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Assessment of sugarcane residues derived biochar for carbon sequestration in the soil in India

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Abstract—Biochar draws attention because of its potential for carbon sequestration and long-term sustainability in agriculture by improving soil health and crop yield. In the present research, the carbon sequestration potential of biochar derived from sugarcane residues has been assessed. It was estimated that about 38.8 MT sugarcane top & leaf (STL) and 96.3 MT sugarcane bagasse (SB) are produced in India annually. Out of which, about 47 % STL and 37 % SB remain unused. Surplus STL & SB has an estimated 17.6±0.4 MT biochar potential, sequestrating 18.8±0.4 MT CO_2e carbon in the soil. STL & SB-derived biochar application at 10 T/ha could sequestrate 51.9±1 and 47±2.2 MT CO_2e carbon due to enhanced crop yield and reduced soil organic carbon mineralization. Also, biochar application at 10 T/ha could reduce about 0.08 MT NPK fertilizer consumption and 0.22±0.13 MT N_2O emissions from sugarcane cultivation, having 0.28±0.17 and 65±38 MT CO_2e reduced carbon footprint, respectively. Overall, sugarcane residues - biochar system for carbon sequestration could reduce 220.3±45.1 MT CO_2e carbon footprint, about 9.5±2 % of total GHG emission from India at the 2019 level. Mapping sugarcane-producing states revealed that Karnataka, Maharashtra, and Uttar Pradesh shared about 75.5 % of surplus STL & SB potential. Andhra Pradesh, Bihar, Gujarat, Haryana, and Tamil Nadu have a 16.5 % combined share in surplus STL & SB potential. The current study's findings would contribute to creating a sustainable and environmentally friendly system for managing sugarcane residue and increasing the nation's sugarcane production.

Keywords— Sugarcane residues, Carbon sequestration, Pyrolysis, Soil amendment, Biochar

I. Introduction

Sugarcane is India's largest cultivated cash crop, having more than 90 % and 51 % share of the national cash crop and total agro production [1]. The sugar industry is essential to the livelihood of around 50 million sugarcane farmers and 0.5 million sugar mill workers in India [2,3]. It also generates employment through various ancillary activities such as transportation, trade, and supply of agricultural inputs & products. Regarding production, India is the second-largest sugarcane producer in the world and the largest sugar consumer. Five hundred six operational sugar mills in the country annually produce about 34 MT of sugar and 110 - 120 MT of sugarcane residues [3–5]. Approximately 50 % of sugarcane residues are utilized for various purposes, such as fuel in bagasse cogeneration plants & small-scale rural industries. However, about 56 - 65 MT of sugarcane residues remain unutilized [4,5]. It is very challenging to manage such large amounts of sugarcane residues.

Biochar, obtained from thermochemical conversion of organic residues for carbon sequestration and soil amendment, has gained widespread attention. The biochar application in the soil can improve soil quality, nutrient availability & sugarcane yield and reduce N_2O emissions from the soil [6–10]. *Chen et al. (2010)* reported that sugarcane bagasse-derived biochar application at 3 % by weight in 30 cm ploughing soil could increase sugarcane yield by 42.5±3.9 %, Nitrogen availability by 29.9±1.3 % and moisture content in soil by 39±12.7 % [11]. *Quirk et al. (2012)* reported that biochar application at 10 T/ha could reduce by 28±16 % N_2O emissions from sugarcane cultivation [10]. Biochar is a stable form of carbon which remain unaffected by rapid microbial degradation [12]. *Kuzyakov et al. (2009)* reported that biochar produced at 400 ºC could remain sequestrated for up to 2000 years [13]. *Lefebvre et al. (2021)* reported that biochar conversion of 100 % surplus sugarcane residues could sequestrate 6.3±0.5 T CO_2e/ha/yr carbon in Sao Paulo state of Brazil [14]. Therefore, it also provides a climate-resilient carbon storage solution. Furthermore, combustible volatile matters obtained during the biochar conversion of biomass can be utilized to generate heat and electricity [15,16]. *Gaunt and Lehman (2008)* reported that energy production from combustible volatile matters and biochar application for carbon sequestration could reduce GHG emissions 2 - 5 times more than solely used for fossil energy offset [16].

With 7.6 GW installed cogeneration facilities, the sugar industry in India is well-positioned to provide energy and first-generation fuels and biochar for carbon sequestration from sugarcane residues such as sugarcane bagasse (SB) and sugarcane top & leaf (STL) [17]. Biochar conversion of sugarcane residues can reduce GHG emissions by providing a sustainable alternative to fossil fuels and mitigating climate change by converting organic carbon into stable organic carbon. However, there is a lack of information about biochar usage in India's agriculture system. There are only a few reports on sugarcane residue biochar production, characterization, and use for soil amendment [7,11,18,19]. This study aims to comprehensively analyze the various aspects of biochar production from sugarcane residues & characterization and quantify the environmental benefits of sugarcane residues - biochar system for carbon sequestration in India.

