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Spatial variation of biochar production potential from surplus crop residues in India

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ABSTRACT

India faces environmental issues due to large-scale seasonal *in situ* burning of crop residues, leading to air pollution and nutrient loss. Biochar application can increase soil carbon content, moisture, and nutrient content while reducing air pollution. India produces 156 Mt. of annual *in situ* surplus crop residues from ten major crops, with the highest potential for rice residue biomass in Sangrur, Punjab. Biochar could reduce greenhouse gas emissions by 405 Tg annually and its application to soil could sequester 7.5 Tg of carbon. However, competition between biochar and other crop residue management technologies requires a life cycle assessment for sustainable management.

1. Introduction

Post-harvest crop residue burning is one of the critical environmental issues in India, particularly during the harvest period of the kharif season crop (October and November) in the Northwestern states (Punjab, Haryana, Uttar Pradesh) of the country. Although the crop residues have different uses, such as for composts, animal feeds, building materials, cooking fuels, and industrial dyes, due to lack of time to clear the residues from the field, high labor costs, and non-availability of a lucrative market, farmers in India often prefer to burn them *in situ* (Azhar et al., 2019; Das et al., 2020). However, apart from the northwestern states, crop residue burning is also prevalent in other states in India. Each of these regions faces unique challenges with residue management due to differences in crop types, harvesting practices, and seasonal constraints.

An estimated 600 Mt. of crop residues are generated in India annually (Jain et al., 2014). Different studies have estimated an annual surplus in India of ~84 to ~140 Mt. of crop residues that are generally burnt *in situ*. Rice, wheat, cotton and sugarcane are the major crop residues burnt *in situ* in India (Jain et al., 2014). However, the burning of different crop residues is not uniform across the country and varies based on the surplus crop residues at different region and harvest period (Fig. 1). It is important to understand the spatial variation of different types of surplus crop residues in India to develop a roadmap to manage crop residues and replace large scale burning.

However, the impact of crop residue burning is similar across the regions; releases varieties of air pollutants like particulate matter (PM), carbon monoxide, different types of Poly Aeromatic Hydrocarbons (PAHs), greenhouse gases like carbon dioxide (CO_2), methane (CH_4) and nitrous oxides, that harm air quality, health and climate. Crop residue burning results in substantial loss of reactive N (nitrogen oxides (NOx), peroxyacetyl nitrate (PAN), nitric acid (HNO_3), and nitrate (NO_3^-)) which otherwise would have been retained in the soil (Kondo et al., 2004; Dey et al., 2020). Kaur et al. (2021) estimated 5.5 kg of N loss from every ton of rice straw burning. It has also been reported that when crop residues are burned frequently, it results in loss of N and carbon (C) from 0 to 15 cm of the topsoil (Bhuvaneshwari et al., 2019). The losses of N from soil due to the crop residue burning are considerably larger (up to 80 %) compared to phosphorus (25 %) and potassium (21 %) losses (Mandal et al., 2004).

The government of India has implemented several policies to curb post harvest crop residue burning particularly in the northwestern states in recent years covering incentives to both *in situ* and *ex situ* managements of crop resides. Although removing crop residues significantly impact soil productivity (Lal, 2010; Nawaz et al., 2021), there is limited understanding of long-term effects of *in situ* crop residue management in different soil types across India as well as its impact on crop yield and pest control. On the other hand, in the absence of a wide range collection market and storage infrastructure of crop residue, the *ex situ* management have also not been attractive to the farmers.

As soil is the second largest global pool of carbon and is important for

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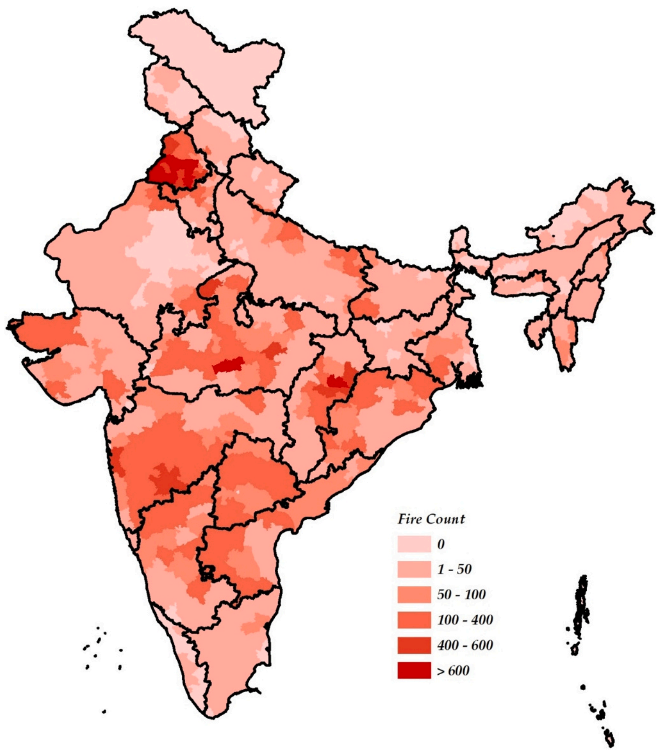

