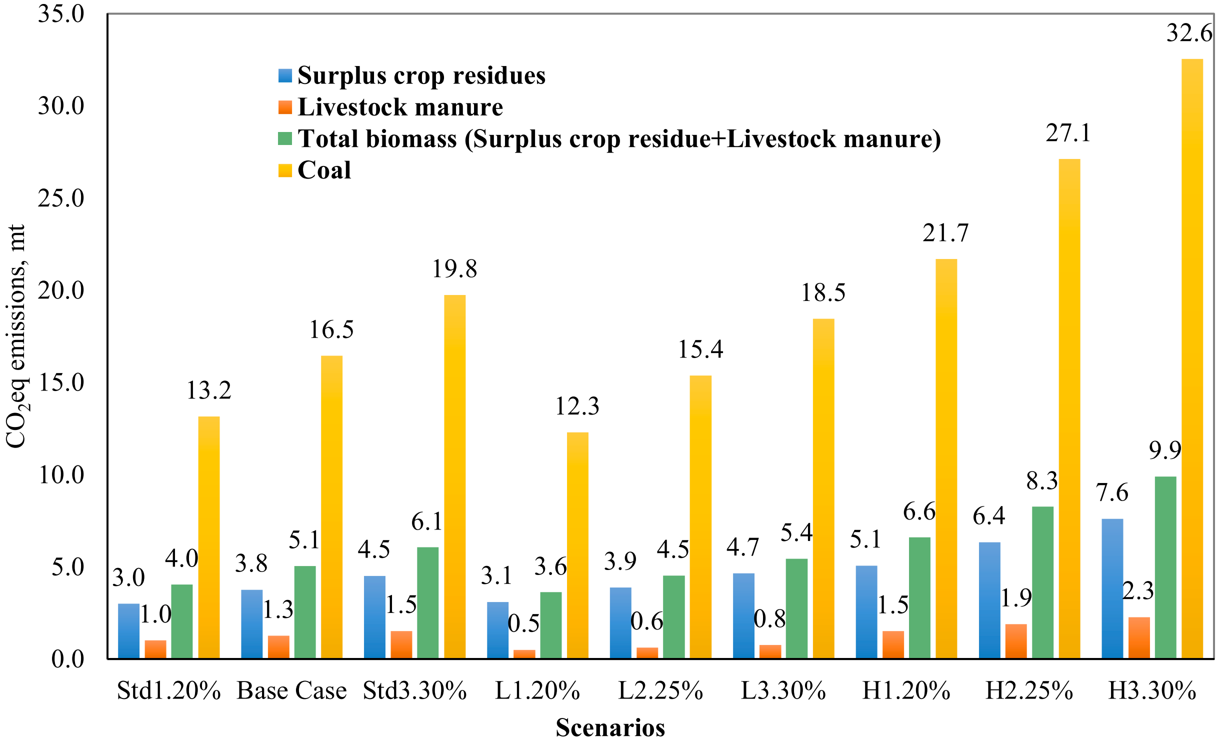

Fig. 6. GHG emissions from biomass power generation and its comparison with coal under different scenarios in Rajasthan, India. (CO_2eq emission is the sum of CH_4, CO_2, and N_2O emissions after accounting for their GWP values).

harvest period extends for 2–3 months, however, biomass is needed every day for continuous operation of a power plant.

Biomass cannot always be used as collected for bioenergy generation because its conversion depends upon factors like calorific value, moisture, and ash content. Pre-treatment is thus required for some residues to improve their utilization prospects depending upon the conversion technology. Selection of technology will depend upon biomass availability, fuel characteristics, plant size, and the end-use of energy (heating, lighting, or motive power).

3.6.2. Technical competence

The skills and know-how needed for local manufacturing, operation, and maintenance of bioenergy technologies are limited (Ravindranath and Balachandra, 2009). Facilities providing bioenergy schemes-related information to the citizens are not developed (Luthra et al., 2015). Prospective project implementers should be regularly trained for new and relevant biomass conversion technologies. More efficient technologies based on the desired end-use, and available manpower for their operational sustenance can then be appropriately adopted for an area and operated with the biomass resources available locally to minimalize the energy production costs (Kumar et al., 2009). Infrastructure and channels for repair, maintenance and operational support needed for continuous technology functioning should be developed to ensure the sustainability of the project.