II. METHODS

A. Goal of the study, functional unit, and system boundary

This study aimed to quantify the benefits of biochar conversion of sugarcane residues (SB & STL), and its application for carbon sequestration in soil. Annual surplus sugarcane residues have been considered the functional unit of the study. In India, sugarcane is crushed and processed at designated sugar mills to produce sugarcane juice and bagasse, i.e., sugarcane residues are generated at sugar mills. Therefore, the study has ignored sugarcane cultivation, and only residue management has been considered. The sugarcane cultivation system and the system boundary have been shown in Fig. 1.

in the i^{th} state; A_i is sugarcane sown area in the i^{th} state; $RGR_{(i,j)}$ is residue generation ratio of j^{th} sugarcane residue in the i^{th} state, $SR_{a(j)}$ is surplus available j^{th} sugarcane residue, $RAF_{(i,j)}$ is j^{th} sugarcane residue availability factor in the i^{th} state, σ is lost sugarcane residue fraction during handling & processing, taken as 1% of surplus available sugarcane residue [20].

Empirical evidence suggests that the residue generation ratio (RGR) of a crop is influenced by various factors such as soil type, fertilizer usage, irrigation facilities, & others and is inversely related to its yield. It. This study used dynamic adjusted RGR as expressed in Eq. (3) to estimate the gross STL generation [21]. Although the exact yield-based relation has not been studied for SB, it is widely believed that the RGR of SB is influenced by crushing techniques. In this study, the average value of the reported range (0.25 - 0.33) of RGR for SB (0.29) was considered [21,22].

$$RGR_{stl(i)} = -0.0970 * \ln(SY_i) + 0.560 \quad (3)$$

Available biochar for carbon sequestration in soil was estimated by Eq. (4):

$$B_{a(j)} = (1 - \Delta)\left(\sum_{i=1}^{n} * BY(\%)_j * SR_{a(i,j)}\right) \quad (4)$$

Where $B_{a(j)}$ is the available biochar from j^{th} sugarcane residue for carbon sequestration, $BY(\%)_i$ is biochar yield of j^{th} sugarcane residue, $SR_{a(i,j)}$ is surplus available j^{th} sugarcane residue in the i^{th} state and Δ is the lost biochar during handling & transport, taken as 3% of the total biochar [23].

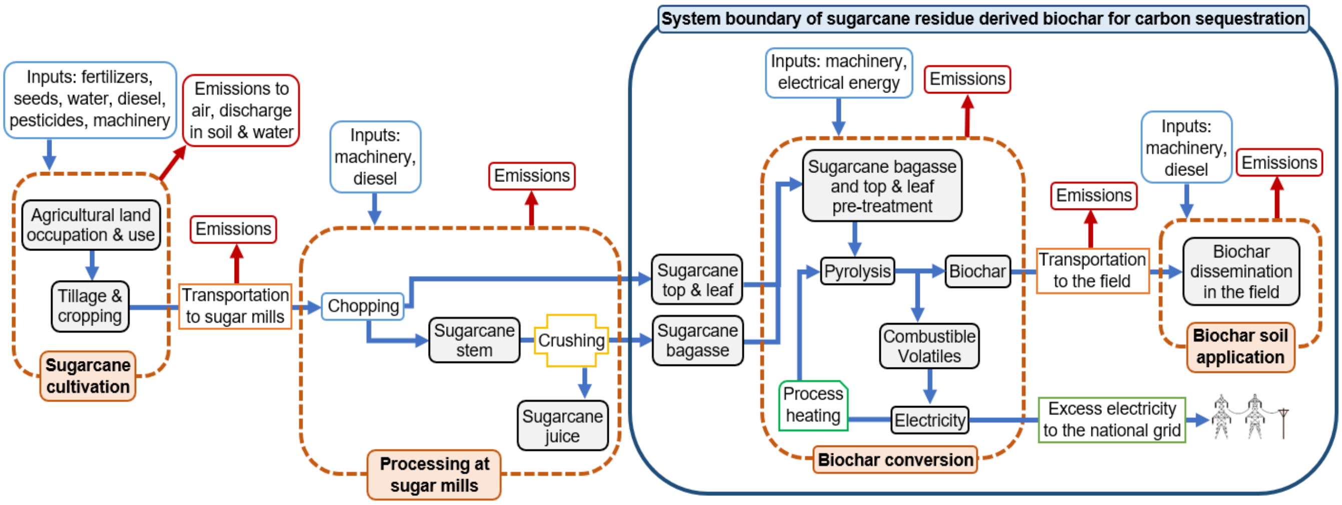

Fig. 1. System boundary of the study

B. Methodology

Gross and surplus available sugarcane residue were estimated by Eq. (1) & (2) [20].