Fig. 1. Spatial variation of annual *in situ* burning of crop residues in India. Data source: Sentinel 2 landcover data and FIRMS active fire data.

food production, soil-based technologies for CO_2 removal have gained popularity in recent years (Roe et al., 2021). Conversion of crop residues to biochar through anaerobic thermochemical decomposition could become economically viable at a lower carbon price than bioenergy with carbon capture and storage (Wolf et al., 2016). Globally, biochar systems could deliver emission reductions of 3.4–6.3 Pg CO_2 equivalents (CO_2 eq), half of which constitutes CO_2 removal (Lehmann et al., 2021). The pyrolysis of surplus crop residues, on one hand generate pyrolytic oil which can be used for different industrial purposes, and on the other, it produces biochar which is rich in carbon. Biochar has been proposed as a tool for climate mitigation (Lehmann et al., 2021). The biochar is known for its use in agriculture to increase fertility, moisture and soil carbon content. Biochar and pyrolytic oil produced from different types of feedstocks have significant variations in their chemical and physical characteristics. Residual biomass feedstock with a high lignin content is highly desirable for pyrolysis to produce biochar with improved physicochemical characteristics, such as high fixed carbon content, surface area and aromatic structure, that are necessary for diverse applications (Wang et al., 2020; Pattnaik et al., 2021; Patra et al., 2022).

Research on biochar production from crop residues in India has been growing. India generates a vast variety of region-specific crop residues, including rice husks, wheat straw, maize stalks, mustard stalks, cotton stalks and sugarcane bagasse, each with different chemical compositions. Few studies have reported biochar production potential from available crop residues in Eastern (IARI, 2017), Southern (TERI, 2019) and northeastern (TERI, 2020) regions of India. It is to be noted that most of the earlier studies are focused on rice and wheat crop residues (Yadav and Agarwal, 2019); however, a systematic assessment of biochar production across the country for all available crop residues would help to assess potential biochar yield from different available crop residues. Earlier studies reported that the biochar application in crop land increased carbon sequestration potential (Pandey and Pathak, 2020; Thomas and Ghosh, 2018; Singh and Meena, 2019). However, estimation of region wise carbon sequestration or carbon emission avoidance potential of agriculture soil with biochar use is required before its implementation. Reliable estimates of soil carbon sequestration potential with biochar in India could support policy decisions for carbon credits or incentives. Variability in pyrolysis conditions (temperature, residence time, feedstock) may lead to inconsistent biochar properties. Thus it is important to standardize a biochar production protocol to maintain the biochar properties across the country. High initial equipment cost of biochar production restrict wider research in biochar in India; with the availability of a simulation model, clear economic model for biochar preparation from crop residue can be designed.

Focusing on above mentioned gaps in the crop residue-based biochar research in India, the present study was undertaken to estimate spatial variations in availability of different types of crop residues and their potential to produce biochar in India vis-à-vis spatial variation in potential of biochar to sequester carbon in crop land. The output of the study could facilitate regional or state-level policy development to utilize excess crop residues for biochar production, facilitating its application to soil to improve productivity, moisture content and arrest topsoil erosion.

2. Materials and methods

2.1. Estimation of distribution of crop residues

There are 788 districts in India spread across 28 states and 8 union territories. District level crop production and cropping area data of rice, wheat, maize, sugarcane, cotton, gram (chickpeas), tur (pigeonpeas), groundnut, mustard and soybean in three major crop growing seasons (rabi, summer and kharif) were collected from the Department of Agriculture Co-operation and Farmers' Welfare (DoAC&FW), Ministry of Agriculture, Government of India for financial year 2019–20 to 2023–24. More than 40 new districts introduced between 2019 and 20 and 2023–24; crop production in the newly formed districts were estimated for the years before commissioning by bifurcating from old district(s) based on the area of the new districts. Different researchers have reported the error in the crop production data of DoAC&FW ranging between 5 % and 20 % (NSSO, 2013; Bhatt and Khetarpal, 2017; Maheshwari and Singh, 2020).

A district-wise survey was undertaken with randomly selected farmers to estimate residue to production ratio (RPR) and surplus factors of different crops. The survey was undertaken in 17 states covering 110 districts and 1332 farmers (Table 1). In states where surveys could not be conducted, the usage pattern of different crop residues was assessed based on literature review and discussion with experts from local farm science centre, Krishi Vigyan Kendra.

District level dry surplus residues of different crops were estimated following Eq. (1);

Table 1
District and state-wise number of farmers surveyed.

