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 ºC (RSB400 and WSB400) and STL at 500 ºC (STLB500) suits co-firing. Biochar produced from RS and WS at 650 ºC (RSB650 and WSB650) and STL at 600 ºC (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_2e 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_2e could be achieved from biochar application in the soil for carbon sequestration, which could sequestrate 13.1 MT CO_2e carbon annually. Scenario analysis showed that crop residue in-situ burning and coal combustion for electricity generation in Punjab and Haryana (CuSc) cumulatively imparted 85.5 MT CO_2e 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_2e 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.