3.6.3. Policies, regulations and government support

There are government schemes/policies supporting the enhancement of biomass-based energy access for several applications, including electricity, transportation, clean cooking. However, the policies related to electricity largely focus on increasing the grid connectivity overlooking the enhancement of decentralized electricity supply. Policy focus on expansion of cooking energy availability through biomass has been less in comparison to electricity. Success of a scheme is measured by the numbers deployed against the target in many schemes and not their sustainability, that is a key reason for ineffectual policy outcomes (Balachandra, 2011a). Despite many policies, access to reliable electricity and availability of modern cooking fuels have not seen greater penetration in rural areas (Richmond et al., 2020). Utilization is lower for the lowest income groups, which are the prime beneficiary targets of such schemes, signifying a strong relationship between income and energy poverty (Balachandra, 2011a). To address the problems in the bioenergy sector, a pre-evaluation of surplus biomass resources and their potential for bioenergy generation is needed for the creation of bioenergy supporting policies. Policies should set clear directives for the development of technology enterprise building mechanisms, regulatory systems, financial institutions, consumer knowledge and information, implementation, market, and incentives. Focus should be given to skill development and capacity building of local youth entrepreneurs and workforce to ensure local operation and maintenance of a project with locally available biomass. This will create employment and income generation opportunities within the region. Policies should strengthen the convergence between different government institutions related to land-use planning, agriculture, forest, and the energy sector. Complicated bureaucratic procedures for approvals and financial support should be simplified. Further, a single-window clearance mechanism should be established.

The high upfront capital cost is a major challenge in setting up bioenergy systems since the local manufacturers and the users do not have the financial capacity to implement/install these technologies. Moreover, getting loans for these technologies is also challenging due to the rigid lending guidelines and uncertain payback period. Partial subsidies (often insufficient) are available in different schemes, but the subsidy is released after the system's commencement and completion of underlying paperwork. This becomes a major hurdle for the population willing to adapt bioenergy technologies (Ravindranath and Balachandra, 2009). Further, these systems have to compete with subsidized fossil fuels (Luthra et al., 2015). There is currently little integration of supply chain and production system into effective biomass to bioenergy management system.

It is critical to build a business model for a bioenergy system that includes cost-economics, cost-benefit analysis, financial arrangements, information on applicable government schemes/support, and workforce requirements for biomass logistics and conversion technology activity for long-term success and sustainability.

3.6.4. Institutional setup

The bioenergy sector at present primarily serves small communities or individuals. It is unorganized, and there is no large industrial or private sector participation with insufficient institutional service support and logistic infrastructure availability (Ramachandra et al., 2014). Therefore, the biomass market has not grown like solar or wind renewable sector having large industry involvement. Due to small-scale operations, industries don't find the bioenergy sector attractive enough to invest. As a result, the sector has failed to translate its demands into market demand. As a result, biomass is commonly regarded as a non-commercial energy source (Balachandra, 2011b).

Low-income group people in rural areas do not consider improved condition of living as strong enough motivation to move towards modern bioenergy as it does not bring a change in their economic condition and also biomass is non-commercially available. Further, the change is also resisted due to the lack of perceived benefits relating to health and the environment, which are not great incentives when compared to the costs involved. Also, the failure of bioenergy systems over the years due to institutional, economic, and operational failures have all been considered technological problems. As a result, an impression has developed among users that bioenergy as a technology is not successful.

To realize the growth of biomass power in Rajasthan, the authors recommend comprehensive and integrated planning for the sector. Plan should include accurate biomass resource assessment with tracking mechanism to appraise the variations in resource potential or supply along with exigencies to support low supply phases; economically viable logistic planning; suitable financial instruments for incentivizing the resource supplier (i.e., farmer) and power plant operator. Hybrid energy (renewable) system (e.g., biomass and solar) is also suggested to increase the benefits, as such a system can supplement each technology's strength and maximize the sustainability of energy supply using renewables irrespective of the seasonal fluctuations. It can also help decrease the demand for biomass, power generation costs, GHG emissions and requirement of land for farming and biomass storage (Sahoo et al., 2015).