$$SR_{g(j)} = \sum_{i=1}^{n} A_i * SY_i * RGR_{(i,j)} * DM_j \quad (1)$$

$$SR_{a(j)} = \sum_{i=1}^{n} (1 - \sigma) * SR_{g(i)} * RAF_{(i,j)} \quad (2)$$

Where $SR_{g(j)}$ is gross j^{th} sugarcane residue, DM_j is dry matter fraction in j^{th} sugarcane residue, SY_i is sugarcane yield

Collection, handling, and biochar conversion processes were powered by electricity produced from coal and transportation & spreading operations were considered to consume diesel. The energy value of combustible volatiles was considered to offset the electricity requirement for the pyrolysis process and material handling. The net carbon footprint of biochar production from the sugarcane residues and material handling (CF_{BPH}) was estimated by Eq. (5 - 7).

$$CF_{BPH} = \left(EC_{BPH} - E_{offset}\right) * \psi_{CC} \quad (5)$$

$$EC_{BPH} = \sum_{j=1}^{n} E_t * SR_{a(j)} \quad (6)$$

$$E_{offset} = \frac{\eta}{3.6}\left(\sum_{j=1}^{n}(CV_{R(j)} * SR_{a(j)} - CV_{B(j)} * B_{a(j)})\right) \quad (7)$$

Where, EC_{BPH} is electricity consumption of biochar production and material handling, E_{offset} is electricity offset produced from combustible volatile matter obtained from sugarcane residues pyrolysis, ψ_{CC} is carbon emission factor of coal combustion for electricity production (MT CO_2e/TWh), E_T is electricity consumption in biochar conversion and handling of 1 T residue, $CV_{R(j)}$ & $CV_{B(j)}$ are calorific values of j^{th} sugarcane residue and biochar obtained from j^{th} sugarcane residue, and η is average efficiency of coal power plants in India, considered 32.8 % [24].

Sugarcane is mainly carried through diesel-run tractors in India. The carbon footprint of biochar transportation from the sugar mill to the field (CF_{BT}) was estimated by Eq. (8)

$$CF_{BT} = \frac{D * \psi_{DC} * \left(\sum_{j=1}^{n} \frac{B_{a(j)}}{1-\Delta}\right)}{T_{LC} * T_{TM}} \quad (8)$$

Where, D is the average distance travel, ψ_{DC} is the carbon emission factor of diesel combustion (kg CO_2e/ltr.), and T_{LC} & T_{TM} are lifting capacity and fuel mileage of tractor.

Biochar spreading operation was considered to use diesel-run equipment. Carbon footprint of biochar spreading (CF_{BS}) in the sugarcane fields was estimated by Eq. (9).

$$CF_{BS} = DC * \psi_{DC} * \left(\sum_{j=1}^{n} B_{a(j)}\right) \quad (9)$$

Where, DC is diesel required for spreading 1 T biochar.

The complexity of estimating environmental impacts is a significant factor that affects the development and implementation of biochar for carbon sequestration on a large scale. Authors attempted to quantify the environmental benefits of sugarcane residues derived biochar application in soil, including carbon sequestration potential, improvement in soil organic carbon (SOC) & crop yield, and reduction in fertilizer usage & N_2O emissions by Eq. (10 - 19) [23].

$$CS_S = \sum_{j=1}^{n} B_{a(j)} \times C_{B(j)} \times C_{FCB(j)} \times 3.67 \quad (10)$$

$$CS_{ISY} = \sum_{i=1}^{n}\left(\sum_{j=1}^{n} \frac{B_{a(j)}}{B_r} \times SY_i \times ISY \times C_{R(j)} \times 3.67\right) \quad (11)$$

$$RF_N = \sum_{j=1}^{n} \frac{B_{a(j)}}{B_r} \times F_{N,r} \times F_N \quad (12)$$

$$RF_P = \sum_{j=1}^{n} \frac{B_{a(j)}}{B_r} \times F_{P,r} \times F_P \quad (13)$$

$$RF_K = \sum_{j=1}^{n} \frac{B_{a(j)}}{B_r} \times F_{K,r} \times F_K \quad (14)$$

$$CER_{N/P/K} = RF_N * \psi_{CN} + RF_P * \psi_{CP} + RF_K * \psi_{CK} \quad (15)$$

$$RE_{N_2O} = \sum_{j=1}^{n} \frac{B_{a(j)}}{B_r} \times E_{N_2O} \times E_{N_2O,r} \times \psi_{N-N_2O} \quad (16)$$

