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A comparative assessment of rice straw management alternatives in Pakistan in a life cycle perspective

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Abstract: Being an agrarian country, Pakistan is facing an agricultural waste disposal problem which has led to environmental and health issues due to the open burning. Rice straw is one of the notable farm residues which is currently being unutilized in the country. On the other hand, the power sector of Pakistan is heavily reliant on thermal energy. Rice straw could be an attractive source of feedstock for power generation from an alternate perspective. However, on a preliminary basis, the environmental implications need to be studied in a life cycle perspective before the exploitation of straw-based power production. In this study, three different scenarios of rice straw management were analyzed with life cycle assessment, including; (1) open burning, (2) straw mulching, and (3) direct combustion for power production. The results revealed that the open burning of rice straw exhibited the significant impacts on the environment in terms of $PM_{2.5}$, terrestrial acidification, freshwater eutrophication and human damage ozone formation. On the other hand, the production phase was found to be the major source of greenhouse gas emissions; as in case of base case scenario, nearly 75% of the total greenhouse gas emissions were contributed by the agricultural stage. The direct combustion scenario presented the highest environmental sustainability followed by the straw mulching. The core benefits were obtained through refraining from the open burning of rice straw in the field and by the substitution of the grid electricity.

Keywords: Rice straw, LCA, straw mulching, direct combustion, zero-tillage happy seeder.

1. Introduction

There is a growing concern around the world to find out multiple energy resources due to the rising price of conventional fuels, climate change, and energy security [1]. One the other hand, the abundant availability, CO_2 neutrality, and the competition avoidance of food and fuels, are the most appealing properties due to which the agricultural residues are gaining attraction as an alternate source of energy (i.e. bioenergy) to substitute conventional fuels [2]. In principle, the modern applications of biomass are progressively becoming significant to the world as a distributed and low-carbon source of national renewable energy [3], especially in the case of agrarian countries such as Pakistan, where the availability of biomass is easy. However, the environmental profile of such utilization pathways must be evaluated and analyzed first in a life cycle perspective to make sure that the environmental impacts are not just being displaced from one phase to another.

Agriculture is the largest sector of Pakistan contributing approximately 18.9% to the GDP and employing almost 42.3% of the total labour force [4]. As an agricultural country, Pakistan is producing all major crops like wheat, maize, rice, sugarcane, and cotton. Rice is one of the most important cash crops in the country sown in the early summer season. Pakistan is ranked as the tenth-largest producer and the 4th largest exporter of rice in the world after India, Vietnam and Thailand, respectively [5]. As shown in Fig. 1, the production of rice reached a historically high

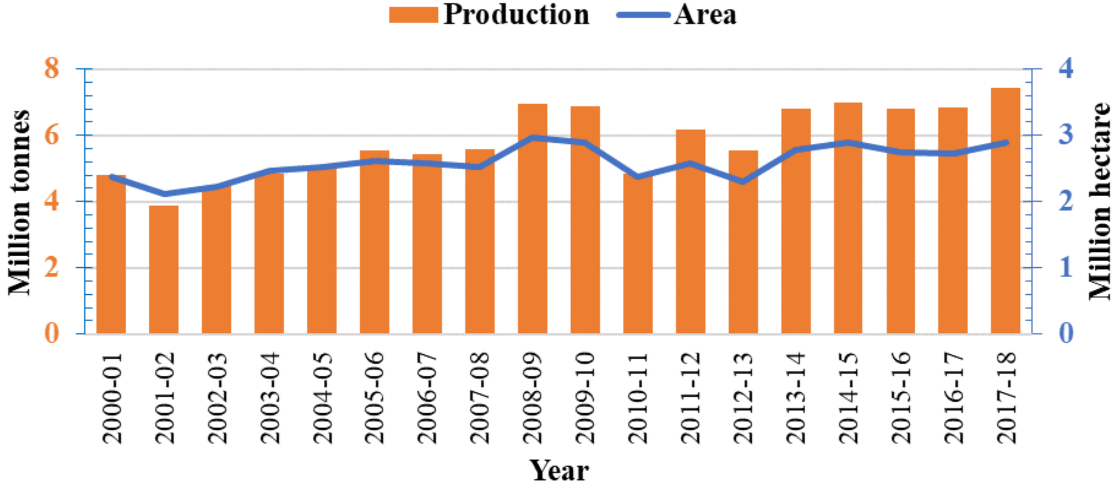

Figure 1. Annual rice production and area under cultivation [6].

level of 7.4 million tonnes during FY 2017-2018 [6]. The cultivation area under rice (i.e. 2.9 million ha) increased by 6.4% as compared to the previous year [4]. Rice is mainly cultivated in interior Sindh and Punjab provinces of Pakistan. The cultivation of rice produces not only wealth and employment opportunities for the people of the cultivating regions but is also responsible for certain environmental repercussions[7-8].

According to the global climate risk index, Pakistan is ranked 7th among the most affected and vulnerable countries to climate change in the world [9]. The total greenhouse gas (GHG) emissions of Pakistan for the FY 2011-2012 were estimated at 374.1 million tonnes of CO_2 eq and the contribution of different sectors to the total is; Energy (45.8%), Agriculture (43.5%), Industrial Processes (5.2%), Waste (2.8%), and Land Use Change and Forestry (2.6%) [10]. Interestingly, the energy and agriculture sectors together are emitting 90% of the total GHG emissions and it is also notable that out of 43.5% of the agriculture sector, nearly half of the GHGs are specifically coming from agricultural soils, rice cultivation and field burning of agricultural residues [10].