3.7. Global outlook on bioenergy problems and prospects

Bioenergy has significant global prospects for energy security and emission reduction. The current global utilization of bioenergy is reported to be around 50 EJ/yr and is expected to increase to 115–180 EJ by 2050 (Daioglou et al., 2019; Lyrio de Oliveira et al., 2020). In 2018, 6890 TWh renewable-based electricity was generated in the world with bioenergy having the third-largest share (637 TWh) (WBA, 2020). Solid biomass sources accounted for 66% of the biomass-power generated and municipal and industrial waste, and biogas had a share of 19% and 14%, respectively. Biomass is estimated to produce 3000 TWh electricity, which could save 1.3 $GtCO_2eq$/yr emissions by 2050 (Antar et al., 2021). In the present scenario, liquid biofuels and biogas are considered to be sustainable transportation options, with the global biofuel production sharply increasing from 9.2 mt oil equivalent in 2000 to 95.4 mt oil equivalent by 2018 (Antar et al., 2021). The bioenergy sector also significantly contributes to employment opportunities and, with an estimated 3.58 million people, is the second-largest employer amongst renewables (WBA, 2020).

Despite the substantial potential of biomass, the economic, societal, and technical constraints hinder the optimal growth of the bioenergy sector. There are several debates happening in the world around 'food *vs* fuel' (Joshi et al., 2017). Major global feedstocks used for bioenergy production are sugarcane, corn, soybean, wheat, sunflower, and rapeseed, which are indirectly or directly used in the food industry (Rajendran et al., 2018). It is suggested that increased use of biomass feedstocks for bioenergy will result in higher food and feedstock prices due to their enhanced demand and reduced supply (Subramaniam et al., 2019). The demand for higher bioenergy production may also lead to non-agricultural lands being converted into agricultural land (Whitaker et al., 2018). There may be increased utilization/diversion of food crops for bioenergy production if the economic returns are higher, unless policies restrict this shift.

To create a balance between bioenergy and the food supply, use of food crops exclusively for bioenergy should be minimized, and their surplus residues should be focused on energy generation using cost-friendly techniques and appropriate logistic mechanisms. This can help in mitigating challenges of food security and food price increase. Identification and utilization of marginalized lands and wastelands for the cultivation of energy crops such as miscanthus, switchgrass, reed canary grass and napier grass can also be explored to avoid competition with food crops for bioenergy (Chen et al., 2019; Nimmanterdwong et al., 2017). Rapidly moving towards second and third-generation biofuels is another option to avoid competition with food production (Ahmed et al., 2021). At the same time, it is imperative to avoid over-exploitation of land resources and monocropping, which may affect environmental parameters such as biodiversity, and focus on sustainable land use and efficient agricultural production (He et al., 2019). It is important to augment biomass production per unit area by selecting appropriate crops, which can help ensure a higher amount of biomass for food and bioenergy. Modern techniques including genetics, breeding, and growth-stimulating microbes can be used to increase biomass production. Intercropping can also play a major role in crop diversity, soil fertility and enhancement of biomass yield by cultivation of two or more crops simultaneously on the same land area (Martin-Guay et al., 2018). Marginal lands could also benefit from intercropping, as it could reduce the nitrogen fertilizer input while enriching the soil organic carbon and improving soil biodiversity.

Biomass is traditionally used for heat and cooking energy applications in developing/underdeveloped countries. This biomass for bioenergy is unsustainably sourced many a times, resulting in forest degradation. Further, the biomass conversion efficiency for these applications is between 10 and 20%, also causing indoor pollution (Antar et al., 2021). Direct combustion-based plants can be used where biomass is burnt to generate steam that runs a turbine generator to produce power with overall efficiency between 15 and 35% (Malico et al., 2019).

