ECONOMIC AND ENVIRONMENTAL EFFECTS OF PRACTICING CROP RESIDUE ON-FIELD COMPOSTING AS A SUBSTITUTE FOR BURNING – A CASE STUDY OF PUNJAB (INDIA)

by

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Abstract

Crop residue burning, a prevalent and urgent issue in India, particularly in the Indo-Gangetic Plains of Haryana, Uttar Pradesh, and Punjab states, has detrimental effects on the climate of the region, agricultural production, and the health of humans, animals, and plants. Despite legal and technological barriers to crop residue burning and the availability of profitable alternatives for farmers, this practice persists in Punjab state. The primary reasons for the ongoing crop residue burning practice are, the amount of surplus crop residue generated, the time constraints of the rice-wheat crop rotation, and the height of stubble left in the field after the mechanical harvesting of rice and wheat crops. One of the proposed alternatives, the incorporation of crop residues directly into the soil before planting the next crop, is considered best. However, this practice is not accepted by farmers of Punjab on a large scale, as it generally decreases crop yields due to Nitrogen (N) immobilization. To counter this constraint, a modified method of incorporation, on-field composting is proposed to manage the rice and wheat crop residues in Punjab. In this method, crop residues will be collected on the field and composted in an on-field composting pit. A valuable product – compost is formed which is broadcasted in the field as an organic fertilizer.

This study includes a theoretical analysis of the on-field composting method to manage rice and wheat crop residues. Firstly, crop residue on-field composting costs are assessed and compared with crop residue burning costs to give farmers of Punjab an idea of cost savings by composting crop residues on the field. For this, various input and output costs of the burning method and on-field composting method are evaluated and compared on a per acre basis for managing rice and wheat crop rotation based residues in all districts of Punjab based on the data for three consecutive years (2020, 2021, and 2022). For all three years, in most of the districts of Punjab,

the burning practices-related costs per acre were found to be higher than on-field composting costs per acre only if a crop residue burning penalty imposed on a farmer is added as an input cost to the Net Burning Costs per acre. However, without adding crop residue burning penalty cost, the on-field composting costs per acre are higher as the chances of imposing penalties on every farmer who burns crop residues are quite low. Secondly, in this study, the variation of input costs of the on-field composting process, such as labor and machinery costs, along with variation in landholding size (number of acres) with farmers, is also analyzed. For this, four on-field composting models (one-acre, four-acre, eight-acre and sixteen-acre) are studied keeping in mind farmer's land-holding categories in Punjab. The input cost (labor and machinery costs) per acre for each on-field composting model varies depending on the size of the farmland (number of acres) in each district. In addition, GHG emissions and the social cost of these emissions on crop residue burning are studied as compared to on-field composting of crop residues.

As per our assessment, the on-field composting method for managing crop residues is better for both the farmers and the environment of Punjab. The practical implication of this study could be a future research project.

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Glossary

1.	Bioinoculant carrier or inoculant	- The vehicle of living latent microbes
2.	Bioremediation	- Living organisms remove contaminants and pollutants from soil, water and other environments.
3.	Collateral damage	- Accidental damage to the properties on burning of residues in the field.
4.	CRR (Crop to Residue Ratio)	- Used to calculate how much crop residue left after harvesting the particular crop.
5.	Genetic diversity	- The biological variation that occurs within species.
6.	Incentive	- A reward or compensation is provided for performing a task.
7.	Incorporation	- Mixing of any substance in the soil through tillage.
8.	Inorganic fertilizer	- Fertilizers are synthetically derived chemicals and minerals from the earth.
9.	MSP (Minimum Support Price)	- It is the minimum price set by the government for certain agricultural products, at which the products would be directly bought from the farmers.
10.	N – immobilization	- The process by which soil organisms take up nitrate and ammonium from soil and make it unavailable to crops.
11.	On-field Composting	- It is the natural process of recycling organic matter, such as crop residues into a valuable fertilizer that can enrich the soil and plants.
12.	Organic fertilizer	- Materials of animal and plant origin used to improve plant nutrition and physical and chemical

properties and biological activity of soils.

13. Penalty	- Punishment for breaking a law, rule or contract.
14. Rupees (Rs)	- Currency of India
15. SF (Surplus Fraction)	- The percentage or amount that remains when use or need is satisfied.
16. Soil contamination	- Soil containing chemical compounds potentially harmful to human health or the environment.
17. Soil erosion	- A gradual process that occurs when the impact of water or wind detaches and removes soil particles, causing the soil to deteriorate.
18. Soil reclamation	- The process of improving soils to make them suitable for more intensive use.
19. Straw	- Dried stalks of grain after threshing.
20. Stubble	- The cut stalks of grain plants are left sticking out of the ground after the grain is harvested.
21. Subsidized prices	- A price for a product that is reduced because the government has paid part of the cost of producing it.
22. Sustainable	- Ability to maintain or support a process over time.

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Chapter 1: INTRODUCTION

1.1 Crop Residues are not waste: until wasted

Crop residues are waste left in the field after the crop is harvested and threshed. On a yearly average from 2010-2014, India generated 121.2 million tons of rice crop residues and 114.14 million tons of wheat crop residues (Retrieved from Devi et al., 2021). These residues have sometimes been regarded as waste materials that require disposal and are burnt, causing various environmental and health issues. However, it has been realized that crop residues are vital natural resources, not waste. Recycling crop residues through composting can convert surplus farm waste into valuable compost product. This nutritional product will improve the overall ecological balance of the crop production system. As per (Odum, 1971) ecological balance is a delicate balance, where each organism and environmental factor plays a role in maintaining harmony and stability within the ecosystem. Composting of crop residues will maintain ecological balance by recycling the soil nutrients, while burning of crop residues openly in the field would disturb the ecological equilibrium by loss of soil biodiversity and emission of GHGs into the environment.

Therefore, in this research, we have made an effort to study the economic and environmental effects of practicing the on-field composting method as a substitute for burning to manage the rice and wheat crop residues.

1.2 Background of the case study

1.2.1 Agriculture in India

India is an agrarian economy and is one of the world's leaders in production volume for various commodities such as Rice, Wheat, Cotton, Sugar, Horticulture, and Dairy (Gulati, 2011). As per a study by Kanwal (2022), **agriculture** employed more than 50% of the Indian workforce and contributed 17–18% to the country's GDP. Due to India's rapid population growth and economic development, there is intense pressure on the country's agriculture sector to compete with the rising demands of food and related industries. In intensive agriculture, the aim is to get maximum yield from minimal land, for which higher inputs are required per unit of agricultural land, such as capital, labor, water, and agrochemicals (pesticides and fertilizers). It results in quicker soil and water degradation, loss of biodiversity, and groundwater pollution (Kuchimanchi et al., 2023). This immense pressure has also led to increased agriculture and multiple cropping nationwide. The leading farming states of India are Uttar Pradesh, West Bengal, Punjab, Madhya Pradesh, Bihar, and Haryana, and agriculture in Madhya Pradesh, Bihar, and Punjab states contributed more than 25 percent of their respective state income (Gupta & Kannan, 2024).

1.2.2 A study of Punjab state, India

Punjab has explicitly played a prominent role in achieving self-sufficiency in food grains by contributing a high percentage of wheat and rice to the country's food reserves (Gulati et al., 2021). Punjab covers an area of 50,362 square kilometers, which is 1.53% of India's total geographical area (3,287,263 square kilometers), and 84% of Punjab's total land is under cultivation, with 75% of its population depending on agriculture {Website - Department of Agriculture and Farmer Welfare, n.d.). The soil of Punjab has the potential for crop diversification to grow many crops (Ray et al., 2005). Punjab state has 23 districts, i.e., Amritsar, Bathinda, Barnala, Faridkot, Fazilka, Ferozepur, Fatehgarh Sahib, Kapurthala, Gurdaspur, Hoshiarpur, Jalandhar, Ludhiana, Malerkotla, Mansa, Moga, Sri Muktsar Sahib (SMS), Shaheed Bhagat Singh Nagar (SBSN), Pathankot, Patiala, Rupnagar, Sahibzada Ajit Singh Nagar (SASN), Sangrur and Tarn Taran. The Malerkotla district was carved out of Sangrur district as the 23rd district on 21 May 2021. So, the data for the Malerkotla district is included in the Sangrur district.

1.2.2.1 Rice -Wheat crop rotation in Punjab

More than half of the districts of Punjab undergo only rice-wheat crop rotation; the rest grow one other crop along with these two significant crops (Kaur & Kaur, 2018). In the Year (2016-2017), a 3468-thousand-hectare area was under wheat production, and rice crop was grown on a 3033-thousand-hectare area (Website – Crops grown in Punjab, n.d.). So, there are two major cereal crops grown in this state, "Wheat" (winter/rabi crop) and "Rice" (summer/kharif crop). Rice is grown in the summer season, also called the Kharif season, while wheat is grown in the winter season, called the Rabi season. Rice alone covered nearly 63% of Punjab's kharif (summer)-cropped area. In comparison, wheat covered 85% of the total rabi (winter)-cropped area, and rice-wheat is the significant crop rotation of Punjab (Bal et al., 2009). According to the National Bank for Agriculture and Rural Development's Punjab State Focus Paper 2021-'22, Punjab state alone contributes more than 35% of wheat and 25% of rice to the central pool of India (website –

State Focus Paper, n.d.). So, only rice and wheat crops and their residues are focused in this study.

The high cropping intensity (189%) of Punjab state depicts severe competition between different crops and it further leads to overlapping of harvesting and sowing seasons. Rice and wheat crops are grown in rotation during a year – Rice (May – late October) and Wheat (mid-November – mid-April). The nursery of rice crops is grown in May, while the transplanting of seedlings is done in June month or even rice crop can be sown directly in the field in June month. Harvesting of high-yielding varieties of rice and wheat crops using combine harvesters leaves large quantities of one-foot-long crop residues in the field.

1.2.2.2 Surplus crop residues of rice and wheat crops

The total residue produced by crops is called the gross residue of crops. However, crop residues have competing uses, and therefore, only a particular portion of gross crop residue, which is unused, needs management or disposal. This portion of gross crop residue is termed surplus crop residue. According to the Indian Ministry of New and Renewable Energy (MNRE), India generates 500 Mt of gross crop residue annually; 28% (140 Mt) of this gross crop residue is surplus. Further, 92 Mt (65% of surplus value) of total surplus crop residue is managed through the burning method in fields (cited in Bhuvaneshwari et al., 2019). In India, Punjab state alone produces about 18% of national residue surpluses, of which 80% are burnt in fields (Downing, et al., 2022).

1.2.3 Management of crop residues of rice and wheat crops

The farmers themselves handle the agricultural waste produced on their farms, but there may also be little intervention from the public sector. The residues of rice and wheat crops are used for various purposes, such as domestic and industrial fuel, for thatching of homes, and as animal fodder or burnt in many places. Most of the wheat straw is collected from fields for cattle fodder but rice straw is a poor cattle feed due to the high silica content present in it (Sidhu et al., 1998).

1.2.3.1 Crop residues of rice-wheat crops – a primary concern

Before the 1980s, farmers manually performed harvesting and ploughing of fields, and later, they used to till plant debris back into the soil. In the 1980s, Combine harvesters were introduced for mechanized harvesting, leaving one-foot stalks behind, which became a significant concern. Combines and harvesters were used for harvesting rice and wheat crops (88.6 % of rice and 56.6% of wheat), leaving the stub ends in a field (Sidhu et al., 1998). The reasons to use combine harvesters were a) high labor cost for manual harvesting, b) rice residues have no significant income-generating alternative, c) combine harvesting speeds up the harvesting process to create a reasonable time duration window for preparation of the field for the next crop, d) presence of high silica content in rice residue making it unfit for use as cattle feed (Sidhu et al., 1998).

One-foot-long crop residues left behind by combine harvesters make it difficult for farmers to remove them from the field and prepare the land for the next crop in a short time. The wheat crop must be sown within a 15-20-days time window after harvesting the rice crop to maintain the yield of crops. Thus, crop waste management is a significant concern for the Punjab agriculture sector.

1.2.3.2 Rice crop residues vs wheat crop residues

The straw reaper is used to chop and thresh the standing ends of wheat crops, producing fine straw. Farmers store some part of this by-product for cattle feed, while most of it is sold in the market to generate revenue. The buyers usually buy wheat straws for various purposes, such as reselling them in the market for animal fodder or as a raw material input in industries such as cardboard and cushioning material, thus making the burning of wheat crop residue less prominent among farmers than rice crop residue. On the other hand, rice crop residues are not a good source of cattle forage, as they contain a high amount of silica content, which is less digestible. Also, wheat straw demand is much higher, and it trades at 16 times the price of rice straw, so farmers do not find any reasonable margin of profit in threshing and chopping rice straw (Hayashida, 2020). Thus, more rice crop residues are burnt as compared to wheat crop residues.

1.2.3.3 Crop residue burning

In Punjab, India, burning residue from the rice and wheat harvest dates back to a few decades. Burning crop residue effectively removes or manages crop residue in fields and facilitates the time window for sowing of the next crop. The time window between the harvesting of one crop and the sowing of another crop is short (15-20 days), which creates the issue of management of crop residues in a short time.

In study (Sidhu & Beri, 2005), it is estimated that 81 percent of rice crop residues and 48 percent of wheat crop residues are burnt in Punjab. 18.4 million tons of rice straw and 8.5 million tons of wheat straw are burnt in Punjab fields (Kumar et al., 2015). This massive crop residue burning in

Punjab results in the deterioration of air quality through emissions of smog, haze, heat waves, and GHGs, contributing to global warming (Bhuvaneshwari et al., 2019). To combat the issue of crop residue burning, sustainable and environmental friendly methods are required to manage the crop residues to protect our environment and public health.

The government of India has banned crop residue burning. Punjab state imposes fines on farmers who perform this illegal activity of burning crop residue on their farms. However, this practice is ongoing because farmers find this method to be the easiest method to clear the fields in a short time.

Numerous studies have focused on alternative and sustainable methods of crop residue management, such as residue incorporation or use in cardboard industries in generating biofuels and composting. However, the acceptance and adoption rate of such practices by farmers of Punjab is low due to the lack of information related to the cost and benefits of such practices as compared to burning residues and it leads to the low adoption rate of such sustainable practices (Mandpe & Kumar, 2020).

Burning crop residues in the open field has become a significant concern in Punjab as it causes climate change and various health problems in animals and humans.

1.2.3.4 Crop residue composting

Crop residues have numerous competing uses that have made them a precious commodity and must not be considered a waste. Punjab locals have traditionally used the composting of crop residues, household waste, or cow dung to generate nutrient-rich fertilizer. The composting method is a fascinating segment for converting on-farm waste materials into a nutrient-rich resource. Composting crop residues helps to prevent soil erosion and reduces reliance on chemical fertilizers. Compost used as manure improves plant growth and promotes higher yields of crops. However, nowadays many farmers in Punjab do not make compost out of crop residues as they used to do in the past due to various reasons. As there is an increase in the volume of crop residues produced which makes it difficult to move it from the field to the place of composting and return the compost to the fields to use it as organic fertilizer. More research is needed on managing crop residues at the farm level, and the cost difference of adopting the composting method as compared to burning practices. Moreover, the exploration of implementing the different on-field composting models, their inputs and outputs, costs and revenues, environmental impacts, and their comparison with the residue-burning practices need to be assessed and evaluated.

1.3 Importance of the Research Study

A significant size of the farming community has adopted the practice of burning crop residues to manage rice and wheat residues. The main reason behind this is that farmers find the burning method of managing crop residues the cheapest and easiest as compared to other methods proposed by various researchers. However, farmers need to be made aware of the costs of openly burning crop residues in their fields. Moreover, an alternative method of composting crop residues is already well known to them, but composting crop residues on the field individually by farmers with costs and revenue has yet to be researched or studied. So, the costs and revenue of crop residue burning are assessed and compared with the on-field composting method to understand their cost differences. Besides the economic effects, the environmental effects of burning crop residues over on-field composting are evaluated.

Hence, this research assesses and analyzes the possible cost and environmental impact of burning and on-field composting crop residues in different districts of Punjab. This research creates a base for sustainable management of crop residues for farmers of Punjab to combat a significant concern: the burning of crop residues.

1.4 Study Objectives

This study will provide farmers of different districts of Punjab with the costs and benefits of adopting the composting method on the field itself. Current research is based on quantitative data on rice and wheat crops, their residues, and the management of crop residues through on-field composting in each district of Punjab. This research addresses four main objectives:

1) What are the costs of crop residue burning for farmers of different districts of Punjab?
2) What are the costs of crop residues on-field composting for farmers of different districts of Punjab?
3) Comparative cost analysis of crop residue burning vs. on-field composting.
4) Comparative environmental impact of crop residue burning vs. on-field composting.

The variation in costs of applying the on-field composting method per acre under 4 different on-field composting models are assessed in this research. These models are based on 4 different landholding sizes in Punjab: one-acre on-field composting model, four-acre on-field composting model, eight-acre on-field composting model and sixteen-acre on-field composting model. These models are chosen as a multiple of four because the average landholding with farmers of Punjab in 2015-16 was 8.9 acres (3.62 ha), which is close to multiple of four and these models would state almost every landholding category of Punjab farmers. 62% of Punjab farmers have land between 4 to 24.71 acres and 33% of farmers have land below 4 acres, while the rest of farmers have land above 24.71 acres (Gulati et al., 2021).

In this study the on-field composting costs and factors affecting the on-field composting costs on different landholding sizes with Punjab farmers are evaluated.

Chapter 2: LITERATURE REVIEW

2.1 Impact of Green Revolution on crop rotation in Punjab

Agriculture in Punjab has undergone several significant changes over the years. Until the 1990s, Punjab was an economically leading state in India with thriving agriculture. This success was attributed to the package program called "Green Revolution," which North America introduced to the government of India. The aim of the Green Revolution was the production of food grains and feeding the growing population of the country. This package included a Hybrid High Yielding Variety (HYV) of crop seeds, chemical fertilizers, various pesticides and herbicides, and extensive use of farm machinery. During this time, Punjab's agriculture significantly changed its cropping pattern. The initially introduced HYV seeds were wheat, the staple food of Punjabis; however, most of the Indian population eat rice. Rice growing was familiar to farmers of Punjab, but it was a marginal crop. In this way, the Green Revolution had a great impact on the selection of rice-wheat crop rotation by most of the farmers of Punjab.

After the introduction of the Green Revolution, cultivating rice on a large scale was no longer a issue for farmers. The tube wells: a new source of irrigation that irrigated rice also took care of the seepage problem from canals and it helped to prepare the field later in the year for the winter (wheat) crop (Shergill, 2005). Since the Food Corporation of India (FCI) procured rice from the farmers, it quickly became a viable commercial crop for farmers. The average agricultural sector growth for the entire country from 1961 to 1986 was 2.6%, but it was 6.4% for Punjab, the highest of all states of the country (Singh & Kohli, 2005). Consequently, rice and wheat emerged as the two main crops of Punjab, and the number of crops grown in the state dropped from 21 in 1960-61 to 9 by 1990-91. The proportion of area under rabi (winter) crops other than wheat declined to 17.12% in 2004-05 from 62.74% in 1960-61. The change was drastic for the rice crop, as the area under rice cultivation increased ten times from 6.05% in 1960-61 to 63.02% in 2004-05 (Toor et al., 2007).