In addition to these long-lived GHGs, many short-lived pollutants (i.e. black carbon and tropospheric ozone; which are produced by the incomplete combustion of biomass and fossil fuels) also have the deleterious effect on the environment. These pollutants can also disturb the temperatures on the regional as well as global scale; the melting of ice in the cryosphere; and the hydrology and agricultural productivity [11]. Augmented amount of these pollutants has already been observed in the Himalayan region, which may result in the increased melting of glaciers [12]. The formation of a hazy layer by the different type of aerosols and black carbon is known as Atmospheric Brown Clouds, which starts from November and end up by May in South Asia [11]. The life of millions of people of this region could be affected by this phenomenon through interrupting the monsoon, resulting in water and food insecurity [13].

On the other hand, a worryingly huge amount of fossil fuels is being imported to fulfil the energy demand, thus, raising serious concern for energy security. The power sector has been the largest sector consuming a major portion of these imported fossil fuels (i.e. liquefied natural gas (LNG), crude oil, and coal) in the country [4]. Though the huge efforts are underway by the government of Pakistan to enhance the share of renewables about 20% by 2025, and 30% till 2030 [14]. The installed capacity for electricity generation until June 2018 was 35,979 MW; the share of electricity generation by type of fuel accounted for; 69% as thermal, 21% as hydel, 7% as nuclear and remaining 3% share from renewables (i.e. wind, solar and bagasse) [15].

Simultaneously, being an agricultural country, Pakistan has been challenged with agricultural waste disposal which has resulted in poor air quality due to the open burning of such residues. As suggested by many studies, biomass-based heat and power generation has now become a mature technology proving to be a sustainable source of renewable energy along with agriculture waste disposal. In the last past few years, straw-based heat and power generation has been investigated in many countries; e.g., China, Thailand, Malaysia and India [16-19]. In particular, it’s also been successfully developed and practically implemented in Spain, China, Denmark and the United Kingdom [1]. However, there is no particular study available in Pakistan on the environmental evaluation of bioenergy from rice straw in a life cycle perspective. Hence, the focus of the present study would be to fulfil this gap along with the quantification of the environmental impacts of common straw management practice. The results were used to determine the environmental impacts of different rice straw management scenarios; and to identify the environmental implications of these pathways, so that the recommendations could be made to promote the sustainable disposal of agricultural waste as well as the practical implementation of biomass-based bioenergy in the country along with the reduction of the negative impacts on the environment in future.

2. Methodology

In this study, the environmental performances of three rice straw management scenarios evaluated and compared which include: Scenario-I (or base case scenario), the open field burning; (2) Scenario-II, on-farm management (i.e. straw mulching); and (3) Scenario-III, the direct combustion for electricity. The consideration of the entire life cycle of rice straw production and management was required to ensure that the impacts from one stage are not simply displaced to the others, showing unexpected environmental consequences in the long run. Therefore, the methodology of life cycle assessment (LCA) was followed according to the principles outlined in ISO 14040 (2006) [20] and ISO 14044 (2006) [21] to estimate the environmental impacts of rice straw management in

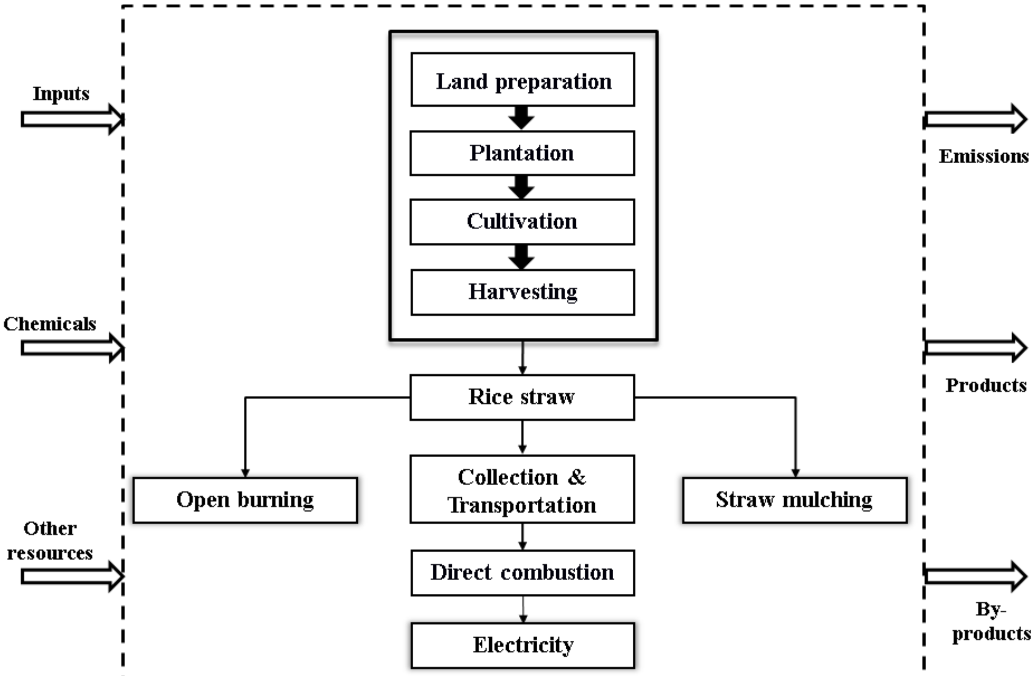

Figure 2. System boundary and boundary conditions with three different scenarios.

