LIFE CYCLE ASSESSMENT (LCA) OF CROP RESIDUE – BIOCHAR SYSTEM FOR ENERGY SECURITY AND CARBON SEQUESTRATION

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by

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"The world will not evolve past its current state of crisis by using the same thinking that created the situation."

Albert Einstein

”दुनिया उसी सोच का उपयोग करके अपने वर्तमान संकट की स्थिति से आगे नहीं बढ़ पाएगी जिसने यह स्थिति पैदा की थी।“

अल्बर्ट आइंस्टीन

This thesis is dedicated to my beloved mother,

"Swargeeya Shrimati Sharda Kumari"

"स्वर्गीय श्रीमती शारदा कुमारी"

a woman of grace and resilience with abundant love, care, and affection who fought every odd and stood firm in the extreme struggle of educating her children.

She had always been the driving force behind my dreams, my quest for their fulfilment and my achievements.

Although she is not amongst us to witness the completion of this thesis, the enduring impact of her spirit resonates in every word, every line, every page and every accomplishment of this thesis.

Her teachings and blessings will keep enlightening me on the path of unfulfilled dreams.

With eternal love

Abhijeet Anand

CERTIFICATE

This is to certify that the thesis entitled "Life Cycle Assessment (LCA) of Crop Residue - Biochar System for Energy Security and Carbon Sequestration", being submitted by **Mr. Abhijeet Anand** to the **Indian Institute of Technology Delhi** for the award of **"Doctor of Philosophy"** is a record of bonafide research work carried out by him. He has worked under our guidance and supervision and has fulfilled the requirements for the submission of this thesis. To the best of our knowledge, the results contained in this thesis have not been submitted in part or full to any other university or institute for the award of any degree or diploma.

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As I conclude this thesis, I am reminded that this achievement is not solely mine but a culmination of the support and encouragement of many individuals. With profound gratitude, I dedicate this work to all who have stood by me, believed in me, and supported me throughout this journey. Their contributions, both big and small, have made this possible, and for that, I am eternally grateful.

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Abhijeet Anand

ABSTRACT

With approximately 328.7 Mha land mass and home to a sixth of the global population, India is the world's seventh largest and most populous country. Agriculture is the primary economic activity in the country, making up about 51.1 % of the total Indian landmass, employing 54 % of the population and contributing 17.7 % to the country's GDP. India is the second-largest crop producer globally, and the average net sown area was 45.2 % of the reported area for land utilization in India (308.3 Mha), with about 143.6 % cropping intensity during 2019 - 20. Normal estimates (average of 2015-16 to 2019-20) show that approximately 678.7 MT of food grains, pulses, oilseeds and cash crops were harvested from 169.8 Mha of the gross sown area. Government estimates showed that rice, wheat, and sugarcane cumulatively have 46 % and 85 % shares in India's average sown area and total agro production, respectively.

Year-round crop cultivation generates approximately 600 MT of crop residues in India, used as animal fodder and fuel for household cooking and heating in various rural industries such as pottery, brick kilns, and rice mills. According to the estimates, India has a potential of 180 - 240 MT surplus crop residues (left-over residues), out of which 120 - 140 MT crop residue is set to open fire in agriculture due to the lack of proper disposal and handling. Rice straw (43 - 53 %), wheat straw (26 - 33 %), coarse cereals residue (10 - 12 %), and sugarcane residues (10 - 13 %) have a significant share in crop residue in-situ burning.

Repeated crop-residue in-situ burning adversely affects the environment, soil health and crop productivity. Literature suggests that in-situ burning of about 116.8 MT of crop residue released approximately 184 MT of GHGs and toxic emissions such as CO_2, CH_4, N_2O, CO, NO_x, SO_x, and others. These pollutants harm the environment and human health and

contribute to global warming and climate change. For example, Delhi NCR, Haryana, and Punjab face a disastrous smog impact from October to November every year. In-situ burning of crop residues also adversely affects the development and maintenance of the soil's microbial ecosystem, soil fertility and water-holding capacity and causes it to develop a hardened surface, which exuberates soil salination and erosion. Therefore, land degradation and loss of agricultural productivity, water quality and biodiversity are repercussions of crop residue in-situ burning.