$$CER_{N_2O} = RE_{N_2O} * \psi_{Ce\,N_2O} \quad (17)$$

$$CS_{SOC} = \sum_{j=1}^{n} \frac{B_{a(j)}}{B_r} \times R_{SOC} \times r_{SOC} \times \psi_{C-CO_2} \quad (18)$$

$$CC_{SR-B-S} = -(CS_{SOC} + CER_{N_2O} + CER_{N/P/K} + CS_{ISY} + CS_S - CF_{BT} - CF_{BS} - CF_{BPH} \quad (19)$$

Where, CS_S is Carbon sequestration potential in the soil; CS_{ISY} & CS_{SOC} are Carbon sequestration potential due to enhanced sugarcane yield & reduced SOC mineralization; $C_{B(j)}$ & $C_{FCB(j)}$ is carbon and fixed carbon content in biochar derived from j^{th} sugarcane residue; B_r is biochar application rate; ISY increase in sugarcane yield after biochar application; $C_{R(j)}$ carbon content in j^{th} sugarcane residue; RF_N, RF_P, & RF_K is reduced N/P/K - fertilizer requirement; $F_{N,r}$, $F_{P,r}$, & $F_{K,r}$ is N/P/K - fertilizer application rate; F_N, F_P & F_K is reduction factor of N/P/K - fertilizer requirement due to biochar application; $CER_{N/P/K}$ is the CO_2 equivalence of reduced N/P/K - fertilizer usage; ψ_{CN}, ψ_{CP} & ψ_{CK} is CO_2e factor of N/P/K - fertilizers; RE_{N_2O} is reduced N_2O emissions; E_{N_2O} is N_2O emissions from sugarcane cultivation; $E_{N_2O,r}$ is N_2O emissions reduction due to biochar application; CER_{N_2O} is CO_2e of reduced N_2O emissions; $\psi_{Ce\,N_2O}$ is CO_2e factor of N_2O emissions; R_{SOC} is SOC reserve in soil; r_{soc} is SOC mineralization reduction due to biochar application; ψ_{C-CO_2} & ψ_{N-N_2O} are Carbon - CO_2, & Nitrogen - N_2O conversion factors; and $CC_{SR\text{-}B\text{-}S}$ is carbon credit of sugarcane residues - biochar system for carbon sequestration.

III. DATA INVENTORY

Factors used in this study have been provided in Table I.

TABLE I. LIST OF FACTORS

Factors	Unit	Value	References
Sugarcane yield	T/ha	79.4	[1]
Biochar application rate	T/ha	10	[25]
N/P/K application rate	T/ha	0.3/0.1/0.2	[19]
SOC (0 - 30 cm)	T/ha	73-77	[26]
Electricity consumption in pyrolysis and material handling	kWh/T	260	Vendor quotation
Average efficiency of coal power plants in India	%	32.8	[24]
Biochar travel distance	km	15	Current estimate
Tractor mileage	ltr	5-7	Vendor quotation
Lifting capacity of the tractor	T	1.8	Vendor quotation
CO_2 equivalence of			
N/P/K application	T CO_2e/T	1.9-7.8/2.3-4.5/0.095-0.161	[27]

N_2O	T CO_2e/T	298	[28]
Diesel combustion	kg CO_2e/ltr	2.69	[29]
Coal combustion for electricity generation	MT CO_2e/TWh	0.91 - 1.04	[30]
Emissions from sugarcane field			
N_2O	T/ha	0.14	[14,31]
Impact of biochar application			
N_2O emission	%	– (12 - 44)	[10]
N/P/K requirement	%	–10/–5/–5	[23]
SOC mineralization	%	–10	[23]
Sugarcane yield	%	+21.7	[18,19]

'+' sign indicates an increase, and '–' sign indicates a decrease

A. *Experimental data*

Experimental data on STL & SB pyrolysis and characterization have been adapted from author's previous studies (*Anand et al. (2022)* [15]) & summarized in Table II.

TABLE II. SUMMARY OF SB & STL PYROLYSIS AND CHARACTERIZATION

Factors	**Materials**			
	STL	**SB**	**STLB**	**SBB**
Carbon content (%)	46.5	48.8	66.7	87.7
Fixed carbon (%)	18.5	19.7	36.2	37.9
Biochar yield (%)	-	-	34.7	31.0
Calorific value (MJ/kg)	20.0	19.3	22.6	29.4

– Not applicable

STLB – sugarcane top & leaf biochar, SBB – sugarcane bagasse biochar

B. *Statistical data*

State-wise sugarcane cultivation statistics were adapted from *Agriculture Statistics at a Glance 2020* [1]. Triennium average of cultivation statistics was used to minimize the yearly variation in sugarcane residues. Triennium average (2017-18 to 2019-20) of cropping area and yield in the major sugarcane cultivating states has been provided in Table III. State-wise, *RAF(i,j)* for each crop was adopted from the studies of *Jain et al. (2018)* & *Trivedi (2020)* [5,33].