Pakistan. The study is intended to quantify the environmental impacts of three different scenarios of rice straw management in the country in an alternate perspective and to provide suggestions for improving the environmental performance of management pathways with enhanced environmental sustainability. The functional unit of this study is defined as one tonne of rice straw produced at farm-gate during the rice cultivation in the harvesting phase.

The scope of the study was from cradle to grave and the system boundaries covered straw production in the agricultural field and straw management phase. The straw production stage involved; land preparation, rice transplantation, agrochemicals application and harvesting. The straw management scenarios were comprised of: (1) Scenario-I (S-I), open field burning or base case scenario; (2) Scenario-II (S-II), straw mulching; and (3) Scenari-III (S-III), direct combustion for electricity. The electricity production through the direct combustion of rice straw is considered as a potential alternative to substitute the grid electricity. Moreover, the straw collection and transportation were also considered for this pathway which encompassed the straw catchment area and transportation distance from cultivation farm to power generation site.

The data for life cycle inventory (LCI) was collected by visiting the rice farms located in different cities of Punjab; Gujranwala, Sialkot, Narowal, Daska, Kasur, Okara, Shorkot, Peermehal, Khanpur, Zaherpir, and Rahimyar Khan. A comprehensive questionnaire was prepared to obtain the primary data or to validate the missing/ secondary data from the literature. In case of missing data, expert opinion was also considered to make reasonable assumptions. The collected information pertained to crop residue management practices, the period of cultivation, rice variety and yield, irrigation time and method, machinery used for field operations, and input amounts of agrochemicals, etc. The information regarding paddy price and paddy yield at farm-gate was taken from primary sources and then validated with the country-specific data. However, most of the emission factors (for agrochemicals, fuels production and combustion, etc.) were taken from the secondary sources (i.e. from the available literature or online inventories). A general summary of data sources and types is presented (in Table A) below in the appendix.

In general, agri-food systems give multiple outputs: one main product with other by-products or co-products. According to ISO 14044 (2006), the allocation should be avoided wherever it is possible by system expansion or division into the unit process. If it is inevitable, then, the allocation must be done to share the burdens among the system outputs [21]. Thus, the economic allocation method has been adopted in this study to attribute the environmental burdens among the products, and to reflect the relationship among the different products (i.e. rice paddy and straw) obtained in the field during harvesting phase. Furthermore, this method has also been considered in many studies related to rice cultivation systems [1, 7, 18]. The obtained value for the allocation factor is approximately 0.063, which is calculated by using the following equation.

$$AF = (SGR \times PS)/(PR + SGR \times PS) \qquad (1)$$

Where, AF = Allocation factor; PR = Paddy price at farm-gate = 322 USD/t (i.e. 50,000 PKR/t and 155 USD = 1 PKR); PS = Straw price at farm-gate = 29 USD/t (i.e. 4,500 PKR/t); and SGR = Straw-to-grain ratio = 0.75.

The IPCC (2006) guidelines were followed for the estimation of field emissions due to fertilizers application [22]. The total P losses were computed according to the Smil (2000) (i.e. the total losses due to application of phosphorus-based fertilizers and crop residues is equal to 1%) [23]. The overall change in carbon stock was assumed to be zero because almost all the visited farms were following the rice-wheat cropping system for a long time. Therefore, it was supposed that there will be no change in the overall soil carbon content. For the calculation of methane emission due to the anaerobic decomposition, the baseline emission factor for continuously flooded fields without organic amendments (i.e. 1.30 kg CH_4 /ha/day) was considered with cultivation period of 130 days on average. The baseline emission factor was also adjusted with scaling factors for the differences in water regime during the cultivation period [22]. CO_2 emissions due to urea fertilization were also calculated. Furthermore, the direct and indirect emissions of nitrous oxide (N_2O) due to the atmospheric deposition of the volatized N and leaching/runoff of N through managed soil were also computed through IPCC (2006) field-emission models [22].

The field emissions due to agrochemicals (i.e. pesticide, weedicide and fungicide) application were taken into account. According to Fusi et al. (2014) and Margni et al. (2002), 85% of the applied active ingredients will be exposed to the soil, while 5% of the remaining stay at the plant surface and 10% will be released to the air and the run-off rate of these ingredients from soil to water will be a maximum of 10% of the applied amount [7, 24].

In the inventory analysis, the determination of the energy grid mix is also very important while scheming the environmental impacts of power option as it can affect the results significantly. According to the “State of Industry Report” published by the National Electric Power Regulatory Authority (NEPRA), for the year 2018, the fuel type consumption of the national grid electric generation comprises of about 38% natural gas, 22% oil and diesel, 21% hydro, 9% coal, 7% nuclear and 3% renewables (i.e. wind solar and bagasse). In other words, nearly 69% of the national grid electricity was generated from fossil fuels, out of which around 38% generated from natural gas followed by the remaining 31% from coal and oil [15].