Surveyed state	Surveyed districts	Surveyed farmers
Andhra Pradesh	5	83
Bihar	8	52
Chattishgarh	7	64
Gujarat	7	58
Haryana	4	45
Karnataka	6	84
Kerela	3	26
Madhya Pradesh	11	125
Maharashtra	7	122
Odisha	6	84
Punjab	5	56
Rajasthan	10	75
Tamilnadu	3	34
Telangana	7	22
Uttarakhand	3	24
Uttarpradesh	15	156
West Bengal	5	62

$$B_{(t)} = \sum_{d=1}^{788} P_{(d,t)} \times R_{(t)} \times D_{(t)} \times S_{(t)} \tag{1}$$

where, Bt is the total dry surplus crop residue (Mg/annum) of crop type t; $P_{d,t}$ is the production (Mg/annum) of crop type t in the district d; R_t is mean state level residue to production ratio of crop type t calculated based on the survey data; D_t of the dry fraction of the *in situ* crop residue of crop type t and S_t is the state level mean surplus fraction of crop residue of the crop type t based on the analysed result of the survey data. There are spatial variations of district level utilization of different types of crop residues; however, mean state level utilization of crop residues was used in the present study, this is a potential source of estimation error. The estimation was having margin of error of about 3 % at 95 % confidence interval. It is to be noted that we have calculated only the primary crop residues generated from the selected crops.

District-wise surplus *in situ* crop residue biomass ($B_{d,t}$) was then attributed to the district-polygons in ArcMap10.8.

2.2. Estimation of biochar carbon production potential of crop residues

The yield of biochar carbon, $(Y_{(C\_Ch)})_t$ in Mg/Annum, was calculated according to Eq. (2) (Karan et al., 2023).

$$Y_{(C\_C_{ch})_t} = Y_{(Ch)_t} \times C_{(ch)_t} \tag{2}$$

where, t is the type of crop residue, $Y_{(Ch)t}$ is the mass of ash free dry biochar generated (Mg/Annum), $C_{(Ch)t}$ is the carbon fraction of biochar.

$Y_{(Ch)}$ of specific crop residue type (t) was calculated following the Eq. (3) (Woolf et al., 2014),

$$Y_{(Ch)_t} = \sum_{d=1}^{788} B_{(td)} \times \left\{ 0.126 + 0.273 L_t + 0.539 e^{(-0.004 \times \delta)} \right\} \tag{3}$$

where, B_t is the surplus dry biomass of crop type t in Mg/Annum L_t is the lignin fraction in dry crop residue (t) biomass and δ is the pyrolytic temperature. Optimal biochar production temperature was reported between 500 °C and 580 °C (Lehmann and Joseph, 2015). While, Mukherjee and Lal (2013); Wang et al. (2016) reported that the biochar produced between 500 °C to 550 °C has highest stability in soil and reported positive impact on soil productivity. It is also reported that the biochar has high fixed carbon content at 550 °C. This improves its ability to sequester carbon and withstand microbial degradation, resulting in a long-lasting amendment (Lehmann and Joseph, 2015). During an earlier study, we have analysed the biochar produced during pyrolysis of cotton crop biomass residue and found that the optimised amount and quality of biochar produced at 550 °C (Table A-1). Hence, during this study δ was considered as 550 °C. The carbon fraction of biochar ($C_{(Ch)}$) produced from crop residue (t) was calculated using the Eq. (4) (Neves et al., 2011),

$$Y_{(Ch)_t} = C_{(bm)t} \times \left\{ 0.93 - 0.92 e^{(-0.0042 \times \delta)} \right\} \tag{4}$$

where, $C_{(bm)t}$ is the carbon fraction in dry crop residue type (t). ($Y_{(C\_Ch)}$) of all selected crops were calculated as presented at district level using ArcMap 10.8.1. The variation in pyrolysis feedstocks with distinct chemical compositions lead to variability in carbon composition even at the same pyrolysis temperature – this may contribute upto 5 % to 10 % error in estimation of carbon fraction in the biochar (Zimmerman, 2010). Additionally, factors like pyrolysis heating rate and residence time interact with temperature to affect carbon yield, introducing non-linearities that lead to an overall error of ~10–15 % in some cases (Tripathi et al., 2016). Again, there are some other factors like temperature precision of the pyrolytic unit and analytical error of measurement of total carbon in the biochar may also add to the error in carbon fraction estimation in the biochar. Overall, there is approximately 15 % to 25 % error in the estimation of carbon fraction in biochar.

2.3. Estimation of CO_2 eq greenhouse gas emission avoidance

Considering the biochar applied to same crop land from where it was produced, the carbon sequestration potential in soil with the estimated amount of biochar production was calculated using the Eq. (5).

$$A = \sum_{t=1}^{10} \left\{ Y_{(Ch)t} \times C_{(Ch)t} \times F_p \times (44/12) + (N_t \times 0.34 \times GWP_{N2O}) \right\} \tag{5}$$

where A is the avoided CO_2 eq GHG emission from the cropland with the application of biochar, F_p is fraction of biochar organic carbon remaining after a defined period of time (F_p was taken to be 0.26 from Woolf et al. (2021) considering average topsoil temperature in India as 20 °C (Alam et al., 2015)), N_t is the estimated nitrous oxide emission during the cultivation of crop type t following the IPCC methodology and GWP_{N2O} is the CO_2 eq global warming potential of N_2O (Forster et al., 2021). Studies have reported about 34 % reduction in N_2O emission from cropland soil with the application of biochar (Cayuela et al., 2014; Verhoeven et al., 2017; Borchard et al., 2019).