TABLE III. TRIENNIUM AVERAGE OF THE SUGARCANE CROPPING AREA, YIELD AND SURPLUS STL & SB AVAILABILITY FACTOR IN THE MAJOR SUGARCANE PRODUCING STATES

States	**Sugarcane cultivation statistcs**[1]		**RAF**[2]	
	Area ('000 ha)	**Yield (kg/ha)**	**STL (%)**	**SB (%)**
Andhra Pradesh	101	79026	79	79
Bihar	230	73902	33	33
Gujrat	168	69479	40	40
Haryana	111	81445	40	40
Karnataka	421	87396	50	38
Madhya Pradesh	103	51999	40	40
Maharashtra	1032	83665	50	33
Punjab	96	82709	40	40
Tamil Nadu	169	101399	40	40
Uttar Pradesh	2229	80024	50	38
Uttarakhand	91	69615	38	38

[1] – Data compiled from [1]

[2] – Data compiled from [5,33]

STL – Sugarcane top & leaf; SB – Sugarcane bagasse, RAF – Residue availability factor

IV. RESLUTS AND DISCUSSIONS

A. *Residue availability and biochar potential*

Due to the impact of climatic factors on India's agriculture production, the triennium average of 2017-18 to 2019-20 has been considered the baseline for sugarcane production data. It was estimated that India annually produces 135.1±2 MT gross and 54.6±1.1 MT surplus sugarcane residues. STL have a 29 % share in gross and 34 % share in available sugarcane residues.

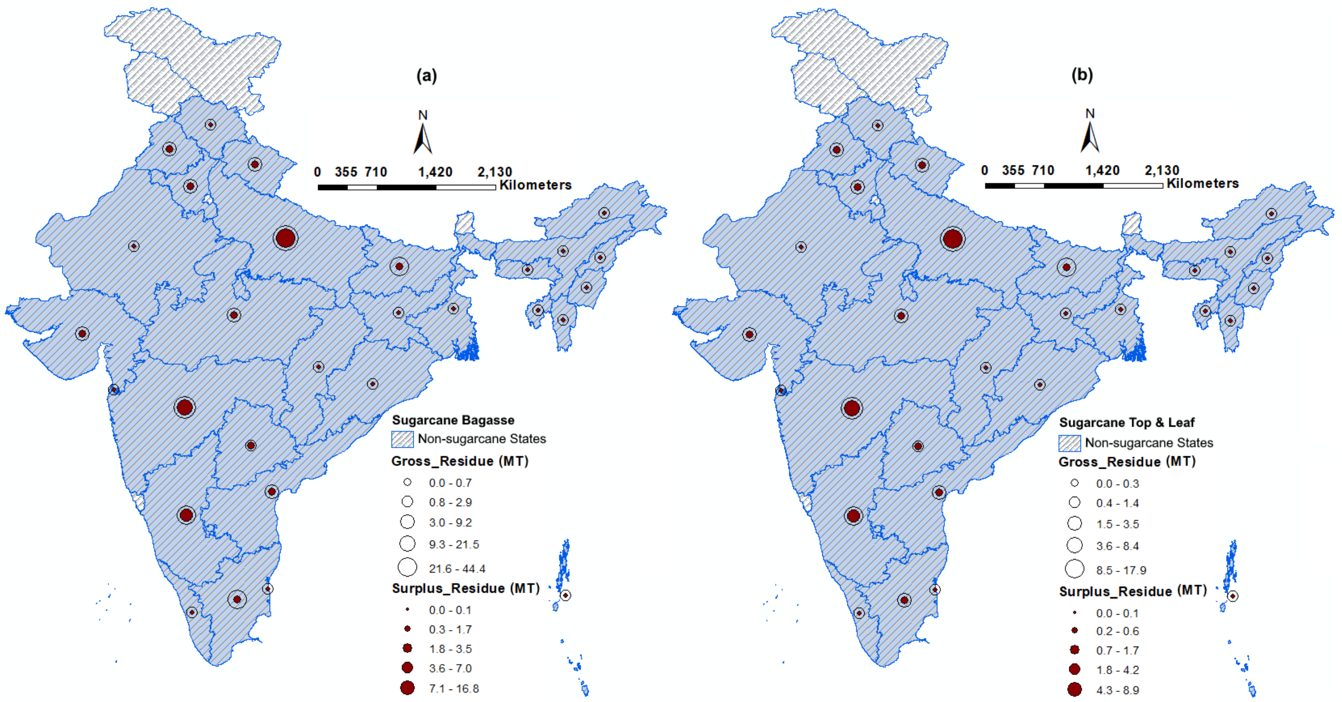

Fig. 2. State-wise distribution of gross and surplus (a) sugarcane bagasse (SB) and (b) sugarcane top & leaf (STL)