The Government of India (GoI) has formulated and implemented various technical, economic, and policy-level measures such as the institutionalization of the Commission for Air Quality Management, the introduction of twin-cutter-combined-harvester, happy seeder, zero-seed-cum-fertilizer drill and others to address the in-situ crop residue burning issue. These measures aimed to integrate sustainable agricultural practices into the broader environmental conservation and climate change mitigation framework. However, these interventions could not be popularised due to a lack of technical know-how, sufficient economic remuneration, social consciousness and awareness among farmers.

In this context, crop residue conversion to such end products (like biochar), which can be utilized in the agriculture sector and for electricity generation, has been pitched as one of the best alternative measures for crop residue management at such a large scale. However, it is essential to evaluate the environmental impact of the end application of biochar to declare biochar conversion of crop residue and its intended end application as an eco-friendly and sustainable route for crop residue management.

Life cycle assessment (LCA) can be a systemic approach to define, quantify, and evaluate the environmental impact of the biochar conversion of crop residues and its end application under the umbrella concept of life cycle thinking (LCT).

The present research focused on crop residue management in the Indian states of Punjab and Haryana through biochar conversion of crop residue and its application for electricity generation and carbon sequestration in soil. Three crop residues from the most cultivated crops in the study area, namely rice straw (RS), wheat straw (WS) and sugarcane top and leaf (STL), have been considered in the study to investigate biochar potential for electricity generation and carbon sequestration. Further emission footprint and cost-benefit analysis of the proposed pathway of crop residue-biochar system for electricity generation and carbon sequestration was done to assess the sustainability and economic viability of the proposed pathways in various scenarios. The results showed that biochar produced from RS and WS at 400 ^{o}C (RSB400 and WSB400) and STL at 500 ^{o}C (STLB500) suits co-firing. Biochar produced from RS and WS at 650 ^{o}C (RSB650 and WSB650) and STL at 600 ^{o}C (STLB600) are suitable for carbon sequestration.

The estimates showed that approximately 52.2 MT RS, WS and STL are annually produced in the study area, of which 21.75±0.17 MT are burned in situ. In-situ burning of RS, WS and STL impart 38.8±2.4 MT CO$_2$e emission footprint. On the other hand, it was estimated that about 6.83 MT of biochar suitable for co-firing and 5.48 MT of biochar suitable for carbon sequestration could be produced from in-situ burned crop residues. Electricity generation from crop residue-biochar systems could reduce 9.7 MT coal consumption in the thermal power plants of Punjab and Haryana and generate 14.2 GWh of electricity annually. Also, 13.1 MT CO$_2$e could be achieved from biochar application in the soil for carbon sequestration, which could sequestrate 13.1 MT CO$_2$e carbon annually. Scenario analysis showed that crop residue in-situ burning and coal-based electricity generation in Punjab and Haryana (CuSc) cumulatively imparted 85.5 MT CO$_2$e emission footprint in 2019-20. However, crop residue-biochar systems for electricity generation and carbon sequestration under the proposed pathway (PP–I and PP–II) would impart 30.7 MT CO$_2$e and 29.9 MT

CO_2e emission footprint, respectively. Therefore, about 54.7 MT CO_2e and 55.6 MT CO_2e annual emission footprint reduction could be achieved from proposed pathways of crop residue-biochar system for electricity generation and carbon sequestration in soil, respectively.

Furthermore, inflation-adjusted annual cost-benefit analysis under life cycle cost analysis showed that the proposed pathway of crop residue - biochar system for electricity generation with carbon credit monetization of net emission reduction @20 USD/T CO_2e and zero-cost crop residue scenario is the most profitable and thus economically preferable.

The sensitivity analysis of input parameters of the emission footprint analysis model under proposed pathways showed that an increase in crop yield and decrease in fuel consumption (i.e., more efficient transportation systems) present the additional benefits of reduced emission footprint of the proposed pathway of crop residue management in Punjab and Haryana. Also, sensitivity analysis of input parameters of the cost-benefits analysis model under proposed pathways showed that an increase in crop yield and a decrease in cost-related expenditure present an additional opportunity to increase net benefit or decrease the revenue deficit under various scenarios of the proposed pathway of crop residue management in Punjab and Haryana.