3. Results and discussion

3.1. Spatial variation of annual mean crop production

After extracting the five years district level production data of rice, wheat, maize, sugarcane, cotton, gram, tur, groundnut, mustard and soybean in three major crop growing seasons, the annual mean of district-wise specific crop production data was used as the annual production of each crop in the specific district ($P_{d,t}$). Accordingly, the mean annual production of rice, wheat, sugarcane and cotton were estimated as 6.9 Tg, 4.9 Tg, 12.7 Tg, and 0.3 Tg, respectively (Table 2). Highest mean state-level annual production of rice, wheat, sugarcane and cotton were estimated in West Bengal, Madhya Pradesh, Uttar Pradesh and Gujarat, respectively (Table 2). At district-level, the highest mean annual production of rice was estimated in Purba Burdwan (1.9 Mt), wheat in Ujjain (1.7 Mt), sugarcane in Kheri (20.6 Mt) and cotton in Amreli (0.2 Mt).

3.2. Residue to production ratio of different crop types

The RPR of different crops were estimated following the data collected from 1172 surveyed farmers (Table 1). As the survey was undertaken in 17 States out of 36 States and Union Territories in India, a mean value of state wise calculated RPR (R_t) was used in the present study. The mean of surveyed RPR of different crop types in different districts of specific state was used as the RPR value of the crop in the state. Mean RPR of rice, wheat, maize, sugarcane, cotton, gram, tur, groundnut, mustard and soybean across the country were estimated as 1.95 ± 0.11, 2.74 ± 0.29, 1.94 ± 0.13, 0.44 ± 0.02, 1.28 ± 0.35, 4.35 ± 0.49, 4.36 ± 0.47, 2.19 ± 0.13, 3.19 ± 0.39 and 2.79 ± 0.32, respectively (Fig. 2). Maximum variation in RPR value were recorded with gram followed by tur and cotton during the survey (Fig. 2). These variations are attributed to morphological differences of these plants (Chhabra and Sharma, 2010), variations in agricultural practices in different regions (Pathak and Wassmann, 2007) and climatic variability (Jat et al., 2014).

3.3. Spatial distribution of different types of surplus crop residues

The surveyed range of surplus *in situ* dry crop residue fractions of different types of crop residues are summarized in Table 2. During the survey, *in situ* burning of crop residues were not considered as an option to manage the crop residues and any *in situ* burning of crop residues were considered as surplus crop residue. Accordingly, the surplus *in situ*

Table 2
Mean annual production (t) of different crops in different states of India during 2019–20 and 2023–24.

State	Tur	Rice	Maize	Wheat	Cotton	Groundnut	Mustard	Soybean	Gram	Sugarcane
Andaman and Nicobar Islands	0	17,981	57	0	0	2	0	0	0	830
Andhra Pradesh	235,729	18,280,182	4,242,440	11	132,414	1,699,290	912	4818	558,745	6,714,729
Arunachal Pradesh	712	244,741	79,205	7742	0	905	28,791	4447	0	46,139
Assam	5040	10,429,608	128,036	14,430	83	0	177,226	0	1523	1,218,118
Bihar	28,157	10,900,295	6,989,179	5,579,348	0	858	89,345	14,779	38,529	13,578,832
Chhattisgarh	22,466	8,569,367	406,821	135,888	984	33,683	15,692	82,999	105,823	699,040
Delhi	0	17,580	102	82,905	0	0	8125	0	4	0
Goa	0	180,750	0	0	0	862	0	0	0	53,708
Gujarat	210,689	3,808,385	1,591,847	4,553,681	1,724,867	9,291,625	333,540	132,661	636,475	11,569,942
Haryana	1404	5,194,600	17,290	11,876,900	492,600	3089	1,142,200	0	47,090	7,730,300
Himachal Pradesh	50	116,879	744,603	619,689	1	51	4911	949	421	36,143
Jammu and Kashmir	0	587,101	541,451	488,297	0	0	38,009	0	3	83
Jharkhand	241,565	3,612,589	968,255	439,401	0	28,782	231,354	1023	275,506	0
Karnataka	1,125,991	7,895,946	9,483,649	180,114	906,759	1,001,744	54	378,700	674,750	36,034,028
Kerala	522	1,211,082	140	2	16	147	0	0	454	120,835
Madhya Pradesh	274,809	9,481,614	8,727,897	37,507,219	167,781	591,429	1,038,355	3,856,153	3,062,879	7,414,530
Maharashtra	1,196,801	5,431,643	3,918,997	1,793,440	1,327,837	599,766	3204	4,825,628	2,240,091	69,312,919
Meghalaya	1540	606,952	41,760	898	1739	0	9242	3570	2004	384
Mizoram	445	120,478	22,243	0	3	0	459	1827	0	46,842
Nagaland	2920	832,629	212,788	6280	1	1100	27,820	31,770	640	193,620
Odisha	144,580	19,510,100	371,010	164	115,700	106,124	2035	0	21,670	504,871
Puducherry	0	118,690	0	0	250	1518	0	0	0	183,120
Punjab	2200	12,675,000	410,500	17,619,000	241,280	2800	42,600	0	1800	7,302,000
Rajasthan	5196	480,554	1,155,671	13,894,293	557,529	1,623,352	4,288,797	525,055	2,658,242	326,262
Sikkim	0	16,137	67,908	178	0	0	2745	2859	0	0
Tamil Nadu	92,419	14,208,143	5,097,305	0	158,973	2,065,796	33	0	5138	14,119,210
Telangana	360,370	23,771,592	7,287,372	9451	1,366,635	528,724	0	311,224	199,000	2,021,771
The Dadra and Nagar Haveli and Daman and Diu	2800	74,387	4	120	0	5	3	0	0	12,000
Tripura	3873	1,620,488	45,951	331	228	6725	6668	262	181	36,372
Uttar Pradesh	279,213	27,088,715	3,586,668	36,209,665	1486	88,371	885,907	11,497	851,211	179,567,765
Uttarakhand	2735	1,193,093	48,794	887,440	0	706	12,472	8838	547	6,838,266
West Bengal	12,768	32,944,412	4,858,949	509,970	118	242,556	712,371	194	47,419	1,527,577