Other inherent challenges with crop residues are that they are seasonal in nature, have low energy density and large volume, leading to logistic issues, and high collection, storage, and transportation costs (Joshi et al., 2017). Pre-treatment technologies such as baling, pelletization/briquetting are required to improve biomass logistics and energy values at additional costs (Albashabsheh and Heier Stamm, 2021). Furthermore, growing crops specifically for biofuel production in developing countries should consider the water availability in the region to avoid increased pressure on local water resources (Luthra et al., 2015). The high water footprint of bioenergy crops is also a cause of concern for large-scale expansion of bioenergy (Ghani et al., 2019). For instance, traveling in a car running on corn-derived bioethanol requires 66 L of water/km travelled, i.e., 187 times higher than gasoline requiring only 0.4 L of water/km (Mekonnen et al., 2018). Moreover, additional soil input of nitrogen fertilizer to meet future global bioenergy demand may make the bioenergy system a major emitter of N_2O.

It is also observed that biomass power systems are not economically feasible without government incentives. Farmers in many regions do not find it economically favorable to collect and transport the residues for bioenergy applications and instead prefer to burn them to save time, energy, and labour. This results in high feedstock costs for biomass power. Some studies report biomass feedstock cost to be as high as 64–75% of the total biomass power generation costs (Antar et al., 2021; He et al., 2019). To ensure profits for bioenergy enterprises, the governments could amend the feed-in tariff and implement a dynamic alteration mechanism based on local conditions, such as flexibility in the price of feedstocks. Moreover, the incentives for biomass power are generally targeted towards the production phase while neglecting biomass collection, storage, and transport, which needs to be considered for the economic feasibility of bioenergy enterprises.

In the current global discussions around net-zero or negative emissions, Bioenergy and Carbon Capture and Storage (BECCS) is emerging as a key pathway and can be implemented through applications including biomass-based power generation, biofuels production, and hydrogen production (Hanssen et al., 2020). Several studies have estimated emission reduction of around 10 Gt CO_2/yr from BECCS by 2050 while delivering >100 EJ/yr (Bhave et al., 2017; Fuss and Johnsson, 2021; Gough et al., 2018). However, there are challenges with BECCS, including it being land and cost-intensive, the scale of deployment, supply-chain management, social acceptance, and appropriate CO_2 sequestration site availability, which needs to be addressed in the near future (Bellamy et al., 2019; Gough et al., 2018).

Overall, the bioenergy sector can significantly influence climate change, agricultural production, socio-economic conditions, employment opportunities, and fuel security for several applications, including power, transportation, and heat. Assessments of biomass resource availability and associated GHG saving potentials hence constitute the foundation for bioenergy planning towards a low carbon future.

4. Conclusions

Biomass can play an important role in reducing energy poverty in rural areas while achieving climate mitigation targets of national policies. Due to wide variations in biomass types, their physico-chemical properties, and spatio-temporal distribution, systematic assessment of biomass energy is essential. However, the biomass database in many states of India is still not available at different spatio-temporal resolutions. This study presents the following major outcomes:

- Through a case study of the state of Rajasthan, India, this paper investigated the potential of locally available biomass (from 25 crop residues and 3 livestock category manure) for decentralized power generation and climate change mitigation.
- The annual biomass power potential of Rajasthan is assessed to be 3056 MW, where crop residues contribute 2496 MW, and livestock manure contributes 560 MW. However, the total potential could vary from 2445 MW to 6045 MW depending upon the biomass collection and energy conversion efficiency.
- Annual emission saving potential of 11.4 mt CO_2eq could be achieved by utilizing the locally available biomass in place of coal for power. This emission-saving potential can vary from 8.7 mt to 22.7 mt CO_2eq based on biomass power generation capacity.
- Rajasthan's surplus biomass distribution and biomass-based electricity capacity (per unit area and per capita) are projected to be 218 t/km^2, 293 kWh/capita, and 8.82 kW/km^2.
- The number of LPG cylinder replacement potential for cooking is estimated to be 74.87 million from the livestock manure-based biogas.

The findings suggest that there is a significant potential for cleaner bioenergy generation in Rajasthan. However, challenges related to biomass availability, logistics, bioenergy policies, and institutional support need to be addressed. The present study can be a suitable example for other agriculturally dominant regions globally to assist the policymakers in efficient planning for energy security and achieving climate change mitigation goals.

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Declaration of competing interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envres.2022.113257.

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