सार

लगभग 328.7 मिलियन हेक्टेयर भूमि और वैश्विक आबादी के छठे हिस्से का घर होने के साथ, भारत दुनिया का सातवां सबसे बड़ा और सबसे अधिक आबादी वाला देश है। लगभग 51.1 % भूभाग पर किये जाने वाला कृषि, भारत में प्राथमिक आर्थिक गतिविधि है, जो कुल आबादी के 54 % हिस्से को रोजगार के अवसर मुहैया कराता है और देश के सकल घरेलू उत्पाद में 17.7 % का योगदान देता है। भारत वैश्विक स्तर पर दूसरा सबसे बड़ा फसल उत्पादक है, और सामान्य अनुमान (2015 – 16 से 2019 – 20 का औसत) के अनुसार 169.8 मिलियन हेक्टेयर के सकल बोए गए कृषि भूभाग से लगभग 678.7 मिलियन टन खाद्यान्न, दलहन, तिलहन और नकदी फसलों का उत्पादन हुआ। भारत सरकार द्वारा जारी किये गये आंकड़ों से पता चला है कि चावल, गेहूं और गन्ने की संचयी रूप से औसत बोए गए भूभाग में 46 % और कुल कृषि उत्पादन में 85 % हिस्सेदारी रही है।

भारत में सालभर होने वाले कृषि उत्पादन से लगभग 600 मिलियन टन फसल अवशेष उत्पन्न होते हैं, जिनका उपयोग पशु चारे के रूप में, घरेलू खाना पकाने और विभिन्न ग्रामीण उद्योगों में ईंधन के रूप में और अन्य दुसरे उद्देश्य की पूर्ति हेतु किया जाता है। अनुमानों के अनुसार, भारत में प्रति वर्ष 180 – 240 मिलियन टन फसल अवशेष अधिशेष रह जाते हैं, जिसमें से 120 – 140 मिलियन टन अधिशेष फसल अवशेषों को उचित निपटान की कमी के कारण खेतों के खुले वातावरण में ही जला दिया जाता है। खेतों के खुले वातावरण में सर्वाधिक जलाये जाने वाले अधिशेष फसल अवशेषों में चावल की खेती से प्राप्त पराली (43 – 53 %), गेहूं की खेती से प्राप्त पराली (26 – 33 %), मोटे अनाज की खेती से प्राप्त अवशेष (10 – 12 %) और गन्ने का ऊपरी भाग और पत्ती (10 – 13 %) का महत्वपूर्ण हिस्सा होता है।

बार–बार फसल अवशेषों को खेतों के खुले वातावरण में जलाने से पर्यावरण, मृदा स्वास्थ्य और फसल उत्पादकता पर प्रतिकूल प्रभाव पड़ता है। साहित्य से पता चलता है कि 116.8 मिलियन टन फसल अवशेषों को खुले वातावरण में जलाने से लगभग 184 मिलियन टन ग्रीनहाउस और अन्य जहरीले गैस

जैसे CO_2, CH_4, N_2O, CO, NO_x, और SO_x का उत्सर्जन होता हैं। ये प्रदूषक पर्यावरण और मानव स्वास्थ्य को नुकसान पहुंचाते हैं और ग्लोबल वार्मिंग और जलवायु परिवर्तन में भी इनका अहम योगदान होता हैं। उदाहरण के लिए, अधिशेष फसल अवशेषों को खेतों के खुले वातावरण में जलाने से राष्ट्रीय राजधानी क्षेत्र दिल्ली, हरियाणा और पंजाब हर साल अक्टूबर से नवंबर तक भयावह धुंध के प्रभाव का सामना करते हैं। साथ ही फसल अवशेषों को खेतों के खुले वातावरण में जलाने से मिट्टी के सुक्ष्मजगतीय पारिस्थितिकी तंत्र और जैव विविधता, मिट्टी की उर्वरता और जल धारण क्षमता पर भी प्रतिकूल प्रभाव पड़ता है और इससे मिट्टी की उपरी सतह सख्त हो जाती है, जिससे मिट्टी का लवणीकरण और कटाव बढ़ जाता है।