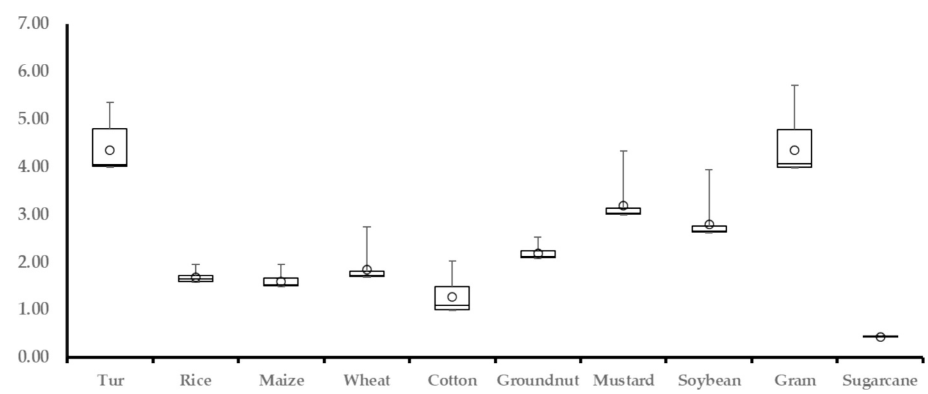

Fig. 2. Variations in surveyed residue to production ratio (RPR) of different crop types.

residue fractions of rice and wheat at some districts were estimated as 0.95 (Table 3). The dry matter fraction of different types of selected crop residues were summarized in Table 3 following Yu et al. (2020). About 156 Mt. of surplus *in situ* crop residues were estimated annually across India with significant spatial variations (Fig. 3) following Eq. (1). Jain et al. (2014) estimated about 132 Mt. to 98 Mt. of crop residue burnt in India during 2008–09. Similarly, MoA (2014) estimated 140 Mt. of annual surplus crop residue in India in 2012–13. The mean annual surplus crop residue biomass was estimated to be approximately 178 Mt. (Jain et al., 2018) over a period of six years from 2010 to 11 (Table 4). The largest surplus *in situ* sugarcane crop residues were found in districts located in southern Maharashtra and northern Karnataka, whereas that of wheat crop residue were highest in Punjab and Madhya Pradesh (Fig. 3). The *in situ* surplus residues from all selected crops were highest in Sangrur, Punjab (2.31 Mt./annum). About 59 % of *in situ* surplus crop residues in this district are attributed to rice production. Belagavi district in Karnataka state was estimated to have the second largest *in situ*

Table 3
Estimated dry matter and *in situ* surplus fraction of different types of *in situ* crop residues.

Crop residue type	Dry matter fraction*	Range of surplus *in situ* fraction
Rice	0.90	0.00 to 0.95
Wheat	0.88	0.00 to 0.95
Maize	0.87	0.00 to 0.74
Sugarcane	0.10	0.15 to 0.85
Cotton	0.35	0.50 to 0.90
Gram	0.90	0.02 to 0.90
Tur	0.90	0.10 to 0.60
Groundnut	0.67	0.00 to 0.70
Mustard	0.90	0.05 to 0.95
Soybean	0.90	0.00 to 0.75