Sugarcane cultivation varies widely in different states due to various factors such as soil type, geographical area, and climatic conditions. Statistical data revealed that sugarcane is not cultivated in the states of Goa & Sikkim and the Union Territories of Jammu & Kashmir, Ladakh, Chandigarh, Delhi & Lakshadweep. It was estimated that Uttar Pradesh produces the largest quantity of gross sugarcane residues (62.3 MT), followed by Maharashtra (29.9 MT) and Karnataka (12.6 MT). Bihar (6 MT), Tamil Nadu (5.7 MT), Gujarat (4.2 MT), Haryana (3.2 MT), Andhra Pradesh (2.8 MT) and Punjab (2.7 MT) are the other states producing significant sugarcane residues. Uttar Pradesh, Maharashtra and Karnataka possess 42 MT (75.4%) sugarcane residues availability. Bihar, Tamil Nadu, Gujarat, Haryana, Andhra Pradesh and Punjab contributed 18.6 % to the surplus sugarcane residue availability. State-wise gross and surplus residues availability of STL & SB have been shown in Fig. 2.

Biochar conversion of surplus sugarcane residues at the sugarcane mill and its application for carbon sequestration in the soil at the farm have been considered. Surplus STL & SB has an estimated 17.6±0.4 MT biochar potential. Sugarcane top & leaf biochar (STLB) and sugarcane bagasse biochar (SBB) have about 36 % & 64 % share in biochar potential from surplus available sugarcane residues. It was observed that state-wise biochar potential followed a similar distribution pattern as surplus sugarcane residues availability.

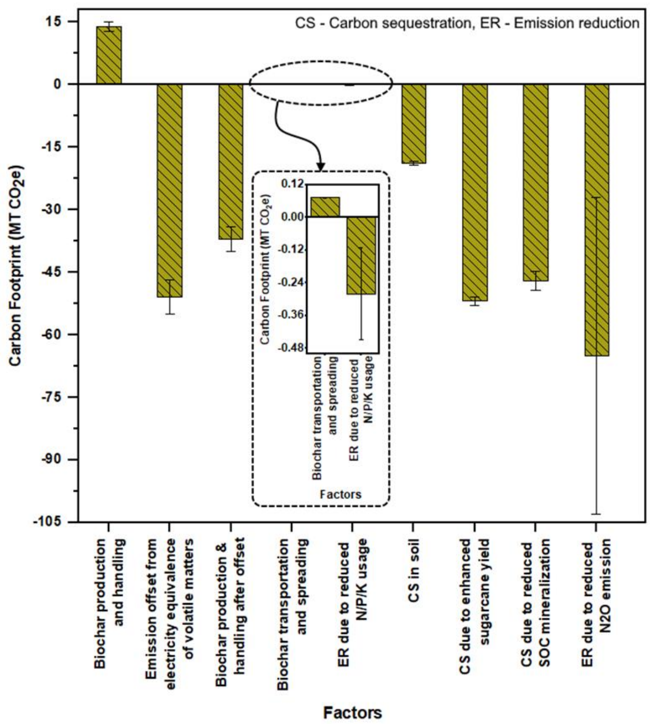

Fig. 3. Carbon footprint of various factors of sugarcane residues - biochar system for carbon sequestration in soil

B. *Carbon footprint of biochar conversion*

The carbon footprint of biochar production, material handling, transportation & spreading in the field have been discussed in this section and illustrated in Fig. 3.

Sugarcane is crushed and processed at sugar mills in India located within 25 km of sugarcane fields, i.e., sugarcane residues (STL & SB) are produced at sugar mills. Therefore, the carbon footprint of biochar conversion of sugarcane residues and its handling, transportation & spreading in the field has been considered. Also, the energy value of the volatile matter released during the pyrolysis process has been considered for electricity production and offset the electricity requirement for the pyrolysis and material handling. Coal-based electricity supply for pyrolysis and material handling has been considered. It was estimated that 14.2±0.3 TWh electricity would be required annually for pyrolyzing 54.6±1.1 MT surplus sugarcane residues with 13.9±1.2 MT CO_2e carbon footprint. Combustible volatile matter released during the pyrolysis has 52.1±0.9 TWh electricity equivalence, having a 37.9±0.6 TWh surplus than the electricity consumed in pyrolysis and material handling. The excess electricity was considered to send to the national grid. Also, electricity equivalence of combustible volatile matter could reduce 50.9±4.2 MT CO_2e carbon emission, and surplus electricity could reduce the national grid's 37±3 MT CO2e carbon emission.

Diesel-powered tractors and farm machinery were considered for biochar transportation and spreading in the field. It was estimated that biochar transportation and spreading would consume 27.5±0.6 million litres producing 72,918±1,462 T CO_2e carbon emissions.