भारत सरकार ने अधिशेष फसल अवशेषों को खेतों के खुले वातावरण में जलाने की समस्या से निपटने के लिए वायु गुणवत्ता प्रबंधन आयोग का गठन करने के साथ साथ विभिन्न तकनीकी (जैसे कि ट्विन–कटर–कंबाइंड–हार्वेस्टर, हैप्पी सीडर, जीरो–सीड–कम–फर्टिलाइजर ड्रिल), आर्थिक और नीति–स्तरीय उपायों को तैयार और कार्यान्वित किया है। इन उपायों का मूल उद्देश्य व्यापक पर्यावरण संरक्षण और जलवायु परिवर्तन के प्रभाव को कम करने वाले कृषि आधारित प्रथाओं को एकीकृत करना था। हालाँकि, तकनीकी जानकारी, पर्याप्त आर्थिक पारिश्रमिक, सामाजिक चेतना और किसानों के बीच जागरूकता की कमी के कारण इन उपायों को लोकप्रिय नहीं बनाया जा सका।

इस संदर्भ में, इतने बड़े पैमाने पर अधिशेष फसल अवशेष प्रबंधन के लिए फसल अवशेषों को कृषि क्षेत्र और बिजली उत्पादन में उपयोग होने वाले उत्पादों (जैसे बायोचार) में परिवर्तित करने को सबसे अच्छे वैकल्पिक उपायों में से एक माना गया है। हालाँकि, फसल अवशेषों के बायोचार रूपांतरण और इसके इच्छित अंतिम अनुप्रयोग को पर्यावरण के लिए अनुकूल फसल अवशेष प्रबंधन के रूप में घोषित करने के लिए बायोचार के अंतिम अनुप्रयोग के पर्यावरणीय प्रभाव का मूल्यांकन करना आवश्यक है। फसल अवशेषों के बायोचार रूपांतरण और इसके इच्छित अंतिम अनुप्रयोग के पर्यावरणीय प्रभाव का मूल्यांकन करने के लिए जीवन चक्र मूल्यांकन (LCA) की छत्र अवधारणा का उपयोग किया जा सकता है।

वर्तमान शोध पंजाब और हरियाणा में अधिशेष फसल अवशेषों के बायोचार रूपांतरण और बिजली

उत्पादन और मिट्टी में कार्बन अधिकृत करने में इसके अनुप्रयोग के माध्यम से फसल अवशेष प्रबंधन पर किया गया। अध्ययन क्षेत्र में सबसे अधिक खेती की जाने वाली फसलों के तीन फसल अवशेषों – चावल की खेती से प्राप्त पराली (RS), गेहूं की खेती से प्राप्त पराली (WS), और गन्ने का ऊपरी भाग और पत्ती (STL) से प्राप्त बायोचार को बिजली उत्पादन और मिट्टी में कार्बन अधिकृत करने की इसकी क्षमता का विश्लेषण किया गया। साथ ही साथ, विभिन्न परिदृश्यों में फसल अवशेष प्रबंधन के लिए फसल अवशेष – बायोचार प्रणाली के प्रस्तावित उपायों (बायोचार का बिजली उत्पादन और मिट्टी में कार्बन अधिकृत करने में अनुप्रयोग) के पर्यावरणीय प्रभाव और आर्थिक व्यवहार्यता का आकलन किया गया। प्रयोगात्मक परिणामों से पता चला कि RS और WS से 400 °C (RSB400 और WSB400) और STL से 500 °C (STLB500) पर उत्पादित बायोचार बिजली उत्पादन के लिए उपयुक्त है। RS और WS से 650 °C (RSB650 और WSB650) और STL से 600 °C (STLB600) पर उत्पादित बायोचार मिट्टी में कार्बन अधिकृत करने के लिए उपयुक्त हैं।