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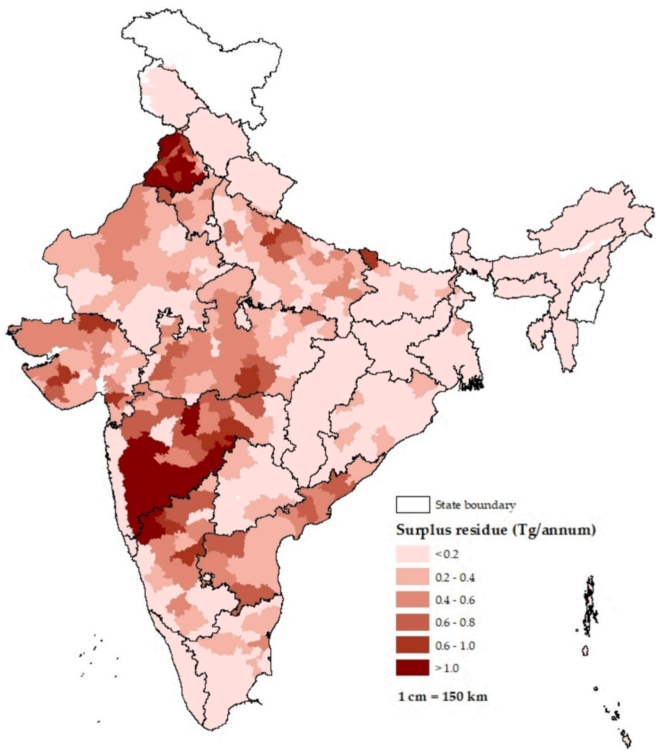

Fig. 3. Spatial variation of annual surplus *in situ* crop residues in India. *vide Annexure* for Spatial variations of surplus *in situ* crop residues of different crop types in India.

surplus crop residues (2.24 Mt./annum). However, 57 % of the surplus residues in Belagavi were attributed to sugarcane. Jain et al. (2018) also reported that rice, sugarcane, cotton and soybean are the major crops contributing to the annual surplus crop residues in India. The spatial variations in surplus crop residues in India is attributed to the agro-ecological diversity (Gupta et al., 2004), variations in cropping pattern and RPR (Jat et al., 2014) (Table 5), agricultural practices like crop rotation, irrigation and mechanization (Sidhu et al., 2007), climatic variation (Pathak and Wassmann, 2007) and fertility and resource availability (Bandyopadhyay et al., 1991).

3.4. Spatial variation of biochar production potential of surplus crop residues

Increasing lignin content in the crop residues increases the stability of biochar, carbon content and porosity while decreasing the pH and CEC of the biochar (Beusch, 2021), so making it more beneficial for application in cropland. Annual biochar production potential of the *in situ* surplus crop residues available in India was estimated as 34.5 Tg following Eq. (3). About 29 % of this was estimated to be from the rice crop residues, followed by 22 % from wheat, 13 % from sugarcane and 9 % from maize (Table 6). Estimated annual biochar production potential of *in situ* surplus crop residues was highest in Punjab and Maharashtra (5.5 Mt) followed by Uttar Pradesh (4.7 Tg) and Madhya Pradesh (4.2 Tg) (Fig. 4). Estimated fraction of total biochar from surplus *in situ* rice crop residue was more in Punjab (55 %) and Uttar Pradesh (48 %) compared to other states, whereas *in situ* surplus sugarcane and wheat residues were estimated to contribute 35 % and 63 % of total biochar production potential in Maharashtra and Madhya Pradesh.

3.5. Spatial variation of biochar carbon sequestration potential of surplus crop residues

The longevity of a carbon stock, in the soil or vegetation, is related to the permanence of the stock. Biochar usually decomposes in soil at least 1–2 orders of magnitude more slowly than the feedstock residues. Estimated total annual biochar production in India can be applied to

Table 4
State wise estimated annual surplus *in situ* crop residue (Mt).