C. *Benefits of biochar application in the field*

The environmental benefits of STLB & SBB application for carbon sequestration have been quantified & discussed in this section and illustrated in Fig. 3.

In the present study, biochar produced from sugarcane residues was considered to apply in sugarcane fields to estimate environmental benefits. It was estimated that biochar application in the sugarcane field could sequestrate 18.8±0.4 MT CO_2e carbon in the soil, 51.9±1 MT CO_2e carbon due to enhanced sugarcane yield and 47±2.2 MT CO_2e carbon due to reduced SOC mineralization. Biochar application in sugarcane field could reduce 51,251±1,028/8,542±171/17,084±343 T annual N/P/K fertilizer usage, which could reduce 0.28±0.17 MT CO_2e carbon emission due to reduced N/P/K fertilizers usage. The estimates also showed that biochar application could reduce 0.22±0.13 MT N_2O emissions from sugarcane fields having 65±38 MT CO_2e GHG emission reduction potential. Overall, biochar production from sugarcane residues and its application in the field could reduce 220.3±45.1 MT CO_2e carbon emission, which is about 9.5±2 % of the annual GHG from India. Carbon footprint of various factors of sugarcane residues - biochar system for carbon sequestration in soil has been shown in Fig. 3.

V. CONCLUSIONS

The present study aimed to quantify India's sugarcane residue- biochar system's environmental benefits and carbon sequestration potential. It was estimated that approximately 38.8 MT of STL and 96.3 MT of SB are produced annually in India. About 40.7 % of total sugarcane residues remain unused, which could produce 18 MT biochar annually and sequester around 18.8 MT CO_2e of carbon in the soil. STL & SB-derived biochar application at 10 T/ha could sequester approximately 98.9 MT CO_2e carbon due to enhanced sugarcane yield and reduced soil organic carbon mineralization. It could also reduce NPK consumption by 0.08 MT and N_2O emission by 0.22±0.13 MT. Overall, biochar conversion of sugarcane residues and its application in soil for carbon sequestration could reduce the annual carbon footprint of the country by 220.3±45.1 MT. In conclusion, the sugarcane residues - biochar system could reduce India's 9.5±2 % annual GHG emission.

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REFERENCES

[1] Directorate of Economics and Statistics. Agricultural Statistics at a Glance 2020. New Delhi: 2021.

[2] Department of Food & Public Distribution. Annual Report: 2021-22. Ministry of Consumer Affairs, Food & Public Distribution; 2022.

[3] Sujata, Anand A, Kaushal P. Life cycle assessment of strategic locations to establish molasses based bioethanol production facility in India. Clean Environ Syst 2021;3:100055. https://doi.org/10.1016/j.cesys.2021.100055.

[4] Hiloidhari M, Das D, Baruah DC. Bioenergy potential from crop residue biomass in India. Renew Sustain Energy Rev 2014;32:504–12. https://doi.org/10.1016/j.rser.2014.01.025.

[5] Trivedi V. Agro-residue for power: Win-win for farmers and the environment? New Delhi: 2020.

[6] Alvarez-campos O, Lang TA, Bhadha JH, Mccray JM, Glaz B, Daroub SH. Agriculture , Ecosystems and Environment Biochar and mill ash improve yields of sugarcane on a sand soil in Florida. Agric Ecosyst Environ 2018;253:122–30. https://doi.org/10.1016/j.agee.2017.11.006.

[7] Lefebvre D, Williams A, Meersmans J, Kirk GJD, Sohi S, Goglio P, et al. Modelling the potential for soil carbon sequestration using biochar from sugarcane residues in Brazil. Sci Rep 2020;10:1–11. https://doi.org/10.1038/s41598-020-76470-y.

[8] Anand A, Kumar V, Kaushal P. Biochar and its twin benefits: Crop residue management and climate change mitigation in India. Renew Sustain Energy Rev 2022;156:111959. https://doi.org/10.1016/j.rser.2021.111959.

[9] Sakhiya AK, Anand A, Kaushal P. Production, activation, and applications of biochar in recent times. Biochar 2020;2:253–85. https://doi.org/10.1007/s42773-020-00047-1.

[10] Quirk RG, Zwieten L Van, Kimber S, Downie A, Morris S, Rust J. Utilization of Biochar in Sugarcane and Sugar-Industry Management. Sugar Tech 2012;14:321–6. https://doi.org/10.1007/s12355-012-0158-9.

[11] Chen Y, Shinogi Y, Taira M. Influence of biochar use on sugarcane growth, soil parameters, and groundwater quality. Aust J Soil Res 2010;48:526–30.