अंकगणितीय गणना से पता चला कि अध्ययन क्षेत्र में सालाना लगभग 52.2 मिलियन टन RS, WS और STL का उत्पादन होता है, जिसमें से 21.75±0.17 मिलियन टन को खेतों के खुले वातावरण में यथावत जला दिया जाता है। RS, WS और STL को खेतों के खुले वातावरण में यथावत जलाने से 38.8±2.4 मिलियन टन CO_2e ग्रीनहाउस गैसों का उत्सर्जन होता है। वहीँ दूसरी ओर, खेतों के खुले वातावरण में यथावत जलाये गये 21.75±0.17 मिलियन टन फसल अवशेषों से बिजली उत्पादन के लिए उपयुक्त लगभग 6.83 मिलियन टन बायोचार और मिट्टी में कार्बन अधिकृत करने के लिए उपयुक्त 5.48 मिलियन टन बायोचार का उत्पादन किया जा सकता है। फसल अवशेषों से बिजली उत्पादन के लिए उपयुक्त लगभग 6.83 मिलियन टन बायोचार से पंजाब और हरियाणा के ताप विद्युत संयंत्रों में सालाना 14.2 GWh बिजली उत्पादन के साथ–साथ 9.7 मिलियन टन कोयले की खपत कम की जा सकती है। साथ ही, मिट्टी में बायोचार के अनुप्रयोग से सालाना 13.1 मिलियन टन CO_2e कार्बन को मिट्टी में अधिकृत किया जा सकता है।

परिदृश्य विश्लेषण से पता चला है कि पंजाब और हरियाणा में फसल अवशेषों को खेतों के खुले वातावरण में यथावत जलाने और कोयला–आधारित बिजली उत्पादन (CuSc) से संचयी रूप से 2019–20 में 85.5 मिलियन टन CO_2e ग्रीनहाउस गैसों का उत्सर्जन हुआ। हालांकि, फसल अवशेष प्रबंधन के लिए फसल अवशेष – बायोचार प्रणाली के प्रस्तावित उपायों, बायोचार का बिजली उत्पादन और मिट्टी में कार्बन अधिकृत करने में अनुप्रयोग (क्रमशः PP-I और PP-II) से सालाना क्रमशः 30.7 और 29.9 मिलियन टन CO_2e ग्रीनहाउस गैसों का उत्सर्जन होगा। इसप्रकार, फसल अवशेष – बायोचार प्रणाली के प्रस्तावित उपायों, बायोचार का बिजली उत्पादन और मिट्टी में कार्बन अधिकृत करने में अनुप्रयोग (क्रमशः PP-I और PP-II) से सालाना क्रमशः लगभग 54.7 और 55.6 मिलियन टन CO_2e ग्रीनहाउस गैसों का उत्सर्जन कम किया जा सकता है।

इसके अलावा, जीवन चक्रीय लागत विश्लेषण के तहत मुद्रास्फीति–समायोजित वार्षिक लागत–लाभ विश्लेषण से पता चला है कि फसल अवशेष – बायोचार प्रणाली के प्रस्तावित उपायों के तहत बायोचार का बिजली उत्पादन में अनुप्रयोग और 20 USD/T CO_2e पर कार्बन क्रेडिट मुद्रीकरण और शून्य–लागत पर फसल अवशेष अधिग्रहण परिदृश्य आर्थिक रूप से सर्वाधिक लाभकारी है। फसल अवशेष प्रबंधन के लिए फसल अवशेष – बायोचार प्रणाली के प्रस्तावित उपायों के तहत उत्सर्जन विश्लेषण मॉडल के इनपुट मापदंडों के संवेदनशीलता विश्लेषण से पता चला है कि फसल की पैदावार में वृद्धि और ईंधन की खपत में कमी (यानी, अधिक कुशल परिवहन प्रणाली) पंजाब और हरियाणा में फसल अवशेष प्रबंधन के प्रस्तावित उपायों के तहत कम ग्रीनहाउस गैसों के उत्सर्जन का अतिरिक्त लाभ प्रस्तुत करती है। साथ ही, फसल अवशेष प्रबंधन के लिए फसल अवशेष – बायोचार प्रणाली के प्रस्तावित उपायों के तहत लागत–लाभ विश्लेषण मॉडल के इनपुट मापदंडों के संवेदनशीलता विश्लेषण से पता चला है कि फसल की पैदावार में वृद्धि और लागत–संबंधित व्यय में कमी पंजाब और हरियाणा में प्रस्तावित उपायों के विभिन्न परिदृश्यों के तहत शुद्ध लाभ को बढ़ाने या राजस्व घाटे को कम करने का एक अतिरिक्त अवसर प्रस्तुत करती है।