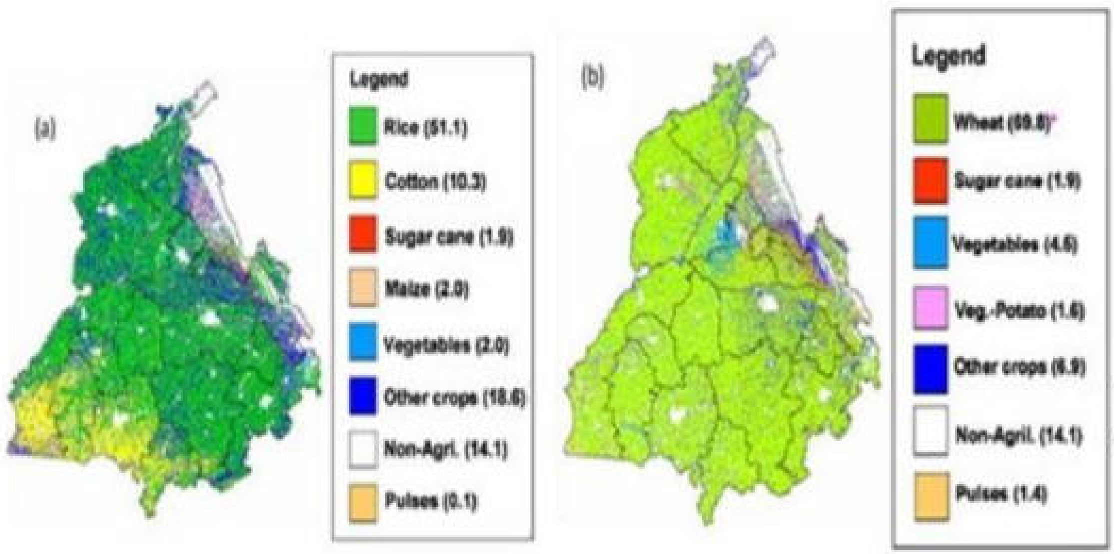


Figure 1- Cropping pattern of Punjab in 2004-05 (a) Kharif, (b) Rabi

(Figures in brackets represent the percentage of area under each crop for the net sown area)

(Website – State Action Plan on Climate Change, n.d.)

In the above figure, rice covers the maximum area in Punjab during the Kharif (summer) season (51.1%) and wheat during the Rabi (winter) season (69.9 %) (Website – State Action Plan on Climate Change, n.d.). Since the Green Revolution in the 1960s, Punjab has contributed substantially to the country's central food grain pool. In 1980-81, Punjab contributed 2.52 million tons of rice and 4.3 million tons of wheat, and this contribution has increased to 9.3 million tons of rice and 10.7 million tons of wheat in 2009- 10 (Website – Statistical Abstract Punjab (SAP) 2015, n.d.).

A careful analysis of constraints and parameters suggests that the rice-wheat crop combination was found to be an optimal specialization for achieving the long-term goals of Punjab's agricultural development. There are sufficient and sound reasons why the farmers continue with the rice-wheat crop combination, such as to sustain their incomes, for the stability of their yields and for the country's food security and good export potential (Shergill, 2005). Punjab's agricultural growth slowed to 3% annually from 1985-86 to 2004-05. Further, it crashed to just 1.6% per annum in a few years (Gulati et al., 2021) due to the adverse effects of the Green Revolution, such as a reduction in genetic diversity and soil fertility, soil erosion, soil contamination, water shortages and greater vulnerability to pests, etc.

2.2 A short time window between rice and wheat crops

Punjab is also known as the 'Rice Bowl of India' because of the usage of high-yielding varieties of rice and new technology. Punjab produces around 13 million metric tons of rice annually and it contributes 10 % of the total rice produced by India (Website - https://www.statista.com/statistics/1019575/india-rice-production-volume-in-punjab/). According to the Package of Practices -2024, rice crop occupied 31.68 lakh hectares with an average yield of 64.79 quintals per hectare (26.22 quintals/acre). Rice crops can be either sown or transplanted in Punjab; the sowing time for rice crops is 20 May – 20 June, and harvested at the end of October, i.e., 130 days after sowing time (Package of Practices for the crops of Punjab, 2024). In the case of transplanting, nursery seedlings are sown at the same sowing time

(20 may-20 June), and 30 -35 days old seedlings are transplanted to the fields from 20 June-10 July. Farmers had to restrict the timely sowing of rice crop nursery (20 May – 20 June) and timely transplanting of the nursery (20 June – 10 July) for better grain quality, water saving and low build-up of pests.

Wheat is a major cereal crop grown in 35.26 lakh hectares during 2021-22, with an average yield of 42.16 quintals/hectare (17.1 quintals per acre). The first fortnight of November is an optimum time for sowing and most wheat varieties harvested at the end of April (Package of practices for crops of Punjab, 2023-24). As per this package of practices, a delay of one week from optimum sowing time reduces wheat yield by about 150 kg per acre.

As per the Package of Practices, the optimal time window between rice and wheat crops in Punjab state is the end of October to the first fortnight of November (15-20 days, after rice harvesting and the end of April to 20 May (20-25 days) after wheat harvesting. This short time duration between the crop harvesting and sowing of the next crop creates an issue of residue management for the farmers of Punjab.

2.3 Various crop residue management strategies used in Punjab

Being an agriculture-rich state, Punjab has high biomass availability in the form of crop residues. According to (Sangeet & Rajkumar, 2016), the total crop residue generated by Punjab is 48.2 million tons. Annually Punjab produces about 23 and 17 million tons of paddy and wheat straw respectively (Kumar et al., 2015). The categorization of crop residue management can be on-field and off-field options. Various crop residue management options are available in Punjab for rice and wheat crop residues (Kumar et al., 2022). The agriculture sector produces multiple kinds of waste, and every agricultural waste has a specific management strategy. Crop residues are leaves, rice straw, wheat straw, oats and barley straw, and seed pods generated in agricultural fields (Koul et al., 2022). The management technology depends on the source, quantity, and type of agricultural waste generated. Crop residues are utilized for different applications, such as feed for cattle, compost making, rural roofing, packaging materials, wood, paper, bioethanol, and many more (Kaur, 2017).

Biochar – The Pyrolysis process converts crop straw into a carbon-rich form called biochar. In this process, straw or crop waste is burnt under low-oxygen conditions, which prevents the complete combustion of the material, resulting in the formation of biochar. There are various benefits of this method of crop residue management as it helps to improve soil; fertility by increasing nutrient availability and soil structure of soil (Jiang, Lian, Wang, & Xing, 2020) (Jiang et al., 2020), reducing carbon emissions by sequestration of carbon into stable form for long periods (Zhang, et al., 2017). While biochar offers various benefits, this crop residue management method is not accepted or used by farmers of Punjab due to certain drawbacks. As this process includes high initial costs for the setup of biochar production facilities, thus can be prohibitive, especially for small-scale farmers. Additionally, if biochar is not produced under the right conditions, it may introduce harmful compounds into the soil such as heavy metals or toxic substances that could harm plants and soil organisms (Kuppusamy, Thavamani, Megharaj, Venkateswarlu, & Naidu, 2016) (Kuppusamy et al., 2016). So, farmers lack the technical expertise to produce or apply biochar effectively.

2.3.1 Use of crop residues as a source of energy

The study conducted by Gross et al. (2021) indicated that cattle and buffalo manure and crop residues could be used together as feedstock to produce biogas by anaerobic digestion and producing organic fertilizer as a byproduct. Many researchers have calculated that bioenergy can also be generated from rice crop residues via anaerobic digestion to produce biogas, mainly methane, which can be collected and combusted to generate electricity (Singh et al., 2020). According to Lohan et al. (2018), many countries such as China, Indonesia, Nepal, Thailand, Japan, Philippines, Malaysia, and Nigeria generate compost and bioenergy from crop residues. It was estimated that total surplus crop residues generated in Punjab have a high annual bioenergy potential of 77.3 MW (Mega Watt) and the contribution of wheat and rice crop residues is maximum due to the higher area under production of these crops in this state (Sangeet & Rajkumar, 2016).

2.3.2 On-field use of crop residues

Mulching - using crop residues to provide a protective covering of the soil to reduce evaporation, prevent erosion, control the weeds, and enrich the soil. Some researchers have focused on residue incorporation in soil for further decomposition that improves soil's organic composition and properties (Singh Y. et al., 2004).

According to Sidhu et al. (1998), in most districts, farmers managed their rice and wheat straws by burning it (Appendix C). Only 0.5 to 0.6 percent of rice straw was used as fuel in Gurdaspur and Jalandhar districts. In contrast, no farmer prepared compost from rice and wheat crop residues, and very few farmers incorporated crop residues into the soil.

2.3.3 District-wise use of rice-wheat crop residues in Punjab

Table 1 – Use of rice crop residues in different districts of Punjab

Districts	Use of rice crop residues (%)				
	Burnt	**Fodder**	**Sold**	**Given to poor families**	**Incorporated**
Bathinda	100	-	-	-	-
Amritsar	52.8	18.2	19.6	9.4	-
Gurdaspur	66.5	12.9	-	20.6	-
Patiala	81.5	11.7	5.9	-	-
Ferozepur	68.1	-	-	18.8	8.8

(Kumar et al., 2015)

Rice crop residues – The study of Kumar et al. (2015) mentioned the end use of crop residues in different districts of Punjab. The rice straw was burnt and had no other end-use in the Bathinda district of Punjab. In the Amritsar district, rice crop residue was used for other uses (apart from burning), with maximum use as fodder (18.2%). Furthermore, 19.6 percent of the total residue produced was sold in the market, and 9.4 percent was given to poor, landless families. Almost 20.6 % of the rice crop residue is provided to poor landless families in Gurdaspur district, 12.9 % is used as fodder, and nearly the rest of the rice residue is burnt. In the Patiala district, 81.5 % of rice residue produced was burnt; from the rest, 11.7 % was used as fodder for animals, and 5.9 % was sold in the market. Except for the Ferozepur district, the rice stubble is hardly incorporated in the soil (8.8 %). In this district, 18.8 % of the rice straw is provided to poor landless families, and 68.1 % is burnt.

Wheat crop residues - However, a significant proportion (47%) of the wheat stubble is used as animal fodder in seven districts: Amritsar, Bathinda, Faridkot, Gurdaspur, Kapurthala, Ludhiana, and Sangrur. Gurdaspur district was the only district in which wheat residue (2.4%) was incorporated into the soil. So, most of the residues burnt belong to rice and wheat crops, and a small amount is incorporated back into the soil.

2.4 Limitations of crop residue management methods used in Punjab

Methods introduced by various studies for managing residues are less accepted by farmers, as they specify limitations for each one; for example, most farmers use wheat straw as fodder, but rice straw has a high amount of silica content (Mirmohamadsadeghi & Karimi, 2020), which contributes to poor nutrient digestibility (< 50%) and thus is unfit for ruminant consumption. Moreover, according to the Department of Agriculture of Punjab, it has been evaluated that less than 1% of farmers in Punjab adopt a method of in situ incorporation of crop stubble. This is because the yield of wheat crops decreases if the rice residue is incorporated in the soil immediately (10d or 20d) before wheat seeds are sown. This is due to incomplete decomposition of residues which leads to nitrogen deficiency in soil due to inorganic nitrogen immobilization (Singh Y. et al., 2004). However, if crop residues are given the required time for decomposition after incorporation of crop residues in the field, there would be no N immobilization issue and there would be considerable increase in soil organic matter and potassium supply. This can be done by complete composting of crop residues, which takes a period of 4-5 months.

Moreover, in a recent study of Punjab, farmers faced various problems regarding rice straw management, including technical, managerial, financial, and domestic usage problems (Singh & Ranguwal, 2023). The (Singh & Ranguwal, 2023) study stated that 100% of surveyed farmers agreed that no other suitable straw management technology exists except for rice crop residue burning. As other alternatives delay wheat sowing, and also there is a high cost of removing residue from fields.

Using crop residues for large-scale bioenergy production is a challenge concerning efficiency and economy. A high alkaline ash content present in crop residues poses an operating issue for electricity generation machinery (Porichha et al., 2021). Economically, feedstock transportation from fields and processing costs would be high for centralized large-scale power plants due to crop residue bulkiness and therefore it might not be profitable for large bioenergy plants to use crop residue as fuel. For this reason, biomass power plants in Punjab consume only 1 million tons of rice straw annually, that is, only 5% of the total residue generated (Porichha. et al., 2021). Crop residues can be used for mulching, as in this process soil of the field is covered with crop residues to retain soil moisture and control weeds. In the mulching process, biomass (crop residue) transfer from the field is required before soil puddling/tilling and it need to be returned after the soil is prepared and this prevents many farmers from applying this method, especially those with large landholdings.

2.5 Effects of Crop Residue Burning on the Environment

The main reason for crop residue burning in the field is the higher cost of removing crop residues from field and time-consuming process of other alternatives, such as bioenergy production, converting it into cushioning materials, and mulching, and farmers believe that it is more expensive and it also needs more time to complete the process. Moreover, Haider (2012) indicates that crop residue burning in the field generates some benefits, that includes land clearing in a short time and weed/pest management. Burning the residues within the field kills residue-borne pathogens and damages weed plants and their seeds in the soil.

Soil - With open field burning, nutrients such as nitrogen, sulphur, and organic carbon decline, ultimately reducing the soil microbial population as soil nutrients are required for their survival (Sharma & Mishra, 2001). Even heat produced by crop residue burning harms the soil's microbes, which further leads to decreased crop yields. As per the study conducted by the Department of Soils, PAU, Ludhiana (2010), one ton of soil loses 6-7 kg Nitrogen, 1-1.7 kg phosphorus, 14-25 kg potassium, and 1.2-1.5 kg sulphur due to crop residue burning. This leads to an additional yearly expenditure of Rs. 150 crore/year to replenish the soil (Kaur, 2017).

<u>Can crop residue burning have a positive effect on soil as well?</u> As, crop residue burning is generally considered harmful to soil health as mentioned above, but there are few potential short-term benefits which are often outweighed by long-term negative impacts. Crop residue burning can lead to quick release of nutrients such as, Nitrogen, Phosphorus and Potassium into the soil due to the breakdown of complex organic compounds from the heat of fire (Biederbeck, Campbell, Bowren, Schnitzer, & Mclver, 1980) (Biederbeck et al., 1980). The Nitrogen in organic matter is particularly sensitive to burning due to its low temperature of volatilization (200 degree Celsius), but there is an increase in inorganic N and there is a temporary increase in the availability of nutrients such as Nitrogen in soil (Sharma & Mishra, 2001). But these are temporary benefits, as negative effect on soil is long lasting.

Air - Burning crop residues releases soot particles and smoke, causing human and animal health problems. There is also an emission of greenhouse gases, namely carbon dioxide, methane, and nitrous oxide, which causes global warming. India-wide, agricultural fire emissions from the northwest states (Punjab. Haryana, Rajasthan, Uttar Pradesh, Himachal Pradesh) contribute more than 90% of the fire-related exposure, with 64% from Punjab (Lan et al., 2022). Crop residue burning has an adverse negative impact on the environment of neighbouring states and countries as well. A recent study by Huang et al. (2022) has shown that $PM_{2.5}$ (Particulate Matter that measures less than 2.5 micrometres) and other harmful gases (CO_2, CH_4, NO_2, etc.) emitted in crop residue burning affect air quality not only in Punjab or India but also being transported by the predominantly north-westerly winds to neighbouring countries; Pakistan, Nepal, and Bangladesh.

Even researchers have suggested that the field's open burning of crop residue leads to Polycyclic Aromatic Hydrocarbons (PAH) emissions (Zhang et al., 2011). Crop residue burning in Punjab strongly influences Delhi's (the capital of India) air quality. As daily average particulate matter and gaseous pollutants data of rice residue burning shows that after burning of rice residues in Punjab, there is an increase of 50-75% in $PM_{2.5}$ and 40-45% in PM_{10} (Particulate Matter that measures less than 10 micrometers) concentration in the air of the capital city of India (Delhi) (Khan et al., 2023).

According to (Godde et al., 2022), open burning of crop residues results in the emissions of harmful chemicals that have toxicological properties and are potential carcinogens like polychlorinated dibenzo-p-dioxins (PCDDs), Polycyclic Aromatic Hydrocarbons (PAH) and Polychlorinated dibenzofurans (PCDFs) referred to as dioxins.

2.6 Effects of Crop Residue Burning on Animal and Human Health

The dioxins released from crop residue burning have toxicological properties and are potential carcinogens. Burning of crop residues has adverse impacts, especially for those people who are already suffering from respiratory disease or cardiovascular disease. Inhaling delicate particulate matter triggers asthma and can even aggravate bronchial attack symptoms. More than half (60%) of the population in Punjab live in rice-growing areas and are exposed to air pollution due to the burning of rice residues (Singh et al., 2008). Irritation in the eyes and congestion in the chest are two main health issues faced by people due to crop residue burning. Even the medical records of the civil hospital of Zira city (Ferozepur district), in the rice-wheat belt, depicted a 10 percent increase in the patients' number within 20–25 days of the crop residue burning period every season (Singh et al., 2008). Ravindra et al. (2019) described that crop residue burning emissions will increase by 45% in 2050, considering 2017 the base year. In addition, crop residue burning led to accidents on the road due to decreased visibility caused by smoke during the peak periods of stubble burning, that is, the months of October and November.

Air pollution can result in animal deaths because inhaling carbon monoxide and carbon dioxide from polluted air can cause hemoglobin to convert to deadly hemoglobin. There can also be a potential decrease in the yield of milk from milk-producing animals.

2.7 Role of Punjab government to restrict crop residue burning

Section 188 of the Indian Penal Code (IPC) makes stubble (crop residue) burning a crime. Additionally, under the Air (Prevention and Control of Pollution) Act, 1981, it was notified as an offence. National Green Tribunal (NGT) is a specialized body with expertise in handling environmental disputes involving multi-disciplinary issues, and it has stated to every district administration of Punjab that fines should be levied on the farmers found burning crop residues. The NGT fines the farmers for burning the crop residues in fields; the amount varies depending on landholding size (Singh & Zaffar, 2017). Despite being banned or penalized, the practice continues, as farmers do not find viable alternatives to clear their fields of stubble in a short time. The Punjab Agriculture and Farmers Welfare Department has taken significant steps, such as an 80% subsidy on Crop Residue Management (CRM) Machines if renting through Custom Hiring Services and 50% on purchasing CRM machines. Farmers will receive these machines at subsidized prices, and the machines being provided are Super Straw Management System, Happy Seeder, Rice Straw Chopper, Mulcher, Super Seeder, Crop Reaper, Straw rake, etc. The state has allocated Rs. 350 crores to curb crop residue burning during harvest (Bajwa, 2023). Even the Agricultural Department has launched an Extension drive to educate and train farmers regarding the usage of this farm machinery. It is advertised in local newspapers to inform people about the adverse impacts of crop residue burning on the environment and the health of humans and animals. The District Commissioner has directed gram Panchayats to restrict crop residue burning in Punjab. By providing subsidies and promoting new advanced machinery, the Punjab government is taking significant strides toward restricting crop residue burning and ensuring a greener future for farmers.