The life cycle impact assessment (LCIA) calculations were performed following the ReCiPe 2016 method [25], up to the midpoint level and the environmental impacts considered are climate change, fine particulate matter formation, photochemical oxidation formation: human health, terrestrial acidification, freshwater eutrophication, freshwater ecotoxicity, fossil resource scarcity and water consumption. The climate change is evaluated in terms of global warming in units of kg CO_2 eq over a 100-year time horizon. The fine particulate matter formation is expressed in terms of $PM_{2.5}$ eq which would lead to the change in ambient concentration after the emission of NH_3, SO_2, NO_x and primary $PM_{2.5}$. The environmental impacts due to acidifying pollutants (i.e. NH_3, SO_2 and NO_x emissions) are measured in terms of terrestrial acidification and expressed as kg SO_2 eq. The impacts of macronutrients (i.e. the nitrogen and phosphorus) are evaluated in terms of freshwater eutrophication as kg P eq. The estimation of ozone formation (human health) is done as photochemical oxidant formation: humans in terms of kg NO_x eq and the freshwater ecotoxicity calculated as kg 1,4-DCB and expressed in terms of freshwater ecotoxicity. The country grid mix is heavily depending on fossil energy, for this reason, the impact category of fossil resource scarcity is being considered and analyzed in terms of fossil fuel as kg oil eq. The water consumption category is also being computed, due to the water-intensive nature of rice cultivation systems, in terms of m^3 of water consumed during the complete management scenarios of the rice straw.

3. Overall System Description of the Rice Cultivation in Pakistan

Rice is one of the major cash crops of the country; it is not only consumed locally but also exported [5]. It is a Kharif or summer crop sown between April to June and harvested between October and December [4]. Punjab and Sindh provinces contribute around 90% of the total production as shown in Fig. 3. However, the central region of Punjab and northwestern region of Sindh are outstanding in terms of the irrigated rice fields and these regions have a huge potential for bioenergy projects from biomass.

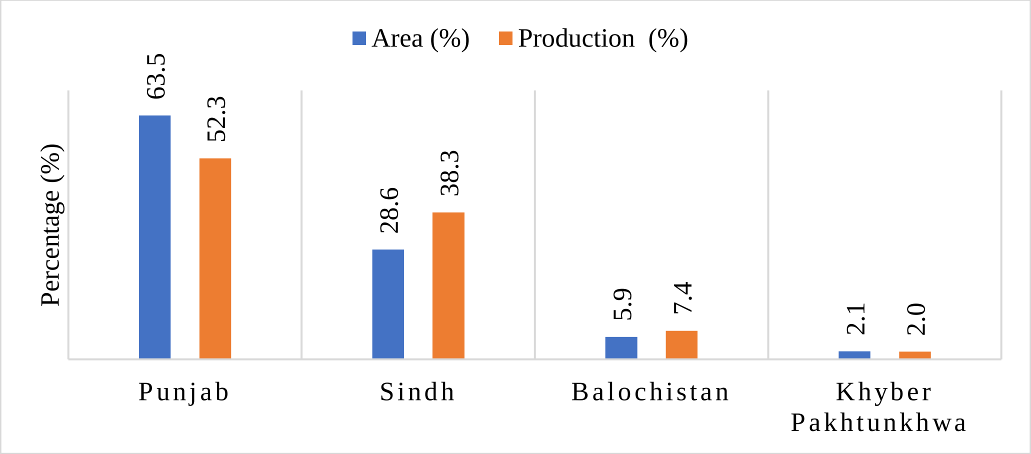

Figure 3. Provincial share in rice production and acreage [6].

In Pakistan, most of the field operations, e.g. transplantation and agrochemicals application etc., are performed manually in the agriculture phase for rice cultivation. Transplantation is a common practice for rice cultivation, and the average seed application rate of 15-16 kg per hectare was obtained through field survey for the nursery preparation. Water management practice is one of the most important factors which may not only affect the paddy yield but also the GHG emissions. The water requirement for the seedling stage is very low as compared to the tillering stage, an appropriate water level in the field is required to avoid weed growth [1]. The maintenance of the crop included the fertilization with Urea, Di-ammonium phosphate (DAP), and Sulfate of potash (SOP); and the application rate on average is 370 kg, 123 kg, and 61 kg per ha respectively. Moreover, the pest, weed, and fungal attacks are being controlled by pesticide, weedicides and fungicides, respectively. On the other hand, the application of these agrochemicals (i.e. pesticide, weedicides and fungicides along with fertilizers) in the cultivation stage are responsible for the deposition of heavy metals and toxic substances [8]. Methane is produced due to the anaerobic decomposition under the submerged soil, and the nitrification and denitrification are responsible for the nitrous oxide emissions due to the application of the fertilizer in the field. In general, harvesting is carried out mechanically by using a combined harvesting machine, while leaving the loose straw behind in the field. The total fuel consumption in different field operations (i.e. levelling, tillage, and harvesting etc.) during the agricultural phase is about 82 L of diesel per ha. The yield of the crop is 4 tonnes per hectare in terms of rough rice (i.e. paddy rice or rice grain with husk and bran). Then, the rough rice is transported to the rice mill for further processing by using the tractor trolleys and straw left in the field as a waste.