State	Tur	Rice	Maize	Wheat	Cotton	Groundnut	Mustard	Soybean	Gram	Sugarcane	Total
Andaman and Nicobar Islands	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Andhra Pradesh	0.20	1.99	0.31	0.00	0.07	0.94	0.00	0.00	0.54	1.90	5.95
Arunachal Pradesh	0.00	0.03	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.05
Assam	0.01	1.55	0.04	0.00	0.00	0.00	0.17	0.00	0.00	0.17	1.94
Bihar	0.02	0.30	1.59	0.86	0.00	0.00	0.07	0.00	0.03	1.20	4.08
Chhattisgarh	0.00	1.17	0.05	0.04	0.00	0.01	0.04	0.06	0.11	0.10	1.56
Delhi	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Goa	0.00	0.06	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.07
Gujarat	0.13	1.56	0.57	0.00	0.00	3.32	0.20	0.08	1.75	1.64	9.24
Haryana	0.00	1.69	0.00	1.48	0.37	0.00	2.02	0.00	0.06	0.93	6.55
Himachal Pradesh	0.00	0.10	0.31	0.18	0.00	0.00	0.00	0.00	0.00	0.00	0.59
Jammu and Kashmir	0.00	0.08	0.06	0.07	0.00	0.00	0.01	0.00	0.00	0.00	0.23
Jharkhand	0.07	0.98	0.12	0.03	0.00	0.00	0.14	0.00	0.75	0.00	2.09
Karnataka	0.35	0.54	4.51	0.02	0.29	0.94	0.00	0.25	1.85	2.59	11.34
Kerala	0.00	0.14	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.17
Madhya Pradesh	0.43	1.29	1.03	11.29	0.00	0.11	0.25	2.56	0.53	0.65	18.13
Maharashtra	0.37	0.74	1.30	0.80	1.41	0.11	0.00	5.49	6.17	8.08	24.47
Meghalaya	0.00	0.25	0.03	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.30
Mizoram	0.00	0.08	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.11
Nagaland	0.00	0.11	0.03	0.00	0.00	0.00	0.00	0.01	0.00	0.02	0.18
Odisha	0.13	3.41	0.01	0.00	0.01	0.02	0.00	0.00	0.01	0.04	3.63
Puducherry	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.02
Punjab	0.00	13.69	0.25	9.71	0.16	0.00	0.09	0.00	0.01	0.37	24.27
Rajasthan	0.00	0.00	0.00	0.00	0.19	0.80	3.08	0.40	2.29	0.00	6.75
Sikkim	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
Tamil Nadu	0.09	1.94	1.51	0.00	0.04	1.07	0.00	0.00	0.01	0.24	4.89
Telangana	0.31	2.59	0.73	0.00	0.70	0.00	0.00	0.22	0.19	0.01	4.75
The Dadra and Nagar Haveli and Daman and Diu	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01
Tripura	0.00	0.18	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.42	0.60
Uttar Pradesh	0.13	10.01	1.59	7.55	0.00	0.00	0.31	0.01	0.83	0.32	20.74
Uttarakhand	0.00	0.24	0.02	0.13	0.00	0.00	0.00	0.01	0.00	0.02	0.44
West Bengal	0.00	1.61	0.58	0.04	0.00	0.00	0.08	0.00	0.06	0.00	2.37

Table 5
Spatial trend of residue fraction in major crops.

Crop	North India	South India	East India	West India
Rice	High RPR (Punjab, Haryana, >1.5) due to high productivity.	Moderate RPR (~1.0, Tamil Nadu) with some residues used as fodder.	Low to moderate RPR (~1.2) due to smaller-scale operations.	Moderate RPR (~1.0, Maharashtra).
Wheat	High RPR (~1.2, Punjab, Haryana) with burning as a common disposal practice.	Low RPR (limited wheat cultivation).	Moderate RPR (~1.1).	Moderate RPR (~1.1, Gujarat).
Sugarcane	High RPR (~3.0, Maharashtra, UP) with significant residues from bagasse and tops.	High RPR (~3.5, Tamil Nadu, Karnataka).	Limited sugarcane cultivation.	Major crop in western Maharashtra.
Maize	Moderate RPR (~1.2, Karnataka, Tamil Nadu).	Moderate RPR (~1.1).	High RPR (~1.3, Bihar, Odisha).	Moderate RPR (~1.2).
Cotton	Low RPR in Punjab (limited cotton area).	Limited cultivation.	Limited cultivation.	High RPR (~2.0, Gujarat, Maharashtra).
Gram	Low RPR (~0.5, Punjab).	Moderate RPR (~0.8).	Moderate RPR (~0.7).	Moderate RPR (~0.8).
Groundnut	Low RPR (~0.8) Uttarpradesh, Punjab	Moderate RPR (~1.2). Andhra Pradesh, Tamilnadu, Karnataka	Low RPR (~0.8) Odisha, West Bengal	High RPR (~2.0, Gujarat, Maharashtra).
Tur	High RPR (~2.0) Uttarpradesh	High RPR (>2.0) Karnataka, Telangana, Tamilnadu	Moderate RPR (1.2 to 1.8) Odisha, West Bengal, Bihar	High RPR (>2.0) Gujarat, Maharashtra, Madhyapradesh
Mustard	High RPR (>2.0) Rajasthan, Haryana, Punjab, Uttarpradesh. Moderate RPR (~1.8) Himachal Pradesh, Uttarakhand	Limited sugarcane cultivation	Moderate RPR (1.8 to 2.0) Bihar, West Bengal	High RPR (>2.0) Gujarat Maharashtra, Madhyapradesh

Table 6
Biochar production potential of *in situ* surplus crop residue of different crops in India.

Crop residue type	Biochar (Mt)
Rice	10.2
Wheat	7.6
Maize	3.0
Sugarcane	4.5
Cotton	0.5
Gram	3.2
Tur	0.5
Groundnut	1.5
Mustard	1.4
Soybean	2.1