However, farmers still find this agro-machinery expensive and there is low availability of all advanced machinery to farmers on rent from Custom Hiring Centers in Punjab as it is not available for all farmers on time. Thus, farmers take the risk of penalty and continue with the crop residue burning.

2.8 On-field composting as a substitute for crop residue burning in Punjab

Crop residue burning wastes valuable resources, as it could be a good source of carbon, bio-active compounds, feed, and energy for small industries and rural households. Instead of being burnt in the field, the agricultural waste, i.e., crop residues, can be composted. On-field composting is one of the strategic technologies for the sustainability of farming activities, which could solve the critical issue of the disposal of crop residues (Pergola et al., 2018).

Composting is a biological process in which organic waste is recycled into value-added products, i.e., compost under aerobic conditions, and this compost can be utilized for crop cultivation (Kim Ho et al., 2022). Compost limits the transport properties of soil, prevents the erosion of pesticides, and retain it in the porosity of soil (Woignier et al., 2016), thus enhancing soil health. Besides agricultural lands, urban soil such as gardening soil can also benefit from this compost, as it would provide soil nutrients and contribute to Soil Organic Carbon (SOC), etc. (Kranz et al., 2020), so it can be a source of income for farmers.

The crop residues have been traditionally used as organic waste to prepare compost. Straw from crops, especially rice and wheat, along with cow dung and kitchen waste, are used in compost preparation. This compost serves as an organic manure for the soil. However, there was a steep decline in using crop residue as household fuel for bedding and composting.

In composting, microorganisms release biochemicals to break down these raw materials (feedstock) by undergoing several biochemical processes, including oxidation. Carbon and nitrogen are the most essential elements required for microbial decomposition. The composting process has four phases: mesophilic, thermophilic, cooling, and maturation. The mesophilic phase is characterized by the explosive growth of mesophilic bacteria and fungi; during the thermophilic phase, more complex compounds such as proteins, fats, and cellulose get broken down by heat-tolerant microbes. In the cooling phase, temperatures drops, and in the maturation phase, a series of secondary reactions take place, which cause condensation and polymerization of the compost. Crop residue would act as a carbon energy source for microbial growth in soils for decomposition and biological nutrient cycling (Singh Y. et al., 2004). Various factors affect the length of the composting process, such as pH, C: N ratio of raw material, moisture, composting technology, oxygen availability, etc. The ideal C: N ratio for the composting process from the northwest states of India is generally considered to be around 30:1, and the C: N ratio of crop residue, such as straw, is 75-80:1. Moreover, adequate phosphorus, potassium, and trace minerals (calcium, iron, boron, copper, etc.) are essential to microbial metabolism, and these are present in ample concentration in the crop residues. In addition, compost positively affects soil's physical and chemical properties (Becker et al., 2010). So, crop residues can be used as a good compost source.

Table 2 - The properties of rice and wheat straw

Parameter	**PH**	**TOC (%)**	**C: N ratio**	**MC (%)**	***Source***
Rice straw	7.6	39.2	61.3:1	11.4	(Jusoh et al., 2013)
Wheat straw	7.5-9	49.6	80:1	9.33	(Lentz et al., 2016-17), (Ferraz et al., 2020)

TOC - Total Organic Carbon, *C/N ratio* - Carbon/Nitrogen ratio, *MC* - Moisture Content

The properties of rice and wheat straw are almost the same, and they would undergo composting similarly.

2.9 Awareness among farmers in Punjab regarding composting method of residue management

Besides burning crop residues, farmers needed help finding a suitable and sustainable crop residue management method. However, farmers are aware of the composting method but very few farmers of Punjab have implemented it on their field (on-field composting) using on-field compost pit. And they might be unaware of the cost savings of recycling the crop residues through the composting process. The composting strategy of crop residue management can allow farmers to adopt organic farming, Bioremediation, Biocontrol, and compost can be a bioinoculant carrier (Koul et al., 2022). Hence, crop residue disposal costs are reduced, and eco-friendly and productive agricultural development is established with composting. A high quality of compost can be produced to overcome the cost of composting (Bernal et al.,2009).

2.10 Research Gap

The awareness of the negative impact of crop residue burning on the environment and health persists among the farmers of Punjab. However, the practice of on-field crop residue burning to manage crop residues has been adopted on a large scale among farmers in Punjab. The main reasons for adopting the residue-burning strategy are the high cost of removing residue from the field as required for other alternatives (industrial use or mulching) and the short time window between harvesting one crop and sowing the next crop (rice and wheat). There is a decrease in the yield of crops due to N-immobilization on incorporating the crop residues directly into the field, and farmers resist this method as well. So, farmers find crop residue burning as the cheapest and easiest method to clear the fields before sowing the next crop in a short time window.

Nevertheless, on-field composting can be an excellent alternative to crop residue burning, as it does not require the removal of residue from the field and can be managed within a short time window without delaying the sowing of the next crop. The on-field composting method of crop residue management will also positively impact the environment and health.

However, the farmers are unaware of the costs of on-field composting crop residues as literature on costs per acre related to burning and composting is not available to farmers to make a rational decision to choose composting over burning. In this research, on-field composting costs would be figured out for farmers of different districts of Punjab and with different landholding sizes within each district. Various factors (inputs or outputs) would affect composting costs, such as labor cost, the quantity of residue production, area required for a compost pit for on-field composting, etc., which are different for farmers in all districts. So, the implications of the on-field composting process and its costs will be studied in each district of Punjab and compared with burning costs on a per-acre basis.

In the on-field composting method, a compost pit would be dug out in the corner of the field where crop residue collected from the field will be composted. In 4-5 months, when the compost matures, then it can be broadcasted in the field as an organic fertilizer. By this method, the field would be ready for the next crop in a short time interval without removing the residue away from the field, and a valuable product would be formed from crop residues (compost), that would be broadcasted back into the field. Using this strategy, residues of rice and wheat crops can be managed by eco-friendly method (on-field composting) and would help to combat the adverse impacts of crop residue burning. This research is all about the cost analysis of managing residues of rice and wheat crops through composting in various districts of Punjab.

The on-field composting costs (labor and farm machinery costs) are assessed under four on-field models: one acre, four acres, eight acres, and sixteen acres to manage the rice and wheat crop residues for different landholding size categories in Punjab state.

Outline of the methodology of the study

Assessment of rice and wheat crop residues generated in Punjab

(Crop residue management methods)

On-field composting method

Inputs

Revenue

On-field composting models

(Variation of labor & farm machinery costs per acre)

- One-acre model
- Four-acre model
- Eight-acre model
- Sixteen-acre model

Burning method

Inputs

Outcomes

Environmental Change

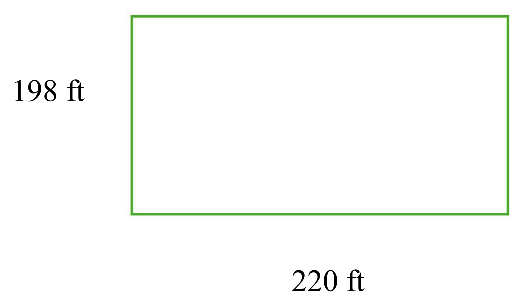
(GHG emissions reduced by on-field composting method)

Chapter 3: METHODOLOGY

To achieve sustainable agriculture and the environment, it is critical to strategically handle and reuse crop residues in various districts of Punjab to produce value-added products such as compost from crop residues.

This research is based on secondary data that is already collected and organized for past years, related to the rice and wheat crop residues generated in various districts of Punjab. This data is used to develop the input and output costs of burning as well as composting crop residues.

In this project, the standard field unit considered is 1 acre size. The dimensions of a 1 acre field are 198 ft (N-S) and 220 ft (E-W) in Punjab.



The dimension of an acre is 198 ft in North-South direction = 60. 3504 meters

The dimension of an acre is 220 ft in East-West direction = 67.056 meters

So, the area of an acre is 4046.856 sq. meters.

The 22 districts of Punjab (Amritsar, Barnala, Bathinda, Faridkot, Fatehgarh Sahib, Fazilka, Ferozepur, Gurdaspur, Hoshiarpur, Jalandhar, Kapurthala, Ludhiana, Mansa, Moga, Pathankot, Patiala, Rupnagar, S.A.S Nagar, Sangrur, SBSN, SMS, Tarn Taran) as per data available for 3 years (2019-20, 2020-21, 2021-22) are covered in this research. This study provides evidence-based insights into the problem of crop residue management. The basic **costs and benefits** analysis approach is used to estimate costs/benefits associated with the crop residue on-field composting vs. crop residue burning to determine which crop residue management approach is more economical, environment friendly and socially sustainable.

3.1 Objectives of the study

1) **To compare the costs of the on-field composting process with that of burning in all districts**- The input and output costs of the on-field composting and burning processes are evaluated and compared, and cost savings are analyzed. No doubt, the on-field composting process to manage crop residues positively impact soil health, crop yield and the environment, as compost is a good source of nutrients and supplies organic matter or a blend of nutrients to the soil that becomes gradually available to the growing crops. However, the main objective here is to assess on-field composting costs and compare it with the burning costs to find out the economic benefits or losses to farmers on adopting the on-field composting method for rice and wheat crop residue management instead of the burning method. It further includes two sub-objectives.

   a) <u>To assess the inputs and outputs (quantity and cost) of the crop residue on-field composting process</u>: - During the on-field composting process, multiple inputs such as the area under the on-field compost pit, labor for implementing the composting process in the field, use of farm machinery for collection of crop residues and preparation of the field for next crop, inorganic fertilizers, farm tools for digging a pit and making a compost pile, gunny bags and inoculants will be required. Once the compost is prepared, it can be used as organic fertilizer for the next crop, as the remains of wheat and rice crops do contain certain amounts of Nitrogen, Phosphorus and Potassium (Abbas et al., 2012), and this would lead to enhanced soil nitrogen content, organic matter, available Phosphorus and Potash, and soil quality through organic fertilization (Herencia et al., 2007). Adding compost in the field as organic fertilizer would reduce the quantity and cost of inorganic fertilizer recommended for crops. This reduction in the cost of inorganic fertilizer could vary from district to district. In addition, rice and wheat straw compost proved to be a good nutrient source for enhancing yield (Moharana et al., 2020), providing farmers with increased crop productivity. Compost as a product can also be sold in the market directly to generate revenue. Even pit sand can be used for various other purposes in fields or households such as bedding for animals, gardening etc.

b) To assess the inputs and outputs (quantity and cost) of the crop residue burning process**: -** Being the easiest but risky method for residue management, the burning process requires less labor to clear the crop residues from the field. However, farm machinery and farm tools are required to reduce the risk of spreading fire to other fields and to prepare the field for the next crop. Along with this, the recommended amount of inorganic fertilizers is applied to rice and wheat crops. The legal penalty in monetary units for burning crop residues will be an input cost for burning crop residues, as this practice is against the law, and this would put farmers at risk of being caught and fined. On the other hand, the outcomes of burning crop residues would be a decrease in soil fertility due to loss of nutrients, and also uncontrolled fire could cause collateral damage.

2) **To evaluate the variations of on-field composting costs with different landholding sizes owned by farmers of Punjab -** In this study, four on-field composting models (land size with one acre, 4 acres, 8 acres, 16 acres) are examined to measure the variations of on-field composting costs per acre. The models include multiples of 4 because, as per data from the Ministry of Agriculture and Farmer Welfare, the average landholding of a farmer in Punjab is **3.62 hectares** (approx. 8.9 acres) and these four models could represent landholding size category of Punjab. After assessing cost savings in the on-field composting process for 1 acre as per the first objective, the next objective is to find whether the input costs increase or decrease per acre with an increase in the land size of a farmer. Some factors, such as labor and machinery costs, may not increase in direct proportion to the increase in land size. The variation in cost savings on adopting on-field composting method with land size may differ, and this study will give an idea of composting costs per acre related to marginal, small, medium, semi-medium and large farmers of Punjab (Categories depending on land size).

<u>Landholdings Size in Punjab</u> -

However, implementing any new technology or method in the field would need a clear understanding of the landholding size owned by farmers.

Table 3 - Categories of landholding size in Punjab

Size Category	**Landholding**	**Percentage of area (%)**	**Percentage of farmers (%)**	**Average size (ha)**
1. Marginal	Below 1 ha (< 2.471 acres)	2.36	14.13	0.60

2. Small	1 – 2 ha (2.471 – 4.94 acres)	7.33	18.98	1.40
3. Semi-medium	2 – 4 ha (4.94 – 9.88 acres)	24.87	33.67	2.67
4. Medium	4 – 10 ha (9.88 – 24.71 acres)	43.75	27.93	5.67
5. Large	10 ha and above (> 24.71 acres)	21.68	5.28	14.85

(Agricultural Census 2015-16, 2018)

The marginal and small farmers dominate the agriculture of all states of India except Punjab, where the semi-medium and medium farmers largely dominate the sector. There has been no significant change in the landholding size of Punjab state from 1995 to 2016 (Appendix D). So, the on-field composting models selected represent the categories of land size holdings in Punjab to some extent.

There was a marginal decline in average landholding size from 3.79 ha in 1995-96 to 3.62 ha in 2015-16 (Agricultural Census 2015-16, 2018). Depending on the farmer's landholding size, the costs of composting crop residues on the field would be impacted. Landholding size could significantly impact labor and machinery costs to compost crop residues.

3) **To evaluate environmental changes by on-field composting crop residues instead of burning in various districts of Punjab –** Crop residue burning in Punjab emits Particulate Matter and various GHGs with detrimental impacts on the health and climate of the region, ultimately threatening agricultural production. The study (Yin et al., 2019)

showed that burning caused the most severe $PM_{2.5}$ (Particulate Matter) pollution around the rice crop harvesting season, and the amount of $PM_{2.5}$, CH_4, CO_2, and NO_2 released in the atmosphere varies from district to district. On-field composting is expected to help farmers, their families and society from various health issues by substituting the burning method to manage crop residues.

The composting of organic waste is a biological process and it also leads to the formation of CO_2, CH_4, NO_x, etc., but the amount of these gases released depends upon the C/N ratio and water content of organic waste (Zhang et al., 2011). Waste with a low C/N ratio and high water content has great potential for generating GHG emissions during composting and storage (Pang et al., 2020). The crop residues (straw) have a C/N ratio between 60 - 80 (high) and humidity is 20 %, which is relatively low (Argun et al., 2017). It is expected that the GHG released during an on-field composting method of residue management would be less than that produced by burning agricultural waste. So, the GHG emissions reduced by adopting the on-field composting method over burning will be analyzed. As per the Canadian government, Social Costs (SC) is assessed to estimate environmental cost savings on adopting the on-field composting method for crop residue management.

Secondary data regarding the inputs and outputs of the on-field composting and burning process is used to achieve the above research objectives.

3.2 Resources required for comparative analysis of on-field composting v/s burning of crop residues

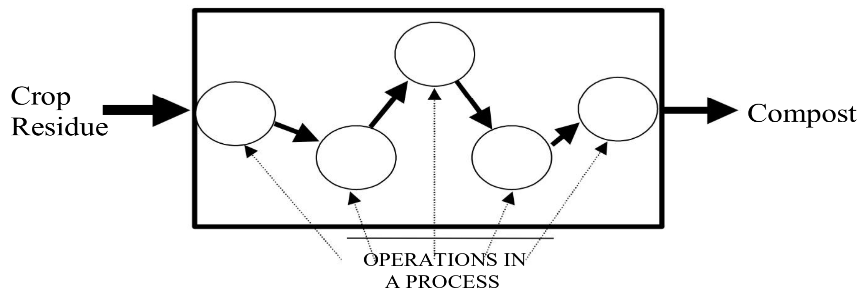


Figure 2 - Operation as a Basic' Work Unit' of a Composting Process

(Adapted from Deo & Strong, 2002)

In on-field composting process, input material, i.e., straw, is routed through a specific sequence of operations to carry out a composting process. On-field composting is completed by routing the material (straw) through pre-defined operations performed in a sequence. Further, in a composting operation, a set of 'tasks' is specifically sequenced, and each task takes some specified time for its completion. The sequence of all the tasks performed in a composting operation is also called 'procedure' (Deo & Strong, 2002).

Based on the eight resource input categories described in the Deo & Strong, (2002) model, the inputs and outputs of each task performed in the composting and burning processes are assessed. Each task of the procedure involves inputs and outputs/outcomes. According to Deo & Strong, (2002) model, the resource content of an 'Operation' can easily be categorized into a maximum of 8 input factor categories. This model helps to highlight most of the resources in the form of inputs and outputs. Considering the on-field composting and burning processes are based on the sequence of operation of the basic unit of work, the inputs and outputs of the composting process and burning process are shown below –

On-field composting method –

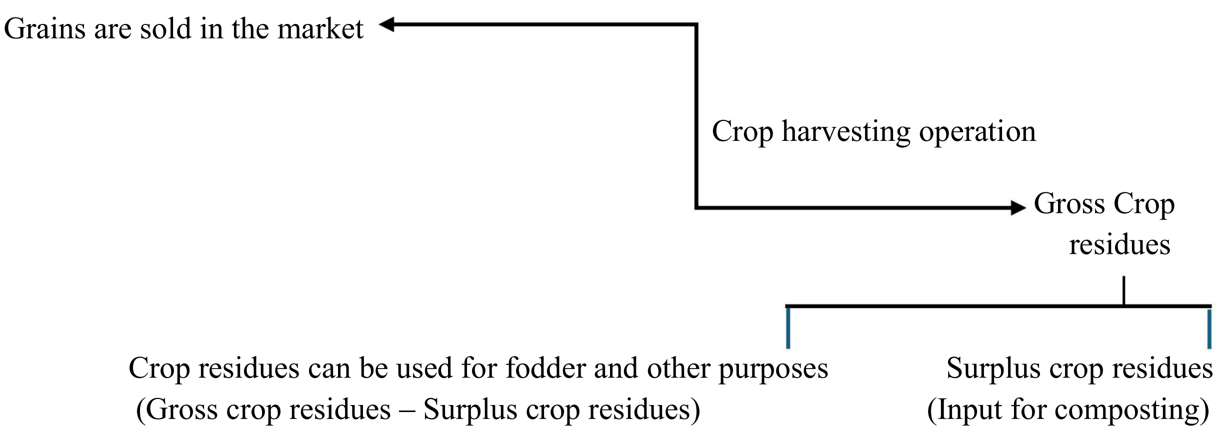


Table 4– Inputs and outputs of the on-field composting method

Tasks	On-field composting method	
	Inputs	**Outputs**
1. Pit digging	1. Decrease in area under production (used for pit) 2. Labor 3. Farm tools	1. Dirt/ Sand from the pit can be used for other purposes.
2. Collection of crop residues	1. Labor 2. Farm machinery	-
3. Chopping, mixing of Crop residues and pit filling	1. Farm machinery 2. Labor 3. Inoculants 4. Farm tools	1. Suitable size of raw waste for composting 2. More stable compost 3. Easy breakdown of waste

4. Moisture the chopped straw and cover it with gunny bags	1.Water 2.Labor 3.Gunny bags	-
5. Compost pit left for 3-4 months and turning of crop residues done for 2-3 times over the composting period	1. Labor	1. Release of GHGs
6. Compost digging out of the pit and broadcasting it back into the field	1. Labor 2. Farm tool 3. Farm machinery	1. Nutrient-rich compost

(Source – Anecdotal information from farmers)

(Output)

Compost cycled it back into the field

Decrease in use of recommended inorganic fertilizers

Increase in yield of crop

On-field composting of crop residues on an individual level can be practiced in Punjab, India. Instead of ploughing (mixing) the crop residues into the soil right away, the crop residues can be collected from the field and decomposed in the on-field compost pit. Then compost can be cycled back into the field to reduce the recommended dose of chemical fertilizers.