The agriculture sector of Pakistan heavily depends on the irrigation water due to the erratic rainfall pattern in the region [26]. In general, the rice is grown in the irrigated or partially irrigated plains (except for a very small amount in the hilly areas); however, the precipitation during the monsoon season (i.e. July–September) plays a vital role in recharging the water bodies that subsequently feed the rivers and the canals [26]. Like other countries in Asia, rice fields in Pakistan are also prepared by tillage (followed by the puddling). The soil layer keeps saturated by standing water during the entire growth period of the crop. The water consumption for paddy production in Pakistan is 2785 m^3/t; 2364 m^3/t is from irrigation, and 421 m^3/t rainwater [27]. Irrigation is performed 20 times on average, either using the surface water or groundwater considered at 83:17 ratio [28]. Based on the types of installed tube wells in the province, it was considered that 86% irrigation is done with diesel tube wells while the remaining 14% performed by electric tube wells [6]. For rice cultivation, the inventory data is presented in Table 1 below for the agricultural phase.

Table 1. Inventory data for agricultural phase.

Inputs	Scenario-I
Seed input (kg)	5
Fertilizers	
Urea (kg)	124
DAP (kg)	41
SOP (kg)	21
Pesticide/Weedicide/Fungicide *	
Thio-carbamate-comp. (g)	297
Acetamide-aniline (g)	494
Trifloxystrobin (g)	82
Bensulfuron methyl (g)	41
Irrigation	
Diesel (L)	99
Electricity (kWh)	75
Field operations	
Diesel (L)	27

Note: Scenario-I is the base case scenario. All the represented values are with respect to the functional unit. i.e., 1 tonne of rice straw; and * The quantity of active ingredients in the agrochemicals.

In this study, the straw-to-grain ratio method has been adopted to quantify the rice straw generated and subjected to open burning in accordance with Gadde et al. (2009) [29]. The following equation (2) was used for the estimation of rice straw generated in the field and subject to open field burning:

$$Q = P_{RR} \times Q_{SB} \times SGR \qquad (2)$$

Where, Q = Quantity of rice straw subject to open field burning (t/ha); P_{RR} = Production of rough rice (t/ha); SGR = Straw-to-grain ratio; Q_{SB} = Rice straw subject to open field burning (%).

For this study, the SGR of 0.75 has been considered to estimate straw yield per unit area by the equation (2), which implies that the yield of rice straw per ha would be 3 tonnes if the yield of rough rice is 4 tonnes/ha. The ratio of the straw subjected to the open burning (i.e. 58% tonne of rice straw per ha) is considered in accordance with Ahmed et al. (2015) and Mir and Ijaz (2016) [10, 12]. According to these considerations, the amount of rice straw would be 1.74 tonnes per ha approximately which is being subjected to the open burning in the field.

4. Rice Straw Management Scenarios

4.1 Rice straw open burning

The open burning of rice straw is an uncontrolled combustion process during which many pollutant species are being emitted as mentioned in Table 2. The Intergovernmental Panel on Climate Change (IPCC) has also proposed a methodology to quantify the emissions by the open field burning. The IPCC (2006) guidelines have been adopted to estimate the pollutant emissions as a result of the open burning of rice straw [22]. The equation (3) was used to estimate the amount of emission per functional unit:

$$E_p = Q_p \times EF_p \times C_f \quad (3)$$

Where, E_p is the amount of pollutant P (kg); Q_p is the quantity of rice straw (tonne); EF_p is the emission factor of pollutant P (kg/t) presented in Table 2, and the default value for combustion factor (C_f) is taken from IPCC (2006) guidelines which is 0.80 (i.e. the fraction of the straw burnt in the field) [22].

Table 2. Pollutant emissions per tonne of rice straw by open burning.

Pollutant	EFs (kg)	E (kg)
*CO_2	1515	1212
*CH_4	2.7	2.16
*N_2O	0.07	0.056
*CO	73.6	58.88
*NOx	2.5	2
**SO_2	2	1.6
**$PM_{2.5}$	12.95	10.36
**NMHC	4	3.2
**PAHs	0.01862	0.014896
**PCDD/F	5E-10	4E-10

Note: Only the PCDD/F is expressed in terms of kg of international toxic equivalency.
Source: * [22] & ** [29].

Emission factors (EFs) were collected from the literature specific to open field burning of rice straw, presented in above Table 2. However, the carbon dioxide emission due to biomass burning is considered as biogenic. The PAHs, NMHC and PCDD/F stand for polycyclic aromatic hydrocarbons, non-methane hydrocarbons, and polychlorinated dioxins and furans respectively.

4.2 Straw mulch

In Pakistan, the rice-wheat cropping system occupies 2.2 million ha [30]. The soil incorporation of the rice straw is also one of the in-situ management options in Asian subtropics, which is beneficial in terms of nutrients recycling. However, this is the least practised management pathway because of energy and time intensiveness, which also requires supplementary (nitrogen-based) fertilizers to maintain the high C:N ratio due to the temporary immobilization of the nutrients in the soil [31]. The net immobilization and the net supply of nutrient from rice straw to a succeeding crop (i.e. wheat) depend upon decomposition rate, straw quality, and soil conditions [32]. To avoid the nitrogen deficiency due to immobilization of nutrients, an adequate period (i.e. 10 to 20 days) is required, which leads to the delay in the plantation of next crop [31]. Moreover, the immediate plantation of next crop after straw incorporation could decrease the crop yields [33].

On the other hand, the zero-tillage happy seeder is an emerging technology to avoid the in-situ burning and soil incorporation of the straw. It has been investigated in many studies with several positive effects including conservation of soil moisture, weed suppression, improved quality of soil, wheat yield, and profitability [30-32]. This technology has a potential to save 21 L/ha of fuel by substituting the conventional tillage operation (i.e. ploughing with a chisel plough, disc plough, and planking with levellers) for wheat sowing [30]. For this scenario, the credits due to the fuel conservation by using the happy seeder were taken into account. However, the other benefits (e.g., water conservation and yield improvement) for wheat cultivation are out of the scope of this study.