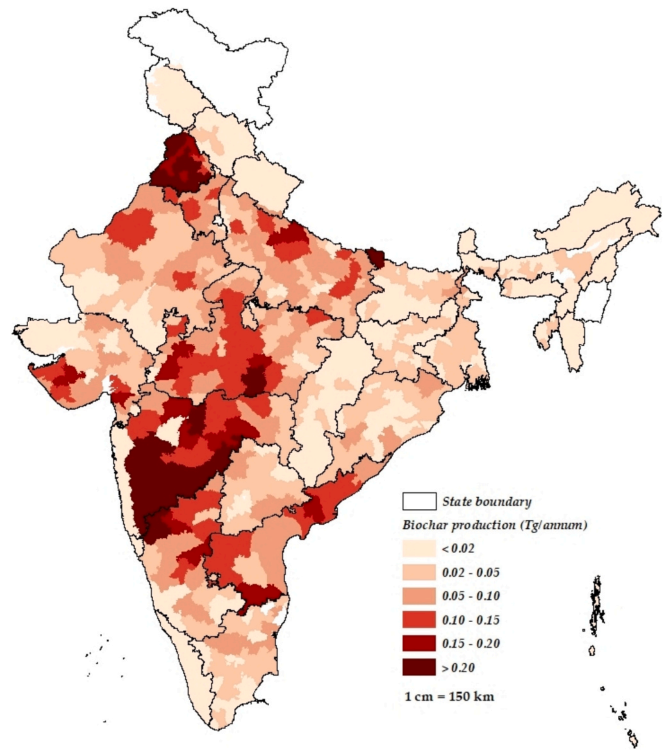

Fig. 4. Spatial variation of annual total biochar production potential from surplus crop residue feedstock in India.

approximately 2 % (about 3451 thousand ha) of the cropping area of selected crops at a rate of 10 Mg ha^{-1} annum^{-1} (Borchard et al., 2019). The potential annual yield of biochar carbon ($Y_{(C\_Ch)}$) was estimated as 29 Mt. following Eq. (2). potential annual yield of biochar carbon from the residues of different surplus crop biomass was estimated to be 2.2 Mt. for rice, 1.7 Mt. for wheat, 0.7 Mt. for maize, 1.0 Mt. for sugarcane, 0.1 Mt. for cotton, 0.7 Mt. for gram, 0.1 Mt. for tur, 0.3 Mt. for groundnut, 0.3 Mt. for mustard and 0.5 Mt. for soybean.

Total annual N_2O emission avoidance from selected crops with biochar application was calculated to be 1456 Mg. Total annual avoided CO_2 eq emission was estimated to be 405 Tg following Eq. (5) with the application of biochar to the cropland of selected crops (Table 7).

However, the biochar production from surplus crop residues has steep competition with the ethanol production and energy use from the same crop residues. Lynd et al. (2024) reported that soil organic carbon levels in soils amended with high lignin fermentation by product of

Table 7
Estimated GHG avoidance potential of biochar produced from surplus *in situ* crop residues in India.

Crop type	Potential biochar application area (000 ha)	Estimated N_2O emission (Mg)	Biochar application related C-sequestration in soil (Tg)	Estimated total GHG avoidance (CO_2 eq Tg)
Rice	1016	1914	2.22	180
Wheat	759	739	1.65	70
Maize	301	236	0.66	23
Sugarcane	452	886	0.98	83
Cotton	51	72	0.11	7
Gram	315	168	0.69	16
Tur	53	17	0.11	2
Groundnut	154	60	0.34	6
Mustard	143	76	0.31	7
Soybean	208	115	0.45	11
Total	3451	4284	7.53	405

ethanol production would not be substantially lower than those occurring when crop residues are left in the field. However, biochar is a stable form of carbon and is known for 200 to 1000 years carbon storage in soil with a half-life of about 100 years (Lehmann et al., 2006) whereas about 50 % of the carbon in the by-products of lignin fermentation is mineralized within the first few years (Bernal et al., 2009).

4. Conclusion

Biochar production offers a sustainable solution to surplus crop residue burning and related environmental issues. Integrating the surplus crop residue into soil as biochar, farmers can simultaneously manage waste, improve soil health, and reduce air pollution. The study estimated that Maharashtra and Punjab states have maximum annual biochar production potential using the *in situ* surplus crop residues. Eastern India was estimated to have the lowest potential for biochar production, mainly due to lesser availability of surplus crop residues. Total annual biochar production potential using *in situ* surplus crop residues in India was estimated to be 34.5 Mt. with most of the biochar from rice and wheat crop residues. However, the Government of India also have a target to generate ~13,565 million gallons of ethanol annually to meet the 20 % ethanol blending target with petrol by 2030. Additionally, the government is subsidizing the agro-machineries to incorporate crop residues directly in the soil and utilizing the crop residues as fuel in industries and thermal power plants. These may reduce the potential for biochar production from the surplus crop residues and carbon sequestration in soils. In India, there is no clear policy in promoting biochar production and application like those related to composting and biofuel production; this restricts the research as well as awareness about the potential environmental impact of biochar production and its importance in carbon sequestration. Thus, the Indian government must conduct more research on the energy and economic feasibility of producing biochar vis-à-vis the regional agronomic effects of applying biochar to a variety of croplands. However, it will be crucial to examine the technoeconomic sustainability of various competing approaches to using surplus crop residue.

Declaration of competing interest

None.

Data availability

Data will be made available on request.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.crsust.2025.100279.

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