Labor is a significant input in the composting process, as it is required in each task of the residue composting process. Following it, farm machinery is required to perform heavy duties such as collecting crop residues, chopping of crop residues, broadcasting of compost in the field, preparation of field for next crop etc. The decrease in area under production due to compost pit would reduce the total area under production of crops per acre. Along with that, agricultural farm tools, gunny bags and inoculants are also used as input in the on-field composting process. Water used in the composting process is an input but will not be studied further as it does not cost farmers, and even does not require extra effort because water passage to the compost pit would be the same through which growing crops beside the compost pits are irrigated. Here, recommended inorganic fertilizers would also be considered as input because, from this, the fertilizer dose applied to crops through compost as organic fertilizer (an output) would be subtracted to calculate net composting costs.

The output of the on-field composting process would be a nutrient-rich compost, which can either be sold directly in the market to earn revenue or used in the same field as organic fertilizer for upcoming crops. If compost is used as an organic fertilizer in the field, there would be a cost reduction due to a reduction in the recommended dose of inorganic fertilizers because of the nutrients present in organic compost. In addition, using compost as a fertilizer would enhance crop yield due to its benefits to the soil environment, such as increasing soil fertility and soil microorganisms' activity. The dirt or sand dug out from the pit can be used for various other purposes, such as soil reclamation and other household requirements. The output of the on-field composting process would also release greenhouse gases such as carbon dioxide, nitrogen oxide, and methane.

These inputs and outputs are analyzed on a cost basis to evaluate the Net Composting Costs (NCC) of crop residues.

Crop residue burning method -

Table 5 – Inputs and outcomes of crop residue burning method

Crop Residue Burning method	
Inputs	**Outcomes**
1. labor 2. Farm machinery 3. Recommended inorganic fertilizers 4. Farm tools 5. Penalty	1. Loss of nutrients 2. Collateral damage 3. GHGs • Environment pollution • Increase in hospital visits by patients

Inputs assessed in the crop residue burning process are labor, farm machinery and farm tools required to control the fire within the field. Farm machinery can also be used to prepare the field for the next crop. The recommended dose of inorganic fertilizers would be input along with the legal penalty cost of crop residue burning. Burning crop residues is banned in Punjab, so using burning as a crop residue management method would involve a risk of being caught and fined or penalized by the government. At the same time, the significant negative outcomes of residue burning would be the instant release of GHGs, which would degrade the environment causing environmental pollution and increasing the number of hospital patients. Crop residue burning also causes the loss of nutrients and soil microorganisms, affecting soil health. An uncontrolled fire could cause other collateral damage. The outcomes of crop residue burning would be a cost to society.

A cost analysis of the burning process would be calculated as Net Burning Costs (NBC) of crop residue.

To calculate the NCC and NBC of crop residues, the data is collected from several government websites, journal articles, Punjab statistics, and Packages of practices for rice and wheat crops published by Punjab Agricultural University.

3.3 Data Sources

Secondary data for rice and wheat crops, residues of these crops, etc. gathered and accessed by researchers supports this research study. The secondary data collected from sources such as, – Practice guidelines for rice crops (Package of Practices for the crops of Punjab, 2024) and wheat crops (Package of practices for crops of Punjab, 2023-24). These packages provide information and data related to rice and wheat crops, such as the sowing and harvesting time, amount of recommended fertilizer, yield of crops, etc. Some organizational records and data were initially collected for other research purposes, such as CRR (Crop-to-Residue Ratios) and SF (Surplus Fraction) values, formulas of CR (Total Crop Residue), formulas of SR (Surplus Residue), nutrients present in crop residues, emissions released on burning crop residues and composting yard waste., etc., are used. Moreover, secondary data related to basic pay for labor in Punjab districts, inorganic fertilizer cost, farm machinery rental cost, etc., are collected from government agencies of Punjab state. The data regarding district-wise production of rice and wheat crops, the area under crops, etc., and other such information is collected from the official website of the Indian government website - (indiastatdistricts, 2000).

https://www.indiastatdistricts.com/Home/Login

3.4 The outline of the on-field composting method to manage crop residues

After harvesting one of the crops of rice-wheat crop rotation, a compost pit is dug out at a suitable site in the field using labor and farm tool. Farmers can use a straw reaper to cut the foot-long stalks of crops (left after mechanical harvesting) from the ground and later cultivator is used to collect the residues near the pit. Then straw chopper is used on collected residues to break down them into small pieces to make them suitable for the on-field composting process. The composting material size must be small enough to decompose quickly and enhance the porosity and water-holding capacity of crop residues (Woignier et al., 2016). The on-field compost pit is filled with chopped straw, watered, and gunny bags are used to cover the pile to provide and retain moisture for the composting process and keep it safe from animals and birds. The entire on-field composting process will be completed within 4-5 months. It is also the time required for the next crop of rice-wheat rotation to grow and to be ready for harvesting and residue composting. The compost prepared is dug out from the pit using labor and farm tools and broadcasted in the fields as an organic fertilizer before sowing the next crop, while crop residues of the next harvested crop undergo the same procedure.

So, the compost prepared from rice crop residues will be used in the rice crop fields and compost prepared from wheat crop residues will be used in wheat crop fields as an organic fertilizer.

The procedure for the on-field composting process is given below -

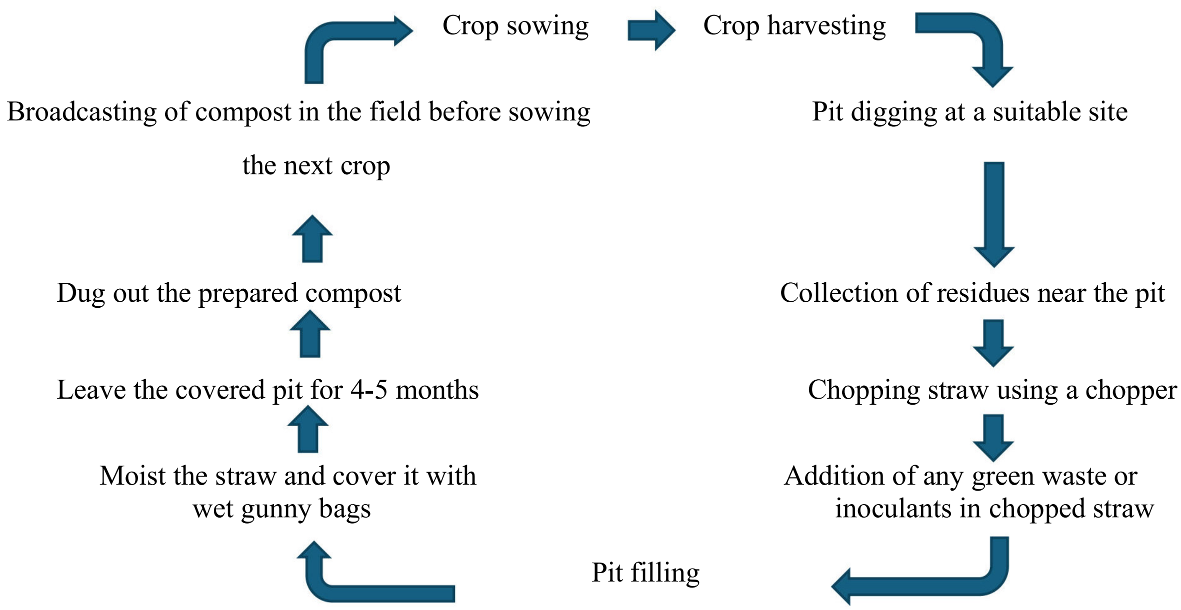


Figure 3 – On-field composting process

The first step in analyzing the inputs and outputs/outcomes of the composting and burning process is to calculate the amount of rice and wheat crop residues generated in each district of Punjab state. The amount of crop residues produced per acre is then used to assess the inputs and outputs of the on-field composting and burning method.

3.5 Assessment of rice and wheat crop residues generated in Punjab

Crop residue generated by rice and wheat crops per year in various districts of Punjab for the three years (2020, 2021, and 2022) is estimated by using the formula, as follows -

$$\boldsymbol{CR} = \sum_{\boldsymbol{i=1}}^{\boldsymbol{\eta}} (\boldsymbol{A_i}) * (\boldsymbol{Y_i}) * (\boldsymbol{CRR_i})$$

(Singh & Ranguwal, 2023)

Where CR = Total crop residue generated

A_i = Area under ‘i^{th}’ crop

Y_i = Average yield of ‘i^{th}’ crop

CRR_i = Crop-to-residue ratio of ‘i^{th}’ crop

The residue generated from a particular crop depends upon three parameters viz area covered by the crop, yield, and CRR of the crop, The data related to area under rice and wheat crops (A_i) and yields of rice and wheat crops (Y_i) in various districts of Punjab for three years (2020, 2021 and 2022) are taken from the official website (indiastatdistricts, 2000) (Appendix A). The total production of crop residues is estimated using crop-to-residue ratios (CRR). The CRR values for rice and wheat are taken from the study of Chauhan, (2012).

Table 6 – CRR values of rice and wheat crops

Crop	**Residue type**	**CRR**
1. Rice	Straw	1.20
2. Wheat	Straw	1.15

(Chauhan, 2012)

Using the above CRR values, gross (total) crop residue produced (tons) is calculated. For instance, in the Amritsar district, using the CRR value from Table 6, and the area and yield of rice and wheat crops from Appendix A, the gross crop residue generated in three years in the Amritsar district is -

a) The Gross crop residue generated (tons) for rice crops in the 2019-20 year is,

= Area (Appendix A) × Yield (Appendix A) × CRR (Table 6)

= 447251 acres × 1.337057 tons/acre × 1.20 = 717600 tons,

b) The Gross crop residue generated (tons) for wheat crops in the 2019-20 year is,

= Area (Appendix A) × Yield (Appendix A) × CRR (Table 6)

= 464548 acres × 1.834041tons/acre × 1.15 = 979800 tons

Similarly, the amount of gross crop residues generated by rice and wheat crops for all districts of Punjab for three years is evaluated.

These crop residues have competing uses, such as animal fodder, bioenergy production, mulching etc. Therefore, only a particular portion of gross crop residue needs to be managed in the field and this percentage of gross crop residue which needs to be managed is called surplus crop residue. The surplus crop residue produced per acre in each district for rice and wheat is required for further evaluation of variables (inputs and outputs). So, the surplus crop residues (tons) generated in Punjab are estimated as follows.

$$\boldsymbol{SR = \sum_{i=1}^{\eta} (CR_i) * (SF_i)}$$

(Hiloidhari et al., 2014)

where SR is Surplus Residue (tons), CR_i is gross crop residue of ith crop (tons), and SF(i) is the Surplus Fraction of ith crop.

Table 7 – SF (Surplus Fraction) mean value of rice and wheat crops

Crop	SF (mean value)
1. Rice	0.15
2. Wheat	0.09

(Kapoor, et al., 2023)

The Surplus Fraction (SF) value of wheat is almost half that of rice because wheat crop residues have more competent uses than rice crop residues. Thus, more rice crop residues need to be managed in the field. For instance, surplus crop residue for the Amritsar district is calculated using the above equation, from which the SF value is taken (Table 7) and the CR (Gross crop residue) is already evaluated above.

For 2019-20 year,

a) Surplus Residue (tons) for rice crop in the 2019-20 year,

$$= CR \times SF \text{ (Table 7)}$$

$$= 717600 \text{ tons} \times 0.15 = 107640 \text{ tons}$$

b) Surplus Residue (tons) for wheat crop in the 2019-20 year,

$$= CR \times SF \text{ (Table 7)}$$

$$= 979800 \text{ tons} \times 0.09 = 88182 \text{ tons}$$

Similarly, the amount of surplus crop residues generated by rice and wheat crops for all districts of Punjab for three years is evaluated.

Later, all the inputs and outputs of on-field composting and burning crop residues are analyzed based on the surplus crop residues of these crops.

3.6 Factors included in the on-field composting of crop residues

Various factors (inputs and outputs) are considered before implementing the on-field composting method to manage the crop residues on the field.

Factors included in the on-field composting method

Inputs **(NCC*)** **Outputs**

Quantity-based	**Cost-based (TICC)**	**Quantity-based**	**Cost-based (TOCR)**
-Decrease in an area under production	- Decrease in yield revenue	- Amount of fertilizer added by compost	- Inorganic Fertilizer cost reduction
- Increase in yield of crops	- Revenue based on increase in crop yield	- Labor	- Labor cost
-Recommended inorganic fertilizer	- Recommended inorganic fertilizer cost	- A nutrient-rich compost	- Revenue generated from selling compost
-Farm machinery	- Farm machinery cost	- Sand as filler for other purposes	- N/A
-Farm tools	- Farm tool cost		
-Gunny bags	- Gunny bag cost		
-Inoculants	- Inoculant cost		

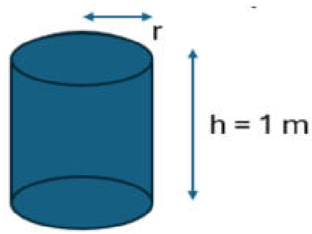
*NCC (Net Composting Costs) = TICC (Total Input Composting Costs) - TOCR (Total Output Composting Revenue)

3.6.1 Inputs of on-field composting method – The inputs of composting crop residues are-

1) **Decrease in an area under production (used for compost pit)**- The area of an acre is 4046.856 sq. meters in Punjab, and if a small portion of a field (acre) is used for composting

in the form of a cylindrical pit, then the area under crop production would be decreased. This would affect the average yield of the crop per acre.

1 acre = 4046.856 sq. meters



To calculate the surface area of the cylindrical compost pit, the formula that would be used is.

$$\text{The surface area of the compost pit (circular)} = \pi r^2,$$

To calculate the surface area of the compost pit, a radius of the compost pit is required, which is not known. So, the surface area under the compost pit can be calculated from the volume of surplus crop residues to be composted.

As the formula of volume is,

$$\text{Volume of compost pit (cylinder)} = \pi r^2 h$$

And the pit's height is assumed to be **1 m** (below and above ground level), h = 1,

$$\text{Volume of compost pit (cylinder)} = \pi r^2 * 1 = \pi r^2$$

So, the value of the surface area of the compost pit will be the same as the volume of crop residues to be filled in the compost pit, if the height of the compost pit is 1m (in total).

Volume of surplus crop residues per acre = The area under the compost pit per acre

Now, the volume of crop residues is calculated using the bulk density values and the mass of rice and wheat crop surplus residues.

Bulk density = Mass/Volume (surplus straw)

The mass (surplus residue) is already calculated; rice and wheat's bulk density now depend on the particles' size, moisture content, and compaction pressure. Rice straw with 12.8 % moisture content and 2.5 -5 cm particle size has a mean bulk density of 43.5 kg/m3 (Gowda & Kumaran, 2014), whereas wheat straw with 8.45 % moisture content and 5-6 cm particle size has a measured bulk density of 24.16 kg/m3 (Lam et al., 2007). The volume of these two kinds of straws (Appendix B) is calculated using mass and bulk densities.

Volume of surplus crop residues = Mass of surplus residue per acre ÷ Density of crop residues

So, the surface area under the compost pit would be the same as the volume calculated. The area under the compost pit for rice and wheat crop residues per acre is calculated (m^2). From this, the estimation of the decrease in area under production and decrease in rice and wheat yield (kg/acre) is calculated.

The decrease in area under production (m^2) = The area under on-field compost pit

This decrease in the area under production is further used to calculate the decrease in yield of crops per acre due to the compost pit made on the field.

The decrease in yield of crop per acre (t/m^2) = (Yield of crop per acre (without pit) ÷ area of acre without pit (4046.856 m^2)) × decrease in the area under production

Further, for cost analysis, this decreased yield per acre is converted into cost/acre that a farmer would lose on making on-field compost pit for composting crop residues.

The central government always fixes Minimum Support Price (MSP) for rice and wheat crops; {Website -(Minimum Support Price-2021-22 (MSP))}. These MSP values for rice and wheat grains fixed by the government are the same for all districts of Punjab. The Indian government sets the Minimum Support Price for about two dozen commodities twice per year. MSP is fixed based on the recommendations of the Commission for Agricultural Costs and Prices (CACP), an apex advisory body for pricing policy under the Ministry of Agriculture, Government of India, website- (Minimum Support Price for various crops).

Decrease in revenue generated due to decrease in yield/acre (Rupees) = Decrease in yield per acre (t/m^2) × MSP of the crop (Rs)

The decrease in the value of yield per acre is multiplied by the MSP value to estimate the cost a farmer would use as an input per acre for implementing the composting method in the field.

2) **Labor** - Composting is relatively a laborious process, as labor is required to collect crop residues in the field, shred and mix straw waste, add inoculants to enhance the composting process, dig pits, fill pits, turn compost, etc. The labor required to compost crop residues per acre is an estimation based on the experience of practicing farmers in Punjab (anecdotal information). This estimation is based on the regular hours a person or labor would spend on each task of the on-field composting process.

   The total number of labors required for each crop (rice/wheat) residue composting process per acre is estimated based on number of hours required for each task. Every district has a different basic wage rate (Rs/day), which varies yearly. The basic wage of labor (Rs/day) prevailing in each district is multiplied by the number of labors to calculate the labor cost for the on-field composting method for residue management in each district of Punjab.

Labor cost per acre (Rs)= labor required per acre × basic wage of labor in the district (Rs/day)

The labor wage per day vary from district to district in Punjab.

3) **Recommended doses of Inorganic fertilizers** –As per the Package of Practices, a recommended amount of fertilizers is required for rice crops (Website - (Package of Practices for the crops of Punjab, 2024) and wheat crops {Website - (Package of practices for crops of Punjab, 2023-24)} in Punjab.

   The recommended fertilizer values are multiplied by the subsidized price of fertilizers fixed by the government of Punjab every year and this subsidized price is almost the same for every district. Hence, the cost of the recommended fertilizer (Urea, DAP, and MOP) per acre is calculated using the subsidized inorganic fertilizer prices and the amount of inorganic fertilizer recommended for crops.

   Inorganic fertilizer cost/acre = Recommended quantity of inorganic fertilizer required by a crop per acre × Subsidized fertilizer price (Rs)

4) **Farm Machinery**– A variety of farm machinery is essential in the composting process for residue collection and field preparation. For instance, based on anecdotal information, after harvesting one of the crops of rice-wheat crop rotation, farmers can use straw reaper to cut stalks of the crops and cultivator to collect the residues near the pit. Then straw chopper is used on collected residues to break down them into small pieces suitable for the on-field composting process. Additionally, a laser leveler, Disc-harrow and cultivator are necessary to

prepare the field for the next crop by ploughing and tilling the soil, levelling the field, and mixing and incorporating the broadcasted compost into the soil . A tractor would be required to operate every tractor-drawn implement in the field.