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LIST OF SYMBOLS

Symbol / Syntax	Description
%	Percentage
±	Plus/minus
>	Greater than
≥	Greater than equal to
<	Less than
≤	Less than equal to
$	US Dollar
α	Conversion ratio
β	Heating rate
$f(\alpha)$	Reaction model
$\Delta H_{vap,w}$	Enthalpy of water vaporization
ΔH_{py}	Enthalpy of pyrolysis
η	TPP efficiency
ψ_c	Coal equivalence factor

ψ_D	Diesel - CO_2e factor
ψ_E	Electricity - CO_2e factor
ϵ_L	Correction factor for loading activity only
ϵ_U	Correction factor for unloading activity only
σ_{BCFH}	Lost fraction of biochar for co-firing during material handling
$\sigma_{BCSTQLUN}$	Lost fraction of material during loading-unloading at the collection nodes
σ_{CRC}	Lost fraction of crop residue during collection
σ_{CRLPT}	Lost fraction of crop residue during pre-processing and handling at TPP
σ_{CRLUN}	Lost fraction of crop residue during loading-unloading at the collection node
γ_{VMCBCF}	Fraction of volatile matter combusted for crop residue pre-heating and pyrolysis for biochar production for co-firing
γ_{VMCBCS}	Fraction of volatile matter combusted for crop residue pre-heating and pyrolysis for biochar production for carbon sequestration

LIST OF UNITS

Symbol / Syntax	Description
°C	degree Celsius
°C/min	degree Celsius per minute
bale/h	Bale per hour
cm	Centimetre
CO_2e	Carbon dioxide equivalent
CO_2e/kWh	Carbon dioxide equivalent per kilo Watt hour
CO_2e/L	Carbon dioxide equivalent per litre
g	Gram
GT	Giga ton
h	Hour
h/day	Hour per day
ha	Hectare
INR	Indian Rupee
kg	kilogram
kg/bale	kilogram per bale

kg CO_2e/T	kilogram carbon dioxide equivalent per ton
kg/ha	kilogram per hectare
kg/ha/yr	kilogram per hectare per year
kJ	kilo Joule
kJ/kg	kilo Joule per kilogram
kJ/kg-K	kilo Joule per kilogram per kelvin
kJ/mol	kilo Joule per mole
kg/T	kilogram per ton
km	kilometre
km/L	kilometer per liter
kW	kilo Watt
kWh	kilo Watt hour
kWh/T	kilo Watt hour per ton
L	Liter
L/T	Liter per ton
L/T-km	Liter per ton per kilometer
mg	Milligram

Mha	Million hectares
min	Minute
ml	Milliliter
ml/min	Milliliter per minute
mm	Millimeter
MJ	Mega joule
MJ/kg	Mega joule per kilogram
MT	Million ton
MT/ha	Million tons per hectare
MW	Megawatt
MWh/T	Megawatt hour per ton
T	Ton
T/h	Ton per hour
T/ha	Ton per hectare
T/kWh	Ton per kilowatt hour
T/T	Ton per ton
T/T-km	Ton per ton per kilometre

T/year/baler	Ton per year per baler
T CO_2e	Ton carbon dioxide equivalent
T CO_2e/T	Ton carbon dioxide equivalent per ton
TPH	Ton per hour
TW	Tera Watt
USD/ha	United States Dollar per hectare
USD/kWh	United States Dollar per kilo Watt hour
USD/T CO_2e	United States Dollar per ton carbon dioxide equivalent
USD/T-km	United States Dollar per ton per kilometre