4.3 Electricity production

Direct combustion is one of the well-established conversion technologies commonly comprising a steam turbine coupled with the boiler to generate electricity. The data sources for rice straw-based power generation are limited because this option has not yet been explored in Pakistan. Therefore, the power production model which has been investigated and referred by these studies: Silalertruksa and Gheewala (2013) and Delivand et al. (2012), was followed to quantify the environmental implications of this pathway in Pakistan. i.e. a 10-MWe straw-based power plant with an overall efficiency of 20% was considered in this study [1, 34]. The feedstock requirement of the power plant would be around 116,000 tonnes of rice straw per annum and net output of 613 kWh/tonne of dry rice straw [1]. The environmental interventions were derived from EPA emission factors for wood residue boiler or retrieved from the rice straw-specific secondary sources.

The rice straw is available for a very short interval of time; therefore, it has to be procured and stored during harvesting season to fulfil the demand of the power plant for the entire year. The transport of straw from the field to the power plant is the prime factor which needs to be considered and its impacts are the direct function of the transportation distance and the bulk density of straw. i.e. 125 kg/m^3 [35]. The storage and transportation efficiencies can be enhanced by densification. In most of the remote areas, diesel driven devices might only be available due to the lack of electricity for this purpose. The moisture content can be reduced up to 10–12% via natural drying in the field. As most of the paddy farms in Pakistan lie within the range of 3-10 ha [6], therefore, the small bale (i.e. 40 kg with bale size 1.0 × 0.5 × 0.4 m with an increased bulk density of 200 kg/m^3) was considered for this study. Diesel is required at 1.2 L per tonne of rice straw (10% moisture) for field operations (i.e. straw baling, hauling and loading to the truck, and unloading and stacking of bales at the plant site) in this stage [1]. For this study, the plant is assumed to be located at the centre of the catchment area where rice straw bales have to be collected and only rice grown area is being considered as the potential catchment area. Then, the circular catchment area can be calculated by equation (4) [2]:

$$C_A=[A_D \times (1 + S_L)] / [Y \times A_f \times F_f \times C_{eff}] \quad (4)$$

Where: C_A = Circular catchment area (km^2); A_D = Annual straw demand (t); S_L = Straw loss during transportation and handling (%); Y = Annual straw yield (t/km^2); A_f = Availability factor; F_f = Farmland factor; and C_{eff} = Collection efficiency.

As the average straw yield in Punjab region is 3 t/ha and the rice can be grown only once a year, hence, the annual rice straw yield would be 300 t/km^2. For this study, the availability factor (i.e. the farm area which is being used for rice cultivation) is supposed to be 100%. The farmland factor is considered as 58% as stipulated by Ahmed et al. (2015), which is the percentage of cultivated rice fields that are being subjected to the open field burning and can be explored for energy purposes in an alternate perspective [12]. During transportation and handling, the collection efficiency and loss of rice straw are assumed to be 80% and 10% respectively in accordance with Silalertruksa et al.

(2013) [2]. Thus, the estimated circular catchment area calculated by equation (4) for establishing the power plant would be 91,667 km^2 and the one-sided radial distance to deliver the straw to the plant can be calculated as 170 km. However, for the system under consideration, the round-trip distance between plant and field is taken as 170 km on average because the plant location is considered in the rice grown areas so the distance from some fields might be negligible. To deliver the one tonne of straw, 3.2 L of diesel will be required (based on the distance of 170 km; and the diesel consumption of 0.3 L/km of the truck with actual load).

5. Results and Discussion

The environmental impacts per tonne of rice straw from each of the scenario are shown in Table 3 and the noteworthy contribution of different materials, processes and stages towards each category are discussed comprehensively in the following paragraphs.

The life cycle GHG emissions for all the scenarios are graphically presented in Fig. 4. In the agricultural phase, the GHG emissions were mainly contributed by the production and application of synthetic fertilizers (i.e. the field emissions of CH_4 and N_2O), followed by consumption of fuel and electricity for farm operations, irrigation and agrochemicals application for all the scenarios. The open burning of rice straw in the field is also one of the major sources of GHG emission in Scenario-I. However, since open burning does not occur in Scenario-II and Scenario-III, hence there is no contribution to GHG emissions from that activity.

The results revealed a maximum net reduction in global warming of -58.5 kg CO_2 eq per tonne of rice straw obtained through the straw-based bioenergy pathway in Scenario-III, followed by rice straw mulching (Scenario-II) and open burning (Scenario-I) with net GHG emissions of about 220 and 363 kg CO_2 eq per tonne of rice straw respectively as shown in Table 3. The main credits in straw-based bioenergy system came through the grid electricity substitution as shown in Fig. 4.

The main contributors to the particulate matter formation are NH_3, NO_x, SO_2 and primary $PM_{2.5}$. For all the three scenarios, the comparative potential impacts of $PM_{2.5}$ emissions on the environment in a life cycle perspective are shown in Table 3, which reveals that the Scenario-I would be responsible for the maximum potential impacts, i.e., 11.3 kg $PM_{2.5}$ eq per tonne of rice straw because of the open burning of rice straw. On the other hand, the Scenario-II and Scenario-III (i.e., straw mulching and bioenergy) presented almost the same results of about 0.2 and 0.1 kg $PM_{2.5}$ eq per tonne of rice straw respectively.