The machinery would be the same for both rice and wheat crop residue management. Some farmers own this machinery, while others rent it from cooperative societies. The rental cost for this machinery is considered as part of the composting cost for a farmer and is calculated on a per-hour basis. The number of hours each farm implement used on an acre might vary as it depends on the type of tractor (horsepower) used. For instance, a HMT 2511 tractor (25 horsepower) needs twice the time required by an HMT 5911 (59 horsepower) tractor to perform field operations. After collecting crop residues near the pit, the remains of crops such as the roots are mixed with soil using rotavator with high horsepower tractor and it takes 40 minutes to perform its operation in one acre, while disc harrow or straw reaper needs 30 minutes approximately to till the soil in one acre using tractor with high horsepower (Source – Anecdotal information from practicing farmers of Punjab).

So, keeping in mind tractors with different horsepower, each farm machinery would spend approximately an average of one hour per acre. The government of Punjab has encouraged the Primary Agricultural Cooperative Societies (PACSs) to establish Agro Machinery Service Centers (AMSCs) to provide farm machinery to farmers on a custom-hire basis.

Farm machinery cost/acre = number of hours farm machinery rented for the composting process per acre × Subsidized renting prices/hour (Rs)

If one hour is the estimated time of each machinery per acre then, Total farm machinery cost/acre = adding subsidized renting prices/hour (Rs) of all farm machinery required in the on-field composting process

The subsidized machinery renting prices are fixed by these societies and are the same for all districts of Punjab.

5) **Farm tools** —The key farm tool used for pit digging and filling is a hoe (spade) for both rice and wheat crop residue management. The cost of this farm tool usage per acre is calculated using the price of this farm tool prevailing in Punjab is considered the same for all districts.

   Farm tool cost/acre (Rs) = Number of spades required per acre × Price of each spade (Rs)

6) **Gunny bags** – Gunny bags are made of jute and are used to store and transport grains, potatoes, and other agricultural products in states like Punjab to prevent grain moisture, thereby preventing the growth of bacteria and fungi. These lightweight bags do not contain proteins and are not affected by dampness, so they cannot support insect life, website - (Top 21 Benefits of Jute and Jute Bags, 2022).

   In the on-field composting process, gunny bags are used to cover the compost pit as there are various benefits of using jute gunny bags. For example, jute bags are breathable, allowing air circulation within a bag and preventing moisture buildup and mould and fungi growth. Jute bags are sturdy and durable, protecting against predators, ruminants, etc. These are readily available and cost-effective, making them a practical choice for small and large farmers. Jute bags are eco-friendly and biodegradable, making them a sustainable option for covering compost. The number of bags required to cover a compost pit depends on the surface area of each gunny bag and compost pit. The surface area of the compost pit will be taken from the above given input factor.

$$\text{Number of gunny bags required per pit} = \frac{\text{Surface area of pit}}{\text{Surface area of gunny bag}}$$

The number of bags required for each pit is multiplied by the price of each bag. The government fixed the price of each used bag weighing 580 gm at Rs 22 per bag. A new gunny bag costs Rs 55 in the wholesale market. So, the cost of bags required per acre is calculated using the Rs 55 price.

Gunny bag costs/acre (Rs) = Number of gunny bags required per acre × Price of each gunny bag (Rs)

The cost input regarding gunny bags would be the same for rice and wheat crops and even for all districts of Punjab.

7) **Inoculants** contain microorganisms that can help to decompose and stabilize organic materials (raw material) into compost. They accelerate the composting process and reduce odours, thus improving its performance. The study (Karnchanawong & Nissaikla, 2014) revealed that mature compost can be used as a starter to improve composting, and it might not be necessary to add commercial inoculants to facilitate composting. Moreover, straw is a brown raw material, so N–rich materials (greens) such as grass clippings, food scraps, tea bags, and rotten fruits and vegetables can be added to reduce the C: N ratio to the ideal level for composting. So, farmers could prevent spending money on buying inoculants for the composting process. Therefore, this input of composting is not included in the cost estimation.

The Total Input Costs of Composting (TICC) is calculated by adding together the costs of all inputs of the composting process discussed above.

3.6.2 Outputs of on-field composting method – The outputs of composting crop residues is the compost that make the soil more fertile and thus reduces the amount of inorganic fertilizer application and increases yield of crops.

1) **A nutrient-rich compost –** The on-field composting process would lead to the production of a nutrient-rich product called compost. The compost can either be used in the farms to get an increase in crop yields and cost reduction of fertilizers as discussed above or can be directly sold in the market to generate revenue. The compost output from 1 ton of straw depends on many factors such as moisture content, C: N ratio, decomposition rate, and volume reduction of straw, website - (Waste and compost volume/weight conversion and process weight reduction, 2022). If wheat straw is composted for 175 days, as much as 45 % of total weight loss can be observed (Verma et al., 2014), the remaining 55% will be wheat straw compost. The weight loss for rice straw compost is 60% (Dash et al., 2022) and 40% is the mass of rice straw compost formed. It is mainly caused by the evaporation of water and the breakdown of carbon into carbon dioxide by microorganisms.

$$\text{Mass of compost formed from rice straw of 1 acre} = 40\ \% \times \text{the mass of the crop residue composted per acre}$$

$$\text{Mass of compost formed from wheat straw of 1 acre} = 55\ \% \times \text{the mass of the crop residue composted per acre}$$

The amount of compost prepared from straw is multiplied by the price of compost prevailing in Punjab. The price of compost in Punjab varies depending on various factors, such as the quality of the compost, the region, local demand, and supply conditions. Additionally, prices may change over time.

Revenue on selling compost per acre (Rs) = mass of compost formed from straw per acre (kg) × Rs 40

As per the website, (https://www.cleantech-mart.com/shop/eco-friendly-products/waste-to-wealth/gardening-corner/natural-compost-cost-rs-40-kg/.); the average price of compost is Rs 40/kg. By using this price (Rs 40/kg), the revenue for compost is assessed.

2) **Inorganic fertilizer cost reduction** – Adding decomposed crop residues into the field instead of burning will increase soil fertility, resulting the reduced amount of inorganic fertilizer cost. The amount of nutrients (Nitrogen, Phosphorus and Potassium) present in rice and wheat crop residues would be deposited back in the soil if composted.

The fertilizer deposited per acre by crop residue-based compost =
Amount of nutrients present in crop residue × Amount of surplus residue produced per acre

The nutrients from the compost will be deposited into the field and this will reduce the amount of inorganic fertilizers required for the next crop. Using the percentage of nutrients present in compost, the amount of fertilizer (Urea, Di-Ammonium Phosphate, and Muriate of Potash) that compost would deposit back into the rice and wheat fields is assessed.

Fertilizer cost reduction would be a savings in cost for farmers by adopting composting methods for residue management.

Fertilizer cost reduction (Rs) = Fertilizer deposited by compost × Subsidized prices of Inorganic fertilizers (Rs)

The quantity of fertilizers deposited by compost would be multiplied by the subsidized price of inorganic fertilizers prevailing in Punjab to calculate the fertilizer cost reduced. The subsidized price of inorganic fertilizers is fixed by the Punjab government. The cost reduction of inorganic fertilizers would differ for rice and wheat crops as the amount of nutrients present in rice and wheat straw are different.

3) **Increase in yield of crops –** The organic fertilizer in the form of compost increases the crop yield in the long run. However, in the first two years, production/yield may not increase. The long-term use of organic fertilizer or compost leads to an increase in the productivity of crops. This is due to higher soil nitrogen content, organic matter, available Phosphorus (P) and Potassium (K), and enhanced soil quality due to organic fertilization (Herencia et al., 2007). When compared, compost-treated soils have improved chemical, physical, and microbiological properties (Tejada et al., 2006). The study (Huang et al., 2023) stated that substituting 10 % of chemical fertilizers with rice straw would increase the yield of rice crops by **6.3** percent. According to a study by Long et al. (2023), the yield of wheat crops with total straw return in the field is **8.21%** more than that of crops without straw return. Using this information every year, an increase in the yield of crops in the long run in all districts of Punjab is assessed.

   For rice crops -

   Increase in rice crop yield/acre for the particular year = 6.3% × Crop yield/acre in the particular year (without composting)

   For wheat crops –

   Increase in wheat crop yield/acre for the particular year = 8.21% × Crop yield/acre in a particular year (without composting)

Further, the increased percentage of yield for rice and wheat crops is multiplied by the Minimum Support Price (MSP) of rice and wheat crops to get the increased profits.

Revenue due to increased yield/acre (Rs) = Increase in yield of crop/acre × MSP of crop (Rs)

These revenues would depend on the previous yields of crops in each district, but the percentage increase is assumed to be the same for all districts.

The central government always fixes yearly MSP (Minimum Support Price) for rice and wheat crops ,website - (Minimum Support Price-2021-22 (MSP)) and is same for all districts in Punjab. As per the MSP fixed by the Government of India, there could be savings in cost to the farmer due to increased crop productivity.

4) **Use of sand from the pit –** Sand from the pit can typically be used for other purposes. It can have various practical uses in agriculture as sand can be used in construction for building structures of agricultural fields, such as barns or irrigation systems; sand can be used to create pathways or driveways on a farm for easy access to fields; In some cases, sand can be used as bedding material for livestock, such as dairy buffaloes or cows; more significantly, sand can be mixed with organic compost to create a potting mixture for home-grown plants, which can improve aeration and drainage for potted plants. However, this sand as an output is not evaluated for the study.

3.7 Factors included in the burning of crop residues

Factors included in the burning process

Inputs **(NBC*)** **Outcomes**

Inputs: Quantity-based	Inputs: Cost-based (TIBC)	Outcomes: Quantity-based	Outcomes: Cost-based (TOBC)
-Labor	- Labor cost	- Loss of soil nutrients	- N/A
-Recommended inorganic fertilizer	-Recommended inorganic fertilizer cost	- Collateral fire damage	- N/A
-Farm machinery	-Farm machinery cost		
-Farm tools	-Farm tool cost		
-Penalty	-Penalty cost		

*NBC (Net Burning Costs) = TIBC (Total Input Burning Costs) - TOBC (Total Outcome Burning Costs)

3.7.1 Inputs of burning method – The inputs of burning crop residues are –

1) **Labor—**Crop residue burning is not a labor-intensive process. Labor is required to check the residue-burning process and control the fire within the field to prevent collateral damage. Each district's cost of labor per day is calculated for each cropping season and it depends on the prevalent labor wage in each district of Punjab.

Labor cost per acre (Rs) = labor required per acre × basic wage/day of labor in the district (Rs)

2) **Farm machinery –** The farm machinery is required to prepare the field for the next crop, as in the composting method. However, the farm machinery required would be different for each crop.

   The estimated costs of farm machinery are on a per-hour basis. The estimated renting cost of farm machinery is calculated based on subsidized farm machinery renting costs prevailing in CHC (Custom Hiring Centers) of Punjab.

   Farm machinery cost/acre (Rs) = Number of hours farm machinery rented per acre × Subsidized rental cost (Rs/hr)

   The machinery cost would be the same for all districts of Punjab but different for rice and wheat crops.

3) **Recommended inorganic fertilizers**—Burning the crop residues would require the recommended amount of inorganic fertilizers as per the package of practices for rice and wheat cultivation in Punjab. This quantity recommendation is same for all districts of Punjab. The amount of inorganic fertilizer required is multiplied by the subsidized fertilizer price in the respective year to calculate the cost of inorganic fertilizers used per acre under the burning process.

   Inorganic fertilizer cost/acre (Rs) = Recommended amount of inorganic fertilizer required for a crop per acre × Subsidized fertilizer price (Rs)

4) **Farm tools** — The rake is the key farm tool used in residue assemblage and burning. The cost of this farm tool is same for all districts and its cost per acre is calculated as -

   Farm tool cost/acre (Rs) = Number of rakes required per acre × Price of each rake (Rs)

5) **Fine or legal penalty (as per the law)** –Despite being legally banned, the crop residue burning practice continues in India, as farmers do not find viable alternatives to clear

their fields in a short time window. Under the Air Prevention and Control of Pollution Act, 1981, it was notified as an offence. The National Green Tribunal (NGT) is a specialized body with expertise in handling multi-disciplinary environmental disputes. Moreover, the NGT had asked every district administration of Punjab to levy fines on the farmers found burning crop residues. These fines are per acre basis and are included as the input cost for burning crop residues.

3.7.2 Outcomes of burning method –

1) **Loss of nutrients -** Mandal et al. (2004) described that about 80 % of N, 25 % of Phosphorus, 21 % of potassium, and 4–60 % of sulphur are lost from the soil through burning rice and wheat crop residues. According to Singh et al. (2008), nutrient loss due to the burning of rice residues in Punjab in 2001–2002 was 973 kg of carbon, 15 kg of Nitrogen, 1.30 kg of phosphorus, 8.5 kg of potassium, and 1.09 kg of sulphur per acre. It also kills soil-borne deleterious pests and pathogens.

   Crop residues are viable nutrient sources as about 25 % of nitrogen and phosphorus, 50 % of sulphur, and 75 % of potassium uptake by cereal crops are retained in crop residues (Gadde et al., 2009). While the loss of carbon and nitrogen was almost total, the loss of phosphorus, potassium, and sulphur was partial (around 20–60 %). This cost is not included in the cost-benefit analysis because farmers do not add fertilizer other than the recommended amount of fertilizer to overcome soil fertility loss. Even the effect of nutrient loss on crop yield could not be assessed. To compensate this, the increase in crop yields by adopting composting methods has already been considered in the cost-benefit analysis.

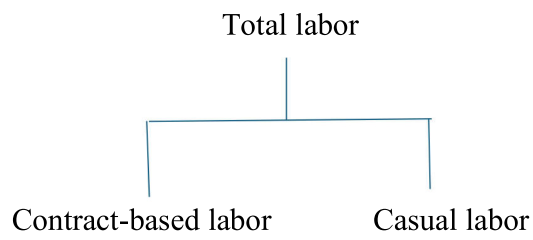
2) **Collateral damage due to uncontrolled fire –** Sometimes, fire in the field can cause various accidents, such as the expansion of uncontrollable fire in neighbouring crop fields, which still need to be harvested. Moreover, some houses are built on farms and are at high risk of catching fire from fields. Furthermore, some crop fields are harvested, but straws need to be collected for other uses, such as wheat straw for fodder or to sell in the market, and such fields can easily catch fire and burn whole straw stock. This kind of damage is difficult to assess due to the absence of the proper data and information.

3.8 Factors affecting on-field composting costs for different landholding sizes in Punjab

There are two main factors: Labor and farm machinery that could affect the costs of the on-field composting process for different landholding sizes in Punjab.

3.8.1 Labor in Punjab

The cultivation of rice crops required more labor throughout the cropping season. Most of the landowners preferably self-cultivate by hiring labors over leasing their lands to tenants. The agriculture sector of Punjab generates two kinds of labor employment. Some of the operations, such as animal care, irrigation, fertilizer, spraying the crops, etc., performed on the farm must be attended regularly. So, in Punjab, farmers usually hire farm workers on annual wage basis by paying them wages in advance, these labors are called **contract labors**. Other tasks, such as sowing and harvesting, generate additional seasonal work, which increases the demand for casual labor. The demand for casual labor is exceptionally high during peak farm operations (harvesting and crop sowing of crops).



The contract labor usually performs daily routine work as per the direction of land/farm owner. Sometimes landowners also hire casual labor in addition to contract labor depending on the additional labor requirement. Marginal (less than 2.5 acres) and small-sized (2.5 -5 acres) farm owners usually fulfill the labor demand through their own family members, whereas the farmers owning medium (10-25 acres) and large-size (above 25 acres) farms hire casual labors from the labor market. So, the number of labors hired or contracted on a farm depends on the number of acres a farmer owns or cultivates.

Table 8 – Percentage of households in Punjab that hired labor on a contract basis

Farm size	**Percentage of households with hired contract labor (%)**			
Acres	**None**	**One contract labor**	**Two contract labor**	**Three or more contract labor**
2.5 or less	99.4	0.40	0.20	-
2.5-5.0	92.95	6.51	0.36	0.18
5.0-10.0	78.68	20.62	0.35	0.35
10.0-15.0	60.34	34.91	3.88	0.86
Above 15.0	36.57	39.48	13.92	10.03
Total	79.15	16.57	02.62	01.66

(Ghuman et al., 2007)

Table 8 depicts a positive relationship between hiring contract-based labor and the size of landholdings with a farmer. With the increase in the farm size with the farmer, there is an increase in the number of contract labors hired by them. This is due to the increased agricultural activities to be performed in fields by labors on daily basis. So, hiring contract labor on an annual salary is not a common practice for farmers with marginal landholdings. So, the number of casual labor a farmer needs during the on-field composting process would decrease by the exact number of contract labor a farmer already have on an annual basis.

The number of casual labors required by farmers per acre for the on-field composting process based on the number of contract labors already hired by various farmer categories (using Table 8) is as follows -

1) **Farmers with upto 2.5 acres** – 99.4 % × $\boldsymbol{x}$ + 0.40 % × ($\boldsymbol{x}$ -1) + 0.20 % × ($\boldsymbol{x}$ -2)
2) **Farmers with 2.5 - 5 acres** - 92.95 % × $\boldsymbol{x}$ + 6.51 % × ($\boldsymbol{x}$ -1) + 0.36 % × ($\boldsymbol{x}$ -2) + 0.18 % × ($\boldsymbol{x}$ -3)
3) **Farmers with 5- 10 acres** – 78.68 % × $\boldsymbol{x}$ + 20.62 % × ($\boldsymbol{x}$ -1) + 0.35 % × ($\boldsymbol{x}$ -2) + 0.35 % × ($\boldsymbol{x}$ -3)
4) **Farmers with 10 - 15 acres** – 60.34 % × $\boldsymbol{x}$ + 34.91 % × ($\boldsymbol{x}$ -1) + 3.88 % × ($\boldsymbol{x}$ -2) + 0.86 % × ($\boldsymbol{x}$ -3)
5) **Farmers** with more than 15 acres– 36.57 % × $\boldsymbol{x}$ + 39.48 % × ($\boldsymbol{x}$ -1) + 13.92 % × ($\boldsymbol{x}$ -2) + 10.03 % × ($\boldsymbol{x}$ -3)

Here, $\boldsymbol{x}$ is the actual number of labor required in on-field composting process per acre.

As, 99.4 percent of marginal farmers do not hire any contract labor, so these farmers need exact number of casual labors as required per acre to perform on-field composting. While 0.40 percent of marginal farmers already have one contract labor, so the number of casual labors they require will be one less than the farmers that do not have any contract labor (99.4 percent) and so on.

The percentage of farmers with no contract labors is further divided into two categories, one who donot not hire any casual labor, even if required (as they can use family labor or farm machinery instead) and the others who can hire casual labors when required.

Number of labors hired on a contract basis

None One Two Three (as in Table 8)

No casual labor **Hire casual labor** (as in Table 9)

On-field composting crop residues would be a seasonal job, and the number of casual labors engaged (hired) would depend on the number of acres owned by the farmer. Some farmers with small landholdings with no contract labor also do not hire casual labors because they use their family labor. On the other hand, some farmers with large landholding sizes with no contract labor also do not hire casual labor because they use more farm machinery for their farm operations. The percentage of households having no contract labor but hiring casual labors also differs with landholding sizes, as shown in Table 9.