LIST OF ABBREVIATIONS

Symbol / Syntax	Description
A	Pre-exponential factor
ADR	Average decomposition rate
ASCs	Agriculture Service Centres
ASTM	American Society for Testing and Materials
ArcGIS	Geographic information system (software)
AW_f	Factor of added water
$BaCl_2$	Barium chloride
$BaCO_3$	Barium carbonate
BAU	Business-as-usual
BC_{aCF}	Biochar availability for co-firing
BC_{aCS}	Biochar availability for carbon sequestration
BC_{pCF}	Biochar potential for co-firing
BC_{pCS}	Biochar potential for carbon sequestration
BCF	Biochar combustion in co-firing
BCFH	Handling of biochar for co-firing

BCP	Biochar production
BCSH	Handling of biochar for carbon sequestration
BCSL_{100}	Loss of biochar carbon during the first 100 years of sequestration in the soil
BCSLDT	Biochar for carbon sequestration long-distance transportation
BCSLT	Biochar for carbon sequestration loading at TPPs
BCSLUN	Biochar for carbon sequestration loading-unloading at the collection node
BCSS	Biochar carbon sequestration in soil
BCSSDT	Biochar for carbon sequestration short-distance transportation
BCSDF	Biochar for carbon sequestration dissemination in the field
BDF	Biochar dissemination in the field
BPP	Biochar permanence potential
$c_{p,r(T_{dry})}$	Specific heat capacity of crop residue at T_{dry}
$c_{p,r(T_0)RS}$	Specific heat capacity of RS at T_0
$c_{p,r(T_0)WS}$	Specific heat capacity of WS at T_0
$c_{p,r(T_0)}$	Specific heat capacity of STL at T_0

$c_{p,w}$	Specific heat capacity of water at T_0
CAGRs	Cumulative Annual Growth Rates
CCEG	Coal combustion for electricity generation
CE	Emission from combustion
CHCs	Custom Hiring Centres
CHN	Carbon hydrogen and nitrogen
CHP	Combined Heat & Power
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
C_{org}	Organic Carbon
CE_{BCCF}	Coal equivalence of biochar suitable for co-firing
CE_{SVMCF}	Coal equivalence of surplus volatile matter obtained from biochar conversion of crop residue for co-firing
CE_{SVMCF}	Coal equivalence of surplus volatile matter obtained from biochar conversion of crop residue for carbon sequestration
CEC	Coal equivalence content
CLS	Carbon lost from the soil

CoalCEGafteroffsetCF	Coal combustion for electricity generation after offsetting coal equivalence of biochar and volatile matter (obtained from crop residue pyrolysis to produce biochar suitable for co-firing)
CoalCEGafteroffsetCS	Coal combustion for electricity generation after offsetting coal equivalence of volatile matter (obtained from crop residue pyrolysis to produce biochar suitable for carbon sequestration)
CPCB	Central Pollution Control Board
CR_a	Crop residue availability for biochar conversion
CRC	Crop residue collection
CRF	Central Research Facility
CRLF	Crop residue loading at the field
CRLUN	Crop residue loading-unloading at the collection node
CRLDT	Crop residue long-distance transportation
CRPT	Crop residue pre-treatment
CRSDT	Crop residue short-distance transportation
CRUT	Crop residue unloading at TPPs
CS	Carbon sequestration
CSE	Centre for Science and Environment

CuSc	Current scenario
CY	Crop yield
DCRTPS	Deenbandhu Choturam Thermal Power Station
DM	Dry matter
DTG	Differential thermogravimetric
E_a	Activation energy
EBC	European Biochar Certificate
EC	Elemental carbon
EG&CCMofNER	Electricity generation and carbon credit monetization of net emission reduction
EoLCR	End-of-life capital recovery
F	Fuel consumption
FAO	Food and Agriculture Organization
FC	Fixed carbon
GC-MS	Gas chromatography-mass spectrometry
GDP	Gross Domestic Product
GGSSTP	Guru Govind Singh Super Thermal Plant