The straw-based electricity yielded the highest net reduction of terrestrial acidification of -0.02 kg SO_2 eq per tonne of rice straw. However, the Scenario-I and Scenario-II showed terrestrial acidification values of about 3.5 and 1.0 kg SO_2 eq per tonne of rice straw respectively. The results from all the scenarios revealed that the utilization of straw for either energy or mulch could reduce the acidification impact on the environment by the reduction in NO_x and SO_2 emissions due to the avoidance of open burning.

The comparative freshwater eutrophication impacts of Scenario-I, Scenario-II and Scenario-III are shown in Fig. 4. The obtained results revealed that the rice straw open burning pathway had the highest net freshwater eutrophication (i.e. 0.16 kg P eq per tonne of rice straw) followed by straw mulching pathway at 0.01 kg P eq per tonne of rice straw. One the other hand, Scenario-III showed a potential reduction in freshwater eutrophication of about -0.02 kg P eq per tonne of rice straw. As graphically represented in Fig. 4, the main credits for Scenario-II and Scenario-III came from the substitution of conventional tillage operation and substitution of grid electricity, respectively.

The human health ozone formation is mainly contributed by the precursor emissions (e.g., NO_x, NMVOCs, hydrocarbons, etc.). For different rice straw management scenarios, the comparative impacts of human damage ozone formation are shown in Table 3, which revealed that the open burning pathway led to the highest human health ozone formation value of 3 kg NO_x eq per tonne of rice straw. However, the straw mulching and direct combustion pathways showed a slight difference in performances in potential reduction of human health ozone formation to around 0.1 and -0.1 kg NO_x eq per tonne of rice straw, respectively.

In the case of freshwater ecotoxicity, the main environmental interventions were the production and application of agrochemicals, and the consumption of fossil fuels, particularly diesel, for field operations and transportation. The open field burning scenario exhibited the highest impact of about 1.9 kg 1,4-DCB per tonne of rice straw followed by the straw mulching which is about 0.7 kg 1,4-DCB per tonne of rice straw. However, the electricity generation pathway led to the minimum freshwater ecotoxicity of about 0.2 kg 1,4-DCB per tonne of rice straw. The results showed that this scenario could deliver the best performance in terms of freshwater ecotoxicity and the major credits for this pathway came from the substitution of grid electricity.

In the agricultural phase, the production and the consumption of synthetic fertilizers, fossil fuels, or fossil-based electricity are responsible for fossil resource scarcity. The Scenario-III had the highest net fossil fuel reduction (i.e., -86.6 kg oil eq per tonne of rice straw) due to the substitution of electricity grid in Pakistan which is largely fossil-based. Nevertheless, the Scenario-I and Scenario-II exhibited the fossil resource scarcity of about 23.3 and 9.5 kg oil eq per tonne of rice straw respectively as shown in Table 3.

For the water consumption impact category, all the scenarios displayed almost the same performance with very minor differences, i.e., 177, 177, and 172 m^3 of water consumed per tonne of rice straw for Scenario-I, Scenario-II and Scenario-III respectively

Table 3. Environmental impacts of open burning (Scenario-I), straw mulching (Scenario-II), and bioenergy (Scenario-III) per tonne of rice straw in Pakistan.

Impact category	Unit	Scenario-I	Scenario-II	Scenario-III
Global warming	kg CO_2 eq	363	220	-58.5
Fine particulate matter formation	kg $PM_{2.5}$ eq	11.3	0.2	0.1
Terrestrial acidification	kg SO_2 eq	3.5	1.0	-0.02
Freshwater eutrophication	kg P eq	0.16	0.01	-0.02
Ozone formation: human health	kg NO_x eq	3.0	0.1	-0.1
Freshwater ecotoxicity	kg 1,4-DCB	1.9	0.7	0.2
Fossil resource scarcity	kg Oil eq	23.3	9.5	-86.6
Water consumption	m^3	177	177	172