Table 9- Percentage of households (with no contract labor) hiring casual labor

Category of farmers	**Farm size group (acres)**	**No contract labor hired (%)**	**Casual labor hired (%)**
Marginal	Up to 2.5	99.4	32.4 % – Hire casual labors 67.6 %– No casual labor hired
Small	2.5 – 5.0	92.95	61.68 %– Hire casual labors 38.32 %-No casual labor hired
Semi-medium	5.0 – 10.0	78.68	43.84 %– Hire casual labors 56.16 %– No casual labor hired
Medium*	10.0 – 15.0	60.34	29.3 %– Hire casual labors 70.7 %– No casual labor hired
Medium* and Large	Above 15.0	36.57	0 %– Hire casual labors 100 % – No casual labor hired

(Ghuman et al., 2007)

Medium* farmers own 10.0 – 25.0 acres of farmland.

In Table 9, it is depicted that 32.4 % of marginal farmers with no contract labors (99.4 %) hire casual labors, while 67.6% of marginal farmers with no contract labors (99.4%) do not hire casual labors, as 67.6% here use the family labor. So, the percentage of households that donot hire casual labors would use family labor (marginal and small farmers) or use farm machinery instead (medium and large farmers).

To clarify, it can be stated in simple words that marginal farmers that do not hire contract labors at all are 99.4% of which 67.6% farmers even do not hire casual labors and so on. So, the above percentage of casual labors hired (Table 9) is only for those households that do not hire contract labors at all.

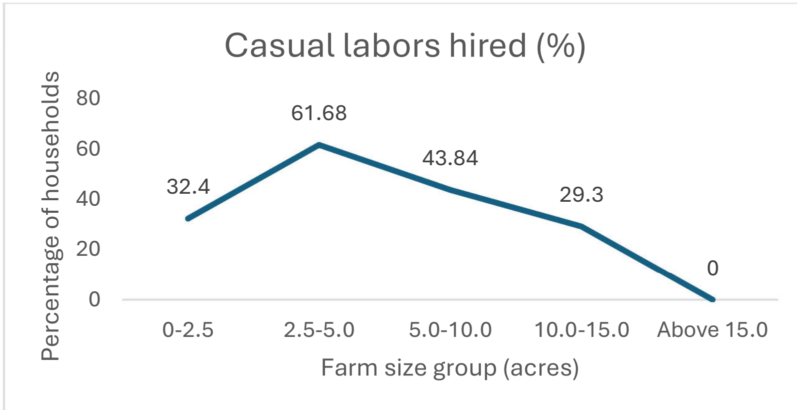


Figure 4 – Percentage of households (with no contract labor) hiring casual labor

The requirement of casual labor for specific or heavy tasks such as composting would form an inverted 'U' shape curve relationship, that is, a positive relationship between casual labors hired and landholdings up to 10 acres and reverse after that. This is explained by farmers with 10 or more acres hiring fewer casual labors, as they can afford farm machinery which could replace the labor in the field (Singh & Singh, 2006). Moreover, labor efficiency is directly related to farm size, as it is more for larger farms (Li et al., 2020).

Using the percentage of contract-based (Table 8) or casually hired labors (Table 9), the number of labors required per acre for the on-field composting method is estimated for farmers with different landholding sizes.

1) <u>Marginal farmers</u> – 32.4% of 99.4 % of households (having no contract labor) will hire casual labor for the composting process
2) <u>Small farmers</u> – 61.68 % of 92.95 % of households (having no contract labor) will hire casual labor for the composting process

3) Semi-medium farmers – 43.84% of 78.68 % of households (having no contract labor) will hire casual labor for the composting process

4) Medium farmers (10- 15 acres) – 29.3% of 60.34 % of households (having no contract labor) will hire casual labor for the composting process

5) Medium (above 15 acres) and Large farmers - 0% of 36.57 % of households (having no contract labor) will hire casual labor for the composting process

So, the percentages of contract labor and casual labor hired are combined and used to estimate the number of labors that a farmer with different landholdings would hire per acre, especially for the on-field composting process to manage crop residues.

So, the labor cost per acre for on-field composting of different categories of farmers is as-

1) Marginal farmers – (**32.4 %** × 99.4 % × $\boldsymbol{x}$) + 0.40 % × ($\boldsymbol{x}$ -1) + 0.20 % × **(**$\boldsymbol{x}$ -2)
2) Small farmers – (**61.68** % × 92.95 % × $\boldsymbol{x}$) + 6.51 % × **(**$\boldsymbol{x}$ -1) + 0.36 % × **(**$\boldsymbol{x}$ -2) + 0.18 % × **(**$\boldsymbol{x}$ -3)
3) Semi-medium farmers – (**43.84 %** × 78.68 % × $\boldsymbol{x}$) + 20.62 % × **(**$\boldsymbol{x}$ -1) + 0.35 % × **(**$\boldsymbol{x}$ – 2) + 0.35 % × **(**$\boldsymbol{x}$ -3)
4) Medium farmers (10- 15 acres) – (**29.3 %** × 60.34 % × $\boldsymbol{x}$) + 34.91 % × **(** $\boldsymbol{x}$ –1) + 3.88 % × **(**$\boldsymbol{x}$ -2) + 0.86 % × **(**$\boldsymbol{x}$ -3)
5) Medium (above 15 acres) and Large farmers– (**0 %** × 36.57 % × $\boldsymbol{x}$) + 39.48 % × **(**$\boldsymbol{x}$ -1) + 13.92 % × **(**$\boldsymbol{x}$ -2) + 10.03 % × **(**$\boldsymbol{x}$ -3)

Here, $\boldsymbol{x}$ is the actual number of labor required in on-field composting process per acre.

The labor cost would be either fixed labor cost (contract-based hired labor cost) or variable cost (casual labor cost). The labor cost of the composting process depends on the number of casually hired (variable labor) and contract-based (fixed labor), as contract (fixed) labor would not require paying extras for the on-field composting process. However, it would reduce the variable labor cost as the number of casually hired workers by farmers would be decreased. As per Table 18, (Page no. 93), in total 8 labors are required per acre for on-field composting, ($\boldsymbol{x}$ = 8) so a household already having 2 contract labors will have to hire 6 casual labors during the on-field composting process. Hence, the variable labor cost would be decreased for the farmer, but the actual cost (variable cost + fixed cost) would be the same for all farmers. On the other hand, a farmer having no contract labor, may either use family labor in place of all 8 casual labors or a combination of family labor and casual labor. So, the variable labor cost would even vary for farmers having no contract labor depending on the number of acres they own.

3.8.2 Farm Machinery Renting in Punjab

Punjab has highly mechanized agriculture, but the economic viability of a farm determines the machinery ownership. Most farmers with small holdings led to the development of custom-hiring services, where farmers rent machinery for their on-farm operation.

A tractor is the most common farm machinery required in field operations and is even used to operate other farm implements such as straw chopper, planker, straw reaper, leveler, cultivator etc.

A field survey done in 2011-12 (Singh & Kingra, 2013) revealed that all farm size categories except marginal farmers own tractors to operate various operations on their landholdings.

Table 10 - The percentage of farmers owning and renting tractors among different farm-size groups

Farm Category (Operational holding)	**Percent of farmers owning tractors (%)**	**Percent of farmers renting tractors (%)**
1. Marginal (< 2.5 acres)	-	100
2. Small (2.5 – 5.0 acres)	34.78	65.22
3. Semi-medium (5-10 acres)	82	18
4. Medium (10-25 acres)	96.15	3.85
6. Large (> 25 acres)	100	-

(Singh & Kingra, 2013)

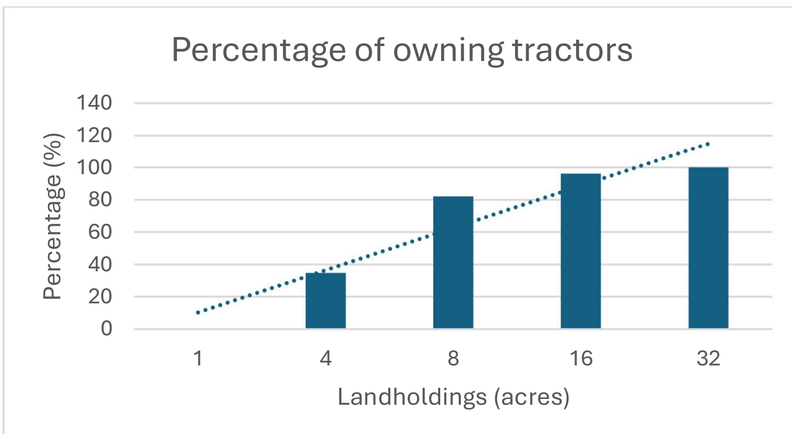


Figure 5 – Percentage of farmers owning tractors within different landholding sizes

The percentage of farmers owning tractors increases with the increase in number of acres they are operating. As per Table 10, all marginal farmers of Punjab rent tractors for field operations, while large farmers do not rent tractors. Semi-medium and medium farmers constitute more than 50% of farmers (Table 3) and 82.97% of these own tractors (Singh & Kingra, 2013)

As in Custom Hiring Centers (CHCs) such as, PACS, AMSC, and ZFS, the price for renting implements along with tractors costs more in comparison to when only implements are rented (without the tractor). Thus, the farmers owning tractors pay less to rent other farm implements required in the on-field composting process. However, farmers with no tractors have to pay much more to rent tractors and farm implements. In addition, the tractor's operational costs are paid by the farmer renting the tractor.

Table 11 – Hourly renting charges of tractor and implements (Rs/hr.)

Farm machinery	Rental cost when implement hired without tractor	Rental cost when implement hired with tractor
Disc harrow	50	700
Cultivator	62.5	650
Rotavator	250	1060
Laser leveler	351.67	575
Straw chopper	250	N/A
Reaper	150	700

(Singh S. , 2017), (Singh et al., 2015)

As per Table 11, tractor ownership will make a quite big difference in the farm machinery costs of the on-field composting process, and this depends on the number of acres a farmer owns.

If the farmer owns a tractor, then the operational charges of the tractor are -

Operating charges = Repair cost + Fuel cost + lubrication cost + labor cost

So, a farmer owning a tractor also pays operational costs and it is the same for a farmer renting a tractor. Thus, the operational costs of machinery are not included in both owning and renting tractors.

Farm machinery includes both tractors and implements used in farms.

Farm Machinery costs for farmers owning a tractor per hour (Rs) = Implement renting cost

Farm Machinery costs for farmers renting tractor per hour (Rs) = Tractor + Implement combined renting cost

All marginal farmers will pay tractor + implement renting costs for the composting process while 65.22 percent of small farmers pay for combined tractor and implement renting costs. This percentage decreases to 18 and 3.85 percent in the case of semi-medium and medium farmers respectively, while 100 percent of large farmers will pay for only implement renting costs. In this way, the farm machinery costs per acre differ with the size of the landholdings with the farmer.

So, the average machinery cost per acre for the on-field composting process for different categories of farmers is as -

1) Marginal farmers – 100 % × (tractor + implement) renting costs
2) Small farmers – 65.22 % × (tractor + implement) renting costs + 34.78 % × (implement renting costs)
3) Semi-medium farmers – 18 % × (tractor + implement) renting costs + 82 % ×(Implement renting costs)
4) Medium farmers – 3.85 % × (tractor + implement) renting costs + 96.15 % × (Implement renting costs)
5) Large farmers –100 % × (Implement renting costs)

The labor and machinery costs per acre is calculated for four on-field composting models based on landholding sizes with farmers.

3.9 Four on-field composting models

Four on-field composting models are studied in this study based on landholding sizes.

3.9.1 One-acre on-field composting model

The labor cost of a farmer owning 1 acre for on-field composting –

The labor costs would exclude the contract labor, which is already hired and is not paid extra for performing the on-field composting process on a seasonal basis. Table 8 depicted that 99.4 percent of total farmers having 2.5 acres or less do not hire contract labor, 0.4 percent hire one contract labor and 0.2 % hire two contract labors for agricultural operations. However, 67.6 % of that 99.4% (those who do not hire contract labor) even do not hire casual labor (Table 9), due to use of their family labor in performing farming operations, and the rest, 32.4% of 99.4%, who do not have contract labor, hire casual labor as and when required. So, the number of casual labors required would decrease by the exact number of contract labor already hired by the farmer.

The equation for calculating labor cost for a farmer with one acre would be evaluated as-

Labor cost (Rs/acre) – {(**32.4 %** × 99.4 % × $\boldsymbol{x}$) + 0.40 % × ($\boldsymbol{x}$ -1) + 0.20 % × ($\boldsymbol{x}$ -2)} × labor wage (Rs/day)

$\boldsymbol{x}$ in the above equation refers to the total number of labors engaged in the composting operation, which is calculated further in chapter 4, Page no. 93.

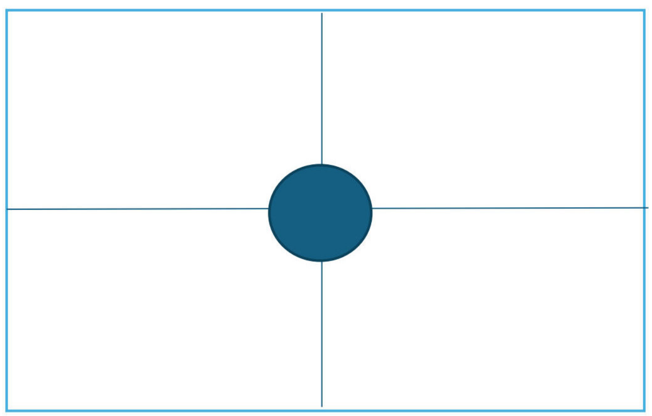
The Farm machinery renting cost per acre for on-field composting –

As per Table 10, farmers with 2.5 acres or less do not own tractors, as 100% of these rent tractors for agricultural operations. So, the equation defining farm machinery hiring costs will be evaluated using Table 10 and Table 11.

Farm machinery cost (Rs/hr) = 100 % × (tractor + implement) renting costs

Farmers with one acre will rent farm machinery with a tractor and pay combined renting costs.

3.9.2 Four-acre on-field composting model



The labor cost per acre of a farmer owning 4 acres for on-field composting –

Table 8 states that 92.5 % of these farmers do not hire contract labor. However, 6.51% of this category of farmers have one contract labor, 0.36% have two contract labors, and 0.18% have three contract labors. Furthermore, Table 9 depicts that 38.32% of this 92.5 percent also do not hire casual labor, as 61.68% of 92.5 percent farmers hire casual labors. So, the equation for calculating labor cost for a farmer with 4 acres would be evaluated as -

Labor cost (Rs) – $\{(61.68\ \% \times 92.95\ \% \times \boldsymbol{x}) + 6.51\ \% \times (\boldsymbol{x} - 1) + 0.36\ \% \times (\boldsymbol{x} - 2) + 0.18\ \% \times (\boldsymbol{x} - 3)\} \times$ labor wage (Rs/day)

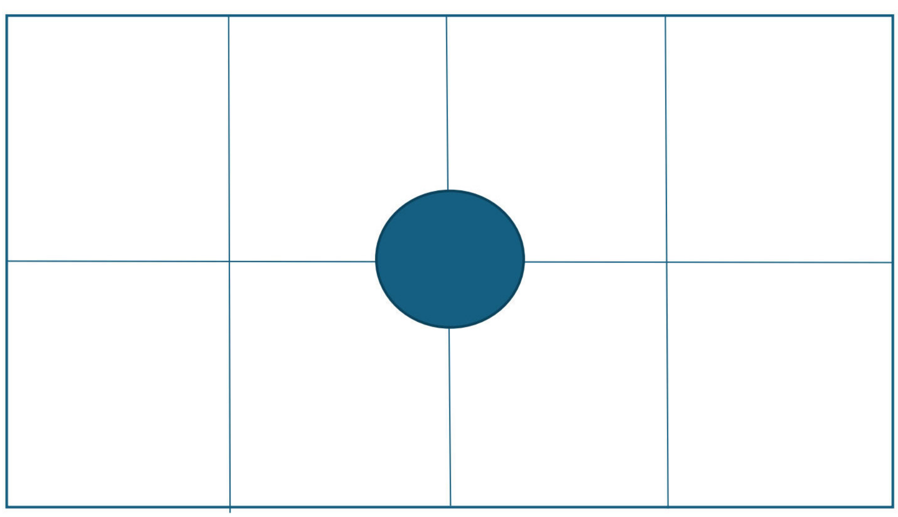
Here $\boldsymbol{x}$ refers to the total number of labors that would be engaged in the on-field composting process.

The Farm machinery cost per acre for on-field composting –

Almost 34.78 percent of farmers with 4 acres own tractors (Table 10), so they will rent only farm implements. While the rest, 65.22% rent tractors and CHCs will charge for the combined renting price of tractor and farm implements. So, the equation would be evaluated to calculate the Farm machinery cost per acre for farmers owning four acres.

Farm machinery cost (Rs/hr) - 65.22 % × (tractor +implement) renting costs + 34.78 % × (Implement renting costs)

3.9.3 Eight-acre on-field composting model



The labor cost per acre of a farmer owing 8 acres for on-field composting –

Table 8 states the percentage of farmers without contract labor is 78.68, of which 56.16% do not hire casual labors either (Table 9). The percentage of farmers having one contract labor, two contract labor and three contract labor is 20.62, 0.35 and 0.35, respectively. So, the equation for calculating labor cost per acre for a farmer owning 8 acres would be evaluated as -

Labor cost (Rs)-{(43.84 % × 78.68 % × $\boldsymbol{x}$) + 20.62 % × ($\boldsymbol{x}$ - 1) + 0.35 % × ($\boldsymbol{x}$ -2) + 0.35 % × ($\boldsymbol{x}$ -3) × labor wage (Rs/day)}

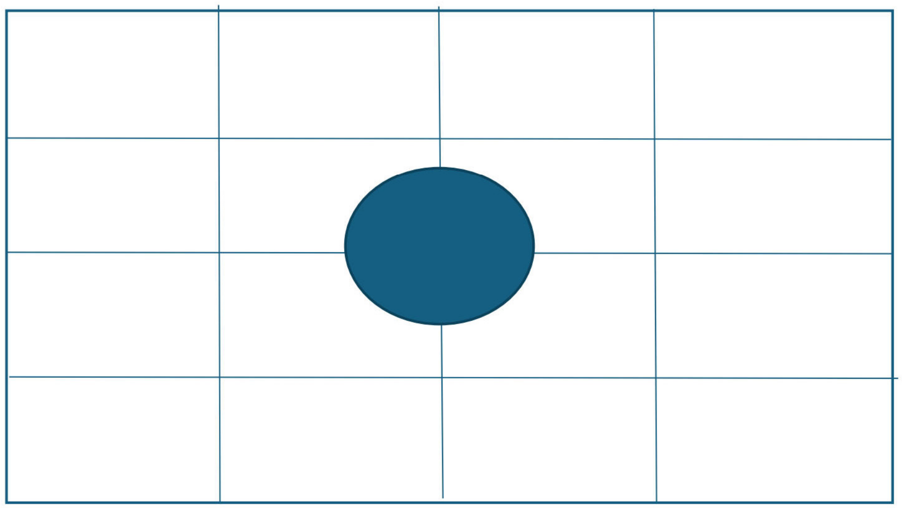
Here $\boldsymbol{x}$ refers to the total number of labors that would be engaged in the on-field composting process.