GHG	Greenhouse gas
GHTP	Guru Hargobind Thermal Plant
GoI	Government of India
GSI	Gained stability index
GSTPP	Goindwal Sahib Thermal Power Plant
GWP_{100}	Global warming potential at 100 years scale
H	Hydrogen
$H_{loss,py}$	Energy loss from pyrolysis
H_{ph}	Energy required for pre-heating
$H_{IMr,py}$	Energy needed for the removal of inherent moisture
$H_{py,CF}$	Energy required for crop residue pyrolysis to produce biochar suitable for co-firing
$H_{py,CS}$	Energy required for crop residue pyrolysis to produce biochar suitable for carbon sequestration
HCl	Hydrochloric acid
$HgCl_2$	Mercuric chloride
H_2SO_4	Sulphuric acid
IB	In-situ burning

IBI	International Biochar Initiative
ICAR	Indian Council of Agricultural Research
IGSTP	Indira Gandhi Super Thermal Power
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
K	Potassium
K_2O	Potash
LCA	Life Cycle Assessment
LCCA	Life Cycle Cost Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LCT	Life Cycle Thinking
LU	Loading-Unloading
LULUCF	Land use, land-use change, and forestry
MGTPS	Mahatma Gandhi Thermal Power Station
MoA&FW	Ministry of Agriculture and Farmers Welfare
MoRD	Ministry of Rural Development

MSW	Municipal Solid Waste
N	Nitrogen
NaOH	Sodium hydroxide
NCR	National Capital Region
NMVOC	Non-methane volatile organic compounds
NPK	Nitrogen, Phosphorous, Potassium
N/P/K/S	Nitrogen, Phosphorous, Potassium, Sulphur
NPMCR	National Policy for Management of Crop Residues
NO_x	Oxides of nitrogen
N_2O	Nitrous oxide
O	Oxygen
OC	Organic carbon
P	Phosphorus
PAH	Poly aromatic hydrocarbon
PDR	Peak decomposition rate
$PM_{2.5}$ & PM_{10}	Particulate matters
P_2O_5	Phosphates

PP	Proposed pathway
PPP	Public Private Partnership
PR	Pyrolysis reactor
PTP	Pre-treatment and pyrolysis
PTPS	Panipat Thermal Power Station
QES	Quality Estimate Scale
R	Universal gas constant
R^2	Correlation coefficient
R_{50}	Recalcitrance Index
RGTPP	Rajiv Gandhi Thermal Power Plant
RPR	Residue-to-produce ratio
RS	Rice Straw
RSB	Rice straw biochar
RTPP	Rajpura Thermal Power Plant
RW	Residual weight
S	Sulphur
SAFAR	System for Air Quality and Weather Forecasting and Research

SHGs	Self Help Groups
SOC	Soil Organic Carbon
SO_2	Sulphur dioxide
STL	Sugarcane top and leaf
STLB	Sugarcane top and leaf biochar
SRT	Solid Residence Time
T_0	Ambient temperature
T_{dry}	Pre-heating temperature
$T_{dry,f}$	Moisture free temperature
T_{SDT}	Short distance transport
TCD	Thermal Conductivity Detector
TG	Thermogravimetric
TGA	Thermogravimetric analysis
TOC	Total Organic Carbon
TPPs	Thermal power plants
TR	Temperature range
TRL	Technology Readiness Level

TSPS	Talwandi Sabo Power Station
UN	United Nation
UNEP	United Nations Environment Programme
VM	Volatile matter
VMCBCF	Volatile matter combustion to produce biochar suitable for co-firing
VMCBCS	Volatile matter combustion to produce biochar suitable for carbon sequestration
VMCEGBCF	Surplus volatile matter (obtained from crop residue pyrolysis to produce biochar suitable for co-firing) combustion for electricity generation
VMCEGBCS	Surplus volatile matter (obtained from crop residue pyrolysis to produce biochar suitable for carbon sequestration) combustion for electricity generation
VOCs	Volatile organic compounds
WL	Weight loss
WS	Wheat straw
WSB	Wheat straw biochar