[12] Lehmann J, Gaunt J, Rondon M. Bio-char sequestration in terrestrial ecosystems - A review. Mitig Adapt Strateg Glob Chang 2006;11:403–27. https://doi.org/10.1007/s11027-005-9006-5.

[13] Kuzyakov Y, Subbotina I, Chen H, Bogomolova I, Xu X. Black carbon decomposition and incorporation into soil microbial biomass estimated by ^{14}C labeling. Soil Biol Biochem 2009;41:210–9. https://doi.org/10.1016/j.soilbio.2008.10.016.

[14] Lefebvre D, Williams A, Kirk GJD, Meersmans J, Sohi S, Goglio P, et al. An anticipatory life cycle assessment of the use of biochar from sugarcane residues as a greenhouse gas removal technology. J Clean Prod 2021;312:127764. https://doi.org/10.1016/j.jclepro.2021.127764.

[15] Anand A, Pathak S, Kumar V, Kaushal P. Biochar production from crop residues, its characterization and utilization for electricity generation in India. J Clean Prod 2022:133074. https://doi.org/10.1016/j.jclepro.2022.133074.

[16] Gaunt JL, Lehmann J. Energy balance and emissions associated with biochar sequestration and pyrolysis bioenergy production. Environ Sci Technol 2008;42:4152–8. https://doi.org/10.1021/es071361i.

[17] Ministry of New and Renewable Energy. Bio Energy: Current Status 2022. https://mnre.gov.in/bio-energy/current-status#energy_o.

[18] Mary PCN, Anitha R. Effect of Sugarcane Trash Biochar on Enhancement of Soil Health and Sugarcane Productivity. Int J Curr Microbiol Appl Sci 2019;8:2650–60.

[19] Snekapriya VK, Jayachandran M. Effect of Sugarcane Trash Biochar on Growth and Yield of Sugarcane Seed Crop. J Madras Agric 2018;105:147–50.

[20] Hiloidhari M, Das D, Baruah DC. Bioenergy potential from crop residue biomass in India. Renew Sustain Energy Rev 2014;32:504–12. https://doi.org/10.1016/j.rser.2014.01.025.

[21] Valk M. Availability and cost of agricultural residues for bioenergy generation: International literature review and a case study for South Africa. Universiteit Utrecht, 2014.

[22] Hiloidhari M, Baruah DC. Crop residue biomass for decentralized electrical power generation in rural areas (part 1): Investigation of spatial availability. Renew Sustain Energy Rev 2011;15:1885–92. https://doi.org/10.1016/j.rser.2010.12.010.

[23] Yang Q, Mašek O, Zhao L, Nan H, Yu S, Yin J, et al. Country-level potential of carbon sequestration and environmental benefits by utilizing crop residues for biochar implementation. Appl Energy 2021;282. https://doi.org/10.1016/j.apenergy.2020.116275.

[24] Central Electricity Authority. Power sector at a glance: All India 2021. https://powermin.gov.in/en/content/power-sector-glance-all-india.

[25] Zhang Q, Xiao J, Xue J, Zhang L. Quantifying the effects of biochar application on greenhouse gas emissions from agricultural soils: A global meta-analysis. Sustainability 2020;12:1–14. https://doi.org/10.3390/SU12083436.

[26] Prabha ACS, Rangasamy VR, Muniyandi S. Soil organic carbon assessment under different land uses in Cauvery delta zone of Tamil Nadu, India. J Appl Nat Sci 2020;12:478–83.

[27] Havukainen J. Carbon Footprint evaluation of biofertilizers. Int J Sustain Dev Plan. 2018;13:1050–60. https://doi.org/10.2495/SDP-V13-N8-1050-1060.

[28] IPCC. Climate Change 2014: Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom: 2014.

[29] Department for Business Energy & Industrial Strategy. Government conversion factors for company reporting of greenhouse gas emissions 2013. https://www.gov.uk/government/collections/government-conversion-factors-for-company-reporting.

[30] Central Electricity Authority. CO_2 Baseline Database for the Indian Power Sector. New Delhi, India: Ministry of Power, Government of India; 2020.

[31] Denmead OT, Macdonald BCT, Bryant G, White I, Wang W, Moody P, et al. Greenhouse gas emissions from sugarcane solis and nitrogen fertilizer management. Proc. Aust. Soc. Sugar Cane Technol., vol. 28, Cairns: 2006, p. 251–9.

[32] Anand A, Sakhiya AK, Aier I, Kakati U, Kumar V, Kaushal P. Assessment of electricity generation potential from biochar in Northern India. Energy Clim Chang 2022;3:100068. https://doi.org/10.1016/j.egycc.2021.100068.

[33] Jain N, Sehgal VK, Singh S, Kaushik N. Estimation of surplus crop residues in India for biofuel production. New Delhi, India: Technology Information, Forecasting and Assessment Council; 2018.