The Farm machinery hiring cost per acre for on-field composting –

Most farmers with 8 acres, that is, 82% own tractors, and 18% rent tractors for field tasks (Table 10). So, the equation defining this percentage will be evaluated.

Farm machinery costs (Rs/hr) = 18 % × (tractor + implement) renting costs + 82 % × (Implement renting costs)

3.9.4 Sixteen-acre on-field composting model



The Labor cost per acre of a farmer owning 16 acres would be –

36.57 percent of farmers with 16 acres do not have contract labor (Table 8), and almost 100% of this 36.57 percent do not hire casual labors as well due to easy access to farm machinery (Table 9). 39.8 percent of farmers have one contract labor, 13.92 percent have two contract labor, and 10.03% have three contract labors. So, the equation for calculating labor cost for a farmer with more than 15 acres would be evaluated.

$$\text{Labor cost (Rs)} = (\mathbf{0\ \%} \times 36.57\ \% \times \boldsymbol{x}) + 39.48\ \% \times (\boldsymbol{x} - 1) + 13.92\ \% \times (\boldsymbol{x} - 2) + 10.03\ \% \times (\boldsymbol{x} - 3) \times \text{labor wage (Rs/day)}$$

Here $\boldsymbol{x}$ refers to the total number of labors that would be engaged in the composting process.

The Farm machinery renting cost per acre for on-field composting –

Table 10 depicts that 96.15 % farmers having 16 acres own tractors, and 3.85% of these farmers rent tractors. So, all farmers would have to pay only for farm implement rental costs for composting crop residues.

Farm machinery costs (Rs/hr) = 3.85 % × (tractor + implement) renting costs + 96.15 % × (Implement renting costs)

3.10 Release of GHGs on Burning Crop Residues

This study includes the assessment of the GHGs released during on-field composting and burning crop residues. The difference in GHG emissions is assessed in terms of quantity and costs and interpreted using the Social Cost of GHGs (SC–GHGs).

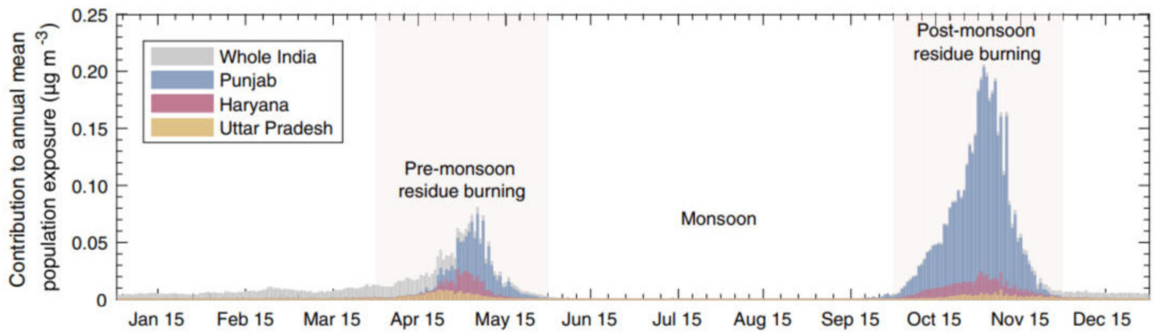


Figure 6 - India-wide annual mean population-weighted $PM_{2.5}$ exposure due to crop residue burning averaged from 2003 to 2019

(Lan et al., 2022)

In Figure 6, the shaded areas in April-May and October–November denote the pre-monsoon fire season (wheat residue burning) and the post-monsoon fire season (rice residue burning), respectively.

The pollution created by burning crop residue is quite different in all districts of Punjab. For instance, districts that rank high in agricultural emissions per unit of production and more mortalities per unit emissions are – Sangrur (includes Malerkotla), Barnala, Patiala, Moga, Ludhiana, and Fatehgarh Sahib because they grow coarse varieties of rice, which generate more residue to be burnt in the field. These districts, on average, are responsible for 40% of India's total air quality impacts due to residue burning, with Patiala and Sangrur alone contributing 20 percent (Lan et al., 2022). On the other hand, districts such as Jalandhar, Kapurthala, Hoshiarpur, Rupanagar, SBSN (Shaheed Bhagat Singh Nagar), and SASN (Sahibzada Ajit Singh Nagar) collectively contributed 14%. Districts such as Fazilka, Ferozepur, Sri Muktsar Sahib, Tarn Taran, and Faridkot have an 11% contribution to the total air quality impact of residue burning in fields. The remaining districts – Amritsar, Bathinda, Mansa, Pathankot, and Gurdaspur are minor contributors to the total effects (Lan et al., 2022).

No doubt, the on-field composting process also leads to the emission of GHG to some extent. In this study, composting is assumed to be done by an aerobic process that uses bacteria that need oxygen for the decomposition of organic matter. Aerobic composting uses organic materials, oxygen, and water, resulting in carbon dioxide, water, and energy in the form of heat. Methane is produced in anaerobic pockets of a compost pile, whereas Nitrous oxide is a product of nitrification or denitrification. Even though the overall emissions of these two GHGs are low relative to carbon dioxide, their emissions are significant because the global warming potential (GWP) is 25 and 298 times greater than CO_2 for CH_4 and N_2O, respectively.

The McGaughey and Gotass (1953) experiment tested that the raw materials having Carbon: Nitrogen ratios varying from 20:1 to 80:1 can undergo composting. They found that the materials having a C: N ratio between 30:1 and 35:1 have an optimum speed range of composting. Below this range, excess nitrogen was lost, while above this range, the composting speed slowed down, website - (The Essential Role of the Carbon - Nitrogen Ratio in Composting, 2023). Waste with a low C/N ratio and high-water content has great potential for generating GHG emissions during storage and composting. The nitrous oxide (N_2O) emission peaked at the low C/N ratio. If the C/N ratio is increased, GHG emissions will decrease. The C/N ratio of the straw to be composted is 60-80:1, which is high and may not release much GHGs. The use of compost in agriculture has a positive effect on GHG emissions (Nordahl et al., 2023) since its application as an organic amendment provokes carbon to stay bound to soil and the content of other nutrients (Nitrogen, Phosphorus, etc.) is typically low. While composting results in greenhouse gases, the amount varies depending on compost maintenance (compost turning and moisture). By mass, CO_2 is the dominant compound emitted to the atmosphere during composting operations.

The emissions from on-field composting crop residues have yet to be evaluated, so the emissions from yard waste can be assumed as emissions from composting rice and wheat straw in the field.

Yard waste (C: N ratio – 30:1) can be considered a substitute for straw waste with a high C: N ratio. These emissions are assumed to be equivalent to straw composting emissions and are compared with the emissions of the straw-burning process. These emissions depend on the amount of surplus feedstock composted (surplus straw). The amount of surplus straw produced by rice and wheat crops in all districts of Punjab for three years estimates each crop's total emissions yearly when composted.

Further, the emissions of the straw-burning process in Punjab are already evaluated for the year 2017-18 (Singh, et al., 2020), which are compared with crop residue composting emissions.

The difference in GHG emitted by composting and burning methods in each district

= GHG emitted by the burning method – GHG emitted by the composting method

This difference in GHGs emitted on composting crop residues and burning crop residues is assessed and converted into Canadian dollars (Social Cost of GHGs) (Table 12) to give an idea of the cost benefits of climatic change after adopting the on-field composting process to manage crop residues. The Social Cost of GHG emissions (2020 as a year of analysis) given in Table 12 is used for environmental costs.

GHG emission cost to be saved on composting crop residues is calculated (in a million $) for each district of Punjab.

Table 12 – SC-GHG estimates (C$2021, $/ton of respective GHG)

Year	SCC/SC-CO_2	SCM/SC-CH4	SCN/SC-NO_2
2020	$247	$2107	$69,230
2021	$252	$2203	$70,797
2022	$256	$2300	$72,364
2023	$261	$2396	$73,932
2024	$266	$2494	$75,499

Source - (Social cost of greenhouse gas emissions, n.d.)

The above table represents annual SC-GHG estimates for use by Government of Canada departments and agencies, effective December 12, 2022.

Environmental savings (Rs/year) – (GHG emitted by burning method – GHG emitted by on-field composting method) per year × Social Cost of GHGs each year

The amount of money (in Canadian dollars) that a farmer of each district could save on substituting crop residue burning with on-field composting would be calculated.

Chapter 4: ANALYSIS AND RESULTS

The data for on-field composting and burning crop residues is taken for all districts of Punjab and for three consecutive years (2019-20, 2020-21, 2021-22). The assessment of data provides an idea about the expenditures and revenue of switching from crop residue burning to the on-field composting method if it would have done in 2020, 2021 and 2022 years. In this study, NCC (Net Composting Costs) are compared with the NBC (Net Burning Costs) of rice and wheat crop residues.

The amount of surplus residue produced by rice and wheat crops for each district is used to assess the cost and benefits of the on-field composting and burning process. First, the gross crop residue generated in each district is assessed and by using it, the surplus crop residue generated in each district is assessed.

4.1 Assessment of crop residue generated in districts of Punjab

4.1.1 Amount of gross residue generated by rice and wheat crops

Using CRR values of crops (Table 6), area under crop production (Appendix A) and yield of crops (Appendix A), the gross residue produced by rice and wheat crops is assessed as –

Gross residue of rice crop = Area under rice crop × Yield of rice crop × 1.20 (Chauhan, 2012)

Gross residue of wheat crop = Area under wheat crop × Yield of wheat crop × 1.15

For instance, in Ferozepur district, the gross crop residue generated in 2021 is –

Gross rice residue = 466030.6 (acre) × 1.765978 (t/acre) × 1.20 = 987600 tons

Gross wheat residue = 484563.1 (acre) × 1.995612 (t/acre) × 1.15 = 1112050 tons

Similarly, the gross residue of rice and wheat crop generated in all districts of Punjab in 3 years is assessed and shown in Table 13.

Table 13 – Gross residue generated by rice and wheat crops in 3 years (tons)

Sr.no.	District	Gross residue generated (tons)					
		2019-20		**2020-21**		**2021-22**	
		Rice	**Wheat**	**Rice**	**Wheat**	**Rice**	**Wheat**
1	Amritsar	717600	979800	740400	1035000	790800	969450
2	Barnala	630000	688850	722400	627900	661200	603750
3	Bathinda	916800	1595050	986400	1455900	994800	**1321350**
4	Faridkot	523200	742900	572400	676200	603600	608350
5	Fatehgarh S.	439200	430100	496800	485300	494400	333500
6	Fazilka	930000	1168400	456000	1131600	426000	1003950
7	Ferozepur	368400	1100550	987600	1112050	992400	944150
8	Gurdaspur	764400	887800	816000	966000	805200	893550
9	Hoshiarpur	374400	700350	396000	676200	349200	592250
10	Jalandhar	855600	1000500	956400	971750	896400	841800
11	Kapurthala	595200	583050	613200	558900	603600	504850
12	Ludhiana	1453200	1466250	1516800	1427150	**1495200**	1200600
13	Mansa	586800	1060300	693600	979800	673200	883200
14	Moga	991200	1083300	1070400	1047650	1033200	894700
15	SMS	764400	1343200	970800	1250050	919200	1140800

16	SBSN	301200	449650	324000	441600	330000	343850
17	Pathankot	103200	181700	126000	209300	116400	165600
18	Patiala	1113600	1283400	1257600	1336300	1209600	1043050
19	Rupanagar	172800	343850	216000	356500	202800	285200
20	SASN	126000	259900	121200	243800	135600	213900
21	Sangrur	**1634400**	**1929700**	**1837200**	**1761800**	1434000	1137350
22	Tarn Taran	848400	983250	913200	1012000	868800	915400
Average		691363.6	920993.2	763200	898306.8	728890.9	765481.8

The above table depicts that Sangrur district in 2020 and 2021 and Ludhiana district in 2022 produced the highest amount of gross residue of rice crops while Bathinda in 2022 and Sangrur district in 2020 and 2021 produced the highest gross residue of wheat crops. This is due to the highest area under production and yield of crops in these districts. Pathankot and SASN districts consecutively produced the least amount of gross residues of both crops, i.e., rice and wheat for three years as the area under crop production and yield of crops is low in these districts. In most districts, wheat produces more crop residues than rice, and the amount of crop residue produced per district is directly proportional to the area under production and the yield of crops.

4.1.2 Amount of surplus residue generated by rice and wheat crops

The Surplus Fraction (SF) values (Table 7) are multiplied by the gross amount of crop residues produced (Table 13) to assess the surplus residues generated by rice and wheat crops.

Surplus residue of rice crop = Gross rice crop residue produced × 0.15 (Kapoor, et al., 2023)

Surplus residue of wheat crop = Gross wheat crop residue produced × 0.09

For instance, in Ferozepur district, the surplus residue produced in 2021 is –

Surplus rice residue produced = 987600 tons × 0.15 = 148140 tons

Surplus wheat residue produced = 1112050 tons × 0.09 = 100084.5 tons

In this way, the surplus crop residue produced in all districts of Punjab is assessed in Table 14

Table 14 – Surplus crop residue generated in Punjab in three years (tons)

No.	Districts	Year (2019-20)		Year (2020-21)		Year (2021-22)	
		Rice	Wheat	Rice	Wheat	Rice	Wheat
1	Amritsar	107640	88182	111060	93150	118620	87250.5
2	Barnala	94500	61996.5	108360	56511	99180	54337.5
3	Bathinda	137520	143554.5	147960	131031	149220	**118921.5**
4	Faridkot	78480	66861	85860	60858	90540	54751.5
5	Fatehgarh S.	65880	38709	74520	43677	74160	30015
6	Fazilka	139500	105156	68400	101844	63900	90355.5
7	Ferozepur	55260	99049.5	148140	100084.5	148860	84973.5
8	Gurdaspur	114660	79902	122400	86940	120780	80419.5
9	Hoshiarpur	56160	63031.5	59400	60858	52380	53302.5
10	Jalandhar	128340	90045	143460	87457.5	134460	75762
11	Kapurthala	89280	52474.5	91980	50301	90540	45436.5
12	Ludhiana	217980	131962.5	227520	128443.5	**224280**	108054
13	Mansa	88020	95427	104040	88182	100980	79488
14	Moga	148680	97497	160560	94288.5	154980	80523

15	SMS	114660	120888	145620	112504.5	137880	102672
16	SBSN	45180	40468.5	48600	39744	49500	30946.5
17	Pathankot	15480	16353	18900	18837	17460	14904
18	Patiala	167040	115506	188640	120267	181440	93874.5
19	Rupanagar	25920	30946.5	32400	32085	30420	25668
20	SASN	18900	23391	18180	21942	20340	19251
21	Sangrur	**245160**	**173673**	**275580**	**158562**	215100	102361.5
22	Tarn Taran	127260	88492.5	136980	91080	130320	82386
Average		103704.5	82889.39	114480	80847.61	109333.6	68893.36

Districts that generate high or low amount of rice and wheat crop gross residues will also generate surplus residues in same ranking, as each district is expected to have same Surplus Fraction value or same percentage of generated residues to be managed on fields. For rice crops, on average, the surplus residue is highest in 2021, followed by 2022 and 2020. but for wheat crops, it is highest in 2020 and decreases with the upcoming year. Surplus residues generated by rice crops are high in amount as compared to wheat crops, and this is due to more competitive uses of wheat residues.

These quantities of surplus crop residue produced in each district are further assessed as surplus residue generated per acre of the district.

4.1.3 Amount of surplus residue produced by rice and wheat crops per acre of districts

Amount of surplus residue produced by rice and wheat crops per acre = The total surplus residue of crops produced in the district (tons) ÷ The area under production of the crop (acres)

For instance, the surplus residue produced per acre in Ferozepur district in 2021 is –

Surplus residue/acre of rice crop = 148140 tons (Table 14) ÷ 466030.6 acres (Appendix A)

= 0.3179 tons/acre or 317.9 kg/acres

Surplus residue/acre of wheat crop = 100084.5 tons (Table 14) ÷ 484563.1 acres (Appendix A)

= 0.2065 tons/acre or 206.5 kg/acre

In a similar way, surplus residue generated per acre of different districts is given in Table 15.

Table 15– Surplus crop residue generated per acre in 3 years (tons/acre)

Sr.no	District	2019-20		2020-21		2021-22	
		Rice	**Wheat**	**Rice**	**Wheat**	**Rice**	**Wheat**
1	Amritsar	0.24067	0.189823	0.243343	0.199457	0.262322	0.186528
2	Barnala	0.33547	0.220085	0.380336	0.201141	0.345716	0.191551
3	Bathinda	0.310914	0.226936	0.337915	0.207463	0.334748	0.184606
4	Faridkot	0.273797	0.233261	0.299028	0.212318	0.31669	0.191841
5	Fatehgarh S.	0.310015	0.184298	0.346244	0.207707	0.343782	0.142402
6	Fazilka	0.295575	0.206583	0.238425	0.19863	0.228647	0.179159
7	Ferozepur	0.19617	0.214357	0.317876	0.206546	0.320782	0.183111
8	Gurdaspur	0.26668	0.174789	0.283541	0.18957	0.279948	0.176781
9	Hoshiarpur	0.29138	0.179637	0.302756	0.173565	0.276374	0.151696
10	Jalandhar	0.296791	0.21064	0.331567	0.205299	0.311478	0.176921
11	Kapurthala	0.301093	0.194827	0.31626	0.193503	0.307391	0.167163

12	Ludhiana	0.3406	0.213618	0.356056	0.208171	0.35085	0.17907
13	Mansa	0.299338	0.225841	0.346824	0.207965	0.333057	0.186483
14	Moga	0.332431	0.224185	0.355264	0.215582	0.345182	0.183177
15	SMS	0.244222	0.228611	0.317862	0.21157	0.304249	0.189557
16	SBSN	0.304735	0.212693	0.317741	0.207004	0.328939	0.162017
17	Pathankot	0.223738	0.165449	0.267438	0.181505	0.256013	0.153085
18	Patiala	0.28766	0.199763	0.325828	0.208264	0.314197	0.1627
19	Rupanagar	0.262242	0.181505	0.325362	0.189005	0.307003	0.151424
20	SASN	0.263749	0.189324	0.265608	0.183089	0.255636	0.155504
21	Sangrur	0.343304	0.241527	0.383513	0.220513	0.364683	0.173472
22	Tarn Taran	0.279899	0.190492	0.299487	0.19711	0.289779	0.179737
	Average	0.293861	0.209596	0.323663	0.2039	0.316139	0.17663

Surplus crop residue per acre (Table 15) is further used to assess all other inputs and outputs of the on-field composting and burning methods.

4.2 Quantitative analysis of factors involved in the on-field composting method

4.2.1 The quantity of Inputs required in the on-field composting method

A. Decrease in the area under production due to on-field compost pit—A small portion of a cropped field (acre) is to be used for digging an on-field compost pit and it will reduce the area under production. This reduction in the area under production is assessed using the volume of crop residues (Appendix B), which is assessed from the mass (surplus residue – Table 15) and density of crop residues. A portion of the field used to make compost pit is counted as an expenditure for the on-field composting process, as crop yields decrease with the decrease in the area under production.