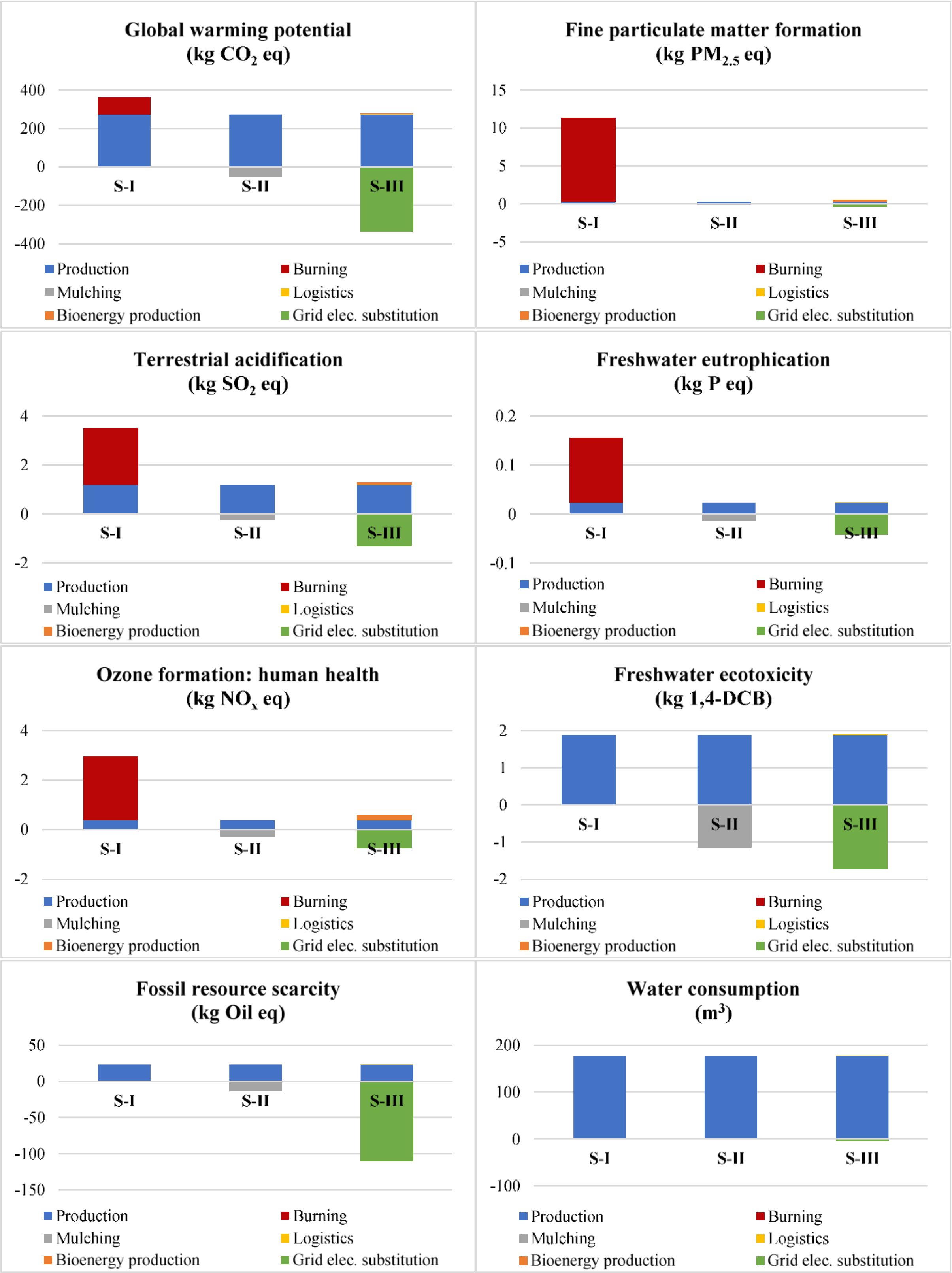

Figure 4. Graphical representation of impact results of open burning (S-I), straw mulching (S-II), and bioenergy (S-III) per tonne of rice straw in Pakistan (reference Table 3).

6. Conclusion and Recommendations

A comparative environmental assessment of three rice straw management scenarios was conducted to investigate their potential impacts in a life cycle perspective. Out of these three scenarios, two are already being practiced in the country (i.e., in-situ burning of rice straw and straw mulching) and the third one (i.e. direct combustion) is considered in an alternate perspective. The study results showed that the Scenario-III (i.e. straw-based bioenergy production) would lead to the maximum net reduction in the global warming, terrestrial acidification, freshwater eutrophication and fossil resource scarcity as compared to the other options. The Scenario-II would also lead to several environmental benefits in terms of fine particulate matter formation, freshwater eutrophication, and human damage ozone formation. Furthermore, the Scenario-III also proved to be a beneficial option in terms of freshwater ecotoxicity and water consumption. Unlike Scenario-II and Scenario-III, the Scenario-I showed the lowest environmental performance for all the impact categories considered. From the obtained results, it can be concluded that the rice straw-based bioenergy production brought the highest environmental benefits as compared to the other options. On the other hand, the rice straw mulching proved to be the second-best option after the bioenergy pathway. Here, it is also mentionable that the straw mulching and sowing of the next crop with zero-tillage happy seeder seems to be a viable option as compared to the bioenergy pathway which requires a higher initial investment.

The authors would like to suggest that the social and economic sustainability assessment must also be conducted to complete the three pillars of sustainability. A more detailed and robust analysis of other potential alternatives (e.g. soil incorporation, composting, mushroom cultivation, knitting crafts and other bioenergy pathways etc.) are recommended to understand the impact on the sector due to the variability in management practice of rice straw. For the sustainability assessment of agricultural residue management, the maintenance of soil fertility is also a primary factor which needs to be considered. In the case of off-farm management, the availability and removable fraction of biomass depend on many factors including cropping patterns, farming practices, accessibility and willingness of farmers to sell. All these factors are very site-specific; therefore, a thorough study is recommended to avoid the long-term negative impacts on the land productivity and rice sector.

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Appendix

Table A. Sources and type of the dataset for Life Cycle Inventory.

Data	Area of inventory	Units	Data source
Foreground data (inputs)	Direct energy consumption Seed Agrochemicals Water	L/ha or kWh/ha kg/ha L/ha or g/ha m^3/ha	Field survey
Outputs	Paddy yield Rice straw	Tonne/ha	Field survey
Economic data	Costs of input and outputs	USD	Field survey/ Market prices
Background processes data	Manufacturing and transportation of materials and chemicals	--	Ecoinvent v 3.0/ LCA databases
Emissions	Direct field emissions Indirect emissions	--	Literature data

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