Volume of rice residues per acre = mass of surplus rice residues per acre ÷ density of rice crop residues

Volume of wheat residues per acre = mass of surplus wheat residues per acre ÷ density of wheat crop residues

For instance, the decrease in area under production per acre after making compost pit for the Ferozepur district in 2021 is assessed –

Volume of rice residues per acre = 317.9 kg (Table 15) / 43.5 kg/m^3 = 7.3074 m^3

Volume of wheat residues per acre = 206.5 kg (Table 15) / 24.16 kg/m^3 = 8.5490 m^3

43.5 kg/m^3 and 24.16 kg/m^3 are bulk densities of rice and wheat straw (as mentioned on Page no. 48). Similarly, volume of crop residues is calculated for all districts of the Punjab (Appendix B).

The volume of crop residues per acre ($\pi r^2 h$) = Area for compost pit per acre (πr^2)

if h =1m, (1 m is the depth of the compost pit) then,

The area for compost pit per acre for all districts of Punjab is given in Table 16.

Table 16 – Area under compost pit (m^2) per acre

No.	Districts	Area under compost pit per acre (m^2/acre)					
		(2019-20)		(2020-21)		(2021-22)	
		Rice	Wheat	Rice	Wheat	Rice	Wheat
1	Amritsar	5.532649	7.856922	5.594081	8.255652	6.030382	7.720539
2	Barnala	7.711963	9.10946	8.743346	8.325357	7.947488	7.928446
3	Bathinda	7.147445	9.393062	7.768168	8.587041	7.695352	7.640991
4	Faridkot	6.294178	9.654843	6.874209	8.787999	7.28023	7.940436
5	Fatehgarh S.	7.126776	7.628222	7.959626	8.597131	7.903027	5.894129
6	Fazilka	6.794834	8.550611	5.481026	8.221436	5.256253	7.415525
7	Ferozepur	4.509662	8.872398	7.307497	8.549083	7.374294	7.579111
8	Gurdaspur	6.130568	7.234629	6.518182	7.846428	6.435596	7.317082
9	Hoshiarpur	6.698391	7.435319	6.959915	7.183988	6.353428	6.278824
10	Jalandhar	6.82279	8.718541	7.622241	8.497479	7.160415	7.322902
11	Kapurthala	6.921671	8.06403	7.270344	8.009238	7.066465	6.918987
12	Ludhiana	7.829876	8.841803	8.185195	8.616362	8.065515	7.411831
13	Mansa	6.88133	9.347715	7.972961	8.607816	7.656474	7.718676
14	Moga	7.642087	9.279165	8.166983	8.923101	7.935216	7.581835
15	SMS	5.614309	9.462366	7.307171	8.757052	6.994231	7.845882
16	SBSN	7.005401	8.803527	7.304384	8.568028	7.561812	6.705982
17	Pathankot	5.143407	6.848063	6.147999	7.512643	5.885362	6.336318
18	Patiala	6.61288	8.268353	7.490305	8.620215	7.222912	6.734279

19	Rupnagar	6.028552	7.512643	7.479593	7.823041	7.057532	6.267556
20	SASN	6.063199	7.836265	6.105934	7.578178	5.876694	6.436442
21	Sangrur	**7.892049**	9.996999	**8.8164**	**9.127177**	**8.383512**	7.180136
22	Tarn Taran	6.43446	7.884587	6.884759	8.158527	6.661587	7.439433
Average		6.755419	8.675328	7.44053	8.439581	7.267565	7.310835

Adopting the on- field composting method decreases the area under production for a farmer in each district, affecting the amount of rice and wheat grains produced per acre. After removing the composting pit area, the area left under production differs for all districts of Punjab. The decrease in area under production per acre for every district is directly proportional to the surplus residue produced in each district of Punjab; higher surplus residue means more area under compost pit (keeping the height of compost pit constant), which leads to a decrease in the crop production area by the exact dimensions. This decrease in the area under production further decreases the yield of crops per acre.

Decrease in yield of crops per acre (kg) = {yield of crops per acre (Appendix A) (× 1000) kg / area of an acre (m^2)} × area under compost pit (m^2) (Table 16)

For instance, in 2021, for Ferozepur district,

Decrease in yield of rice crops per acre (kg/m^2) = (1765.978 kg /4046.856 m^2) × 7.3074 m^2

= 3.1888 kg/acre

Decrease in yield of wheat crops per acre (kg/m^2) = (1995.612 kg /4046.856 m^2) × 8.5490 m^2

= 4.2157 kg/acre

Similarly, a decrease in crop yield per acre is calculated for all districts of Punjab in the Table 17

Table 17 - Decrease in yield of crops on making a compost pit (kg/acre)

No.	District	Decrease in yield of crops (kg/acre)					
		2019-20		2020-21		2021-22	
		Rice	Wheat	Rice	Wheat	Rice	Wheat
1	Amritsar	1.827954	3.560768	1.868773	3.931349	2.171644	3.438223
2	Barnala	3.55164	4.786567	4.565143	3.998016	3.771888	3.625893
3	Bathinda	3.050708	5.089243	3.603597	4.253299	3.536356	3.367737
4	Faridkot	2.365794	5.376866	2.821919	4.454704	3.165113	3.636868
5	Fatehgarh S.	3.03309	3.356491	3.783418	4.263301	3.729803	2.00391
6	Fazilka	2.757126	4.217287	1.794001	3.898829	1.649877	3.171923
7	Ferozepur	1.214471	4.540679	3.188866	4.21578	3.24743	3.313411
8	Gurdaspur	2.244401	3.019057	2.537184	3.551263	2.473299	3.088266
9	Hoshiarpur	2.679415	3.188879	2.892723	2.97694	2.410545	2.274026
10	Jalandhar	2.77986	4.384565	3.46948	4.165039	3.06179	3.09318
11	Kapurthala	2.86102	3.750966	3.156522	3.700166	2.981971	2.761365
12	Ludhiana	3.661076	4.509418	4.000895	4.282394	3.884751	3.168764
13	Mansa	2.827768	5.040224	3.796106	4.273904	3.500714	3.436564
14	Moga	3.48757	4.966571	3.98311	4.592725	3.760248	3.315793
15	SMS	1.882312	5.164619	3.188582	4.423385	2.921318	3.550769
16	SBSN	2.930657	4.47046	3.18615	4.234485	3.414686	2.593962

17	Pathankot	1.579795	2.705044	2.257182	3.25555	2.068451	2.315862
18	Patiala	2.611441	3.943455	3.35041	4.286225	3.115471	2.615899
19	Rupanagar	2.170326	3.25555	3.340834	3.530125	2.974436	2.265872
20	SASN	2.195344	3.542069	2.2264	3.312596	2.062363	2.38963
21	Sangrur	3.719448	5.764719	4.641748	4.805203	4.197116	2.973748
22	Tarn Taran	2.472425	3.585888	2.830587	3.839391	2.650052	3.192409
Average		2.631984	4.19179	3.203801	4.011121	3.03406	2.981549

The decrease in yield per acre is directly proportional to the area under the compost pit.

The decrease in crop yield for rice and wheat crops is highest in Sangrur district.

B. Labor— Labor required for one acre per crop residue composting, as per estimation is in Table 18.

Table 18 – Estimated labor required for one acre per crop residue composting method

Tasks	Labor/acre	days	Total
Pit digging and collection of crop residues	2	1	2
Straw chopping, addition of inoculants and pit filling	2	1	2
Moisture and turning of compost	0.5	4	2
Leave the pit for 4-5 months	0	0	0
Pit dug out and broadcasting of compost	2	1	2
Total			8

(Source – Anecdotal information from practicing farmers)

Based on the anecdotal information from farmers, the total number of labors required for each crop residue on-field composting process is eight. This number is estimated and is assumed to be the same for both rice and wheat crops and all districts of Punjab. No doubt, the labor required for pit digging would not be required next year, as pit is already dug out. But for next year same labor could be used for pit maintaince or after few years pit site could be changed to maintain fertility of soil of field.

C. The amount of inorganic fertilizers recommended – The amount of fertilizers to be used in crops is recommended by the agricultural experts. According to the Package of Practices of rice, website- (Package of Practices for the crops of Punjab, 2024) and wheat crops, website- (Package of practices for crops of Punjab, 2023-24) , the amount of fertilizers required is shown in Table 19.

Table 19 – Inorganic fertilizer recommended for rice and wheat crops in Punjab

Sr.No.	**Crop**	**Inorganic Fertilizer required (kg/acre)**
1.	Rice	Urea - 90 DAP- 27 MOP - 20
2.	Wheat	Urea - 110 DAP- 55 MOP - 20

(Source - (Package of Practices for the crops of Punjab, 2024) for rice crops and (Package of practices for crops of Punjab, 2023-24) for wheat crops).

Urea fertilizer is the source of Nitrogen (N – 46.6%), DAP (Di-ammonium Phosphate) is a source of Phosphorous (P - 46%) and MOP (Muriate of Potash) consists of 60-62% of Potassium (K) as per the specifications given on the packets of fertilizers. These inorganic fertilizers would act as an input of the on-field composting process.

D. Farm machinery – Farm machinery required in the on-field composting process for chopping and collection of crop residues after crop harvesting, preparation of field for next crop, broadcasting of compost in field etc., are –

Table 20 – Farm machinery required for on-field composting and preparation of fields

Machinery required for composting crop residues
1. Straw reaper + tractor
2. Cultivator + tractor
3. Laser Leveler + tractor
4. Straw chopper
5. Rotavator + tractor
6. Disc harrow + tractor
7. Tractor

(Source – Anecdotal information from practicing farmers)

The kind of farm machinery that could be used is based on anecdotal information from farmers of Punjab. The implements can either be rented alone or in combination with a tractor from hiring centers. The farm machinery required is assumed to be the same for rice and wheat crops. The tractor rental charges are added separately to operate the Straw chopper in the field (Straw chopper + tractor combined rental charges are not found).

E. Farm tools - One farm tool (spade) is required per acre for digging a pit and the same farm tool can be used to dig out compost from the pit as well.

F. Gunny bags – The dimension of each gunny bag is 94cm × 57 cm, website - https://asiajute.com/jute-sack-specifications/.

Area of 1 jute bag is – 0.5358 m^2

So, the number of bags used to cover one compost pit /acre is –

= Surface area under compost pit / area of one gunny bag

The surface area of the compost pit (on average) – 7.26 m^2 for rice and 7.31 m^2 for wheat crop residues

= 7.26/0.5358 (rice) or 7.31/0.5358 (wheat) = 13.54 (rice) or 13.64 (wheat)

No. of bags required per acre is 13-14 bags for a pit.

4.2.2 The quantity of outputs from on-field composting method

A. Amount of fertilizers added to fields by compost - The crop residues based compost consist of plant nutrients, which are broadcasted into the field and crops grown in the field uptake these nutrients. There might be nutrient loss during the composting process through leaching and emissions. During the on-field composting process, nutrient loss through leaching will ultimately enrich the soil of the surrounding field of the on-field compost pit. Secondly, rice and wheat straw have a high C: N ratio, which would allow the least emission of nitrogenous (ammonia and nitrous oxide) gases during composting. So, it is estimated that most of the nutrients present in crop residues transfer to the compost produced out of crop residues.

Table 21 - Amount of nutrients present in rice and wheat crop residues

Nutrients (g/kg of straw)	**Rice Straw**	**Wheat Straw**
N (g/kg)	7.9	6.0
P (g/kg)	1.97	0.45
K(g/kg)	17.41	23.45

(Wang et al., 2020)

Along with the above macronutrients (N, P & K), trace amounts of micronutrients such as Zinc, Iron, Manganese, Sulphur etc., are present in rice and wheat crop straw (Shukla & Warsi, 2000).

Amount of fertilizers deposited by the crop residue compost per acre (g) = (Urea + DAP + MOP)(g/kg of straw) × Amount of surplus crop residues produced per acre (kg)

<u>Amount of fertilizers deposited by the rice residue compost per acre (g)</u> = {7.9 × 2.17* (Urea) + 1.97 × 2.17* (DAP) + 17.41 × 1.67* (MOP)}(g/kg of straw) × Amount of surplus rice residue produced per acre (kg) (Table 15)

<u>Amount of fertilizers deposited by the wheat residue compost (g)</u> = {6.0 × 2.17* (urea) + 0.45 × 2.17* (DAP) + 23.45 × 1.67* (MOP)}(g/kg of straw) × Amount of surplus wheat residues produced per acre (kg) (Table 15)

* Here, 2.17, 2.17 and 1.67 are multiplying factors to convert Nitrogen to Urea, Phosphorus to DAP and Potassium to MOP respectively.

Using the percentage of nutrients present in crop residues (Table 21) and the standard amount of nutrients present in fertilizers (46.6% N in urea, 46% P in DAP and 60% K in MOP), the fertilizers added to the field by adding compost is assessed.

For instance, for Ferozepur district in 2021 –

Amount of fertilizers equivalent of Urea, DAP and MOP deposited by the compost of rice residue (kg/acre)

$= \{(7.9 \times 2.17) + (1.97 \times 2.17) + (17.41 \times 1.67)\}(g) \times 0.317876$ (ton/acre) (Table 15)

$= 16.06294$ kg/acre

Amount of fertilizers equivalent of Urea, DAP and MOP deposited by the compost of wheat residue (kg/acre) is,

$=\{(6.0 \times 2.17) + (0.45 \times 2.17) + (23.45 \times 1.67)\}(g) \times 0.206546$ (ton/acre) (Table 15)

$= 10.98489$ kg/acre

The amount of total fertilizer added to crops through each crop residue compost for all districts in Table 22.

Table 22 – Amount of fertilizer added to fields from crop residue compost

Sr.no.	**District**	**Wheat (kg/acre)**			**Rice (kg/acre)**		
		2020	**2021**	**2022**	**2020**	**2021**	**2022**
1	Amritsar	10.09552	10.60786	9.92028	12.16157	12.2966	13.25566
2	Barnala	11.70493	10.69742	10.18742	16.95202	19.21915	17.46973
3	Bathinda	12.06934	11.03367	9.818066	15.71112	17.07556	16.9155
4	Faridkot	12.40571	11.29188	10.20283	13.83552	15.11051	16.00301

5	Fatehgarh S.	9.80166	11.04663	7.573488	15.66569	17.49642	17.372
6	Fazilka	10.98686	10.56389	9.528361	14.93603	12.04809	11.55401
7	Ferozepur	11.40033	10.98489	9.738555	9.912894	16.06294	16.20977
8	Gurdaspur	9.295923	10.08204	9.401869	13.47588	14.32791	14.14638
9	Hoshiarpur	9.553795	9.230854	8.06779	14.72404	15.29891	13.96576
10	Jalandhar	11.20263	10.91859	9.409347	14.99748	16.75479	15.73963
11	Kapurthala	10.36164	10.29124	8.890349	15.21484	15.98127	15.53312
12	Ludhiana	11.36102	11.07134	9.523615	17.21121	17.99225	17.72918
13	Mansa	12.01107	11.06036	9.917885	15.12616	17.52573	16.83004
14	Moga	11.92299	11.46548	9.742056	16.79842	17.95222	17.44276
15	SMS	12.15839	11.25212	10.08134	12.34107	16.06223	15.37434
16	SBSN	11.31183	11.00924	8.616654	15.39889	16.0561	16.62196
17	Pathankot	8.799218	9.65315	8.141665	11.30596	13.5142	12.93688
18	Patiala	10.62418	11.07629	8.653013	14.53607	16.46478	15.87701
19	Rupanagar	9.65315	10.05199	8.053312	13.25163	16.44123	15.51348
20	SASN	10.06898	9.737357	8.270318	13.32779	13.42173	12.91783
21	Sangrur	12.84535	11.7277	9.225904	17.34787	19.37973	18.42818
22	Tarn Taran	10.13107	10.48306	9.559081	14.14388	15.1337	14.64314
Average		10.9	10.7	9.2	14.5	16	15.6

When composted, rice residues add more fertilizers to the soil than wheat residues, and the amount varies with the variation in surplus residue produced by each crop per acre.

On average, wheat residue compost deposit 9.2 to 10.9 kg of fertilizers/acre, and rice residue compost deposit 14.5 to 16 kg of fertilizers/acre to the field.

B. Increase in crop yields on applying crop residue compost fertilizer in fields — Adding compost as fertilizer increases the yield of crops per acre by 6.3% for rice crops (Huang et al., 2023) and 8.21% for wheat crops (Long et al.. 2023).

Increase in rice crop yield for the particular year = 6.3% × Crop yield in a particular year with inorganic fertilizer (no compost added) (from Appendix A)

Increase in wheat crop yield for the particular year = 8.21% × Crop yield in a particular year with inorganic fertilizer (no compost added) (from Appendix A)

For instance, for Ferozepur district in year 2019-20 –

For Rice crop -

Increase in rice crop yield in 2020 (with composting) = 6.3% × 1.08907 (from Appendix A) = 0.0686 tons/acre

For Wheat crop -

Increase in wheat crop yield in 2020 (with composting) = 8.21% × 2.07287 (from Appendix A) = 0.1701 tons/acre

Similarly, the increase in crop yield for each crop and year is assessed for all districts of Punjab in Table 23.

Table 23 – The quantity of crop yield increased on using crop residue compost as fertilizer

No.	District	Rice (t/acre)			Wheat(t/acre)		
		2020	**2021**	**2022**	**2020**	**2021**	**2022**
1	Amritsar	0.08417	0.090493	0.097523	0.150572	0.170579	0.161917
2	Barnala	0.117583	0.140549	0.130008	0.174504	0.173873	0.166177
3	Bathinda	0.108911	0.12521	0.125216	0.180155	0.179323	0.161306
4	Faridkot	0.095903	0.110617	0.11792	0.18514	0.183721	0.167318
5	Fatehgarh S.	0.108656	0.127999	0.128453	0.146251	0.176872	0.127533
6	Fazilka	0.103555	0.089929	0.085755	0.163868	0.171006	0.156302
7	Ferozepur	0.068611	0.115529	0.119505	0.170183	0.17784	0.159854
8	Gurdaspur	0.093352	0.1051	0.104565	0.138606	0.161952	0.153564
9	Hoshiarpur	0.102024	0.112533	0.103758	0.142595	0.149316	0.132584
10	Jalandhar	0.10381	0.122593	0.116889	0.167191	0.176597	0.154767
11	Kapurthala	0.10534	0.117333	0.115028	0.154561	0.166253	0.146272
12	Ludhiana	0.119368	0.132245	0.131271	0.169518	0.179115	0.156968
13	Mansa	0.10483	0.128013	0.124628	0.179157	0.179906	0.162683
14	Moga	0.116308	0.131797	0.129202	0.177828	0.18578	0.160506
15	SMS	0.085445	0.11659	0.113961	0.181484	0.182756	0.165576
16	SBSN	0.106615	0.117923	0.122717	0.168853	0.178063	0.143253
17	Pathankot	0.078304	0.09854	0.095734	0.131294	0.154703	0.167262
18	Patiala	0.100749	0.120359	0.117514	0.158549	0.178214	0.143598

19	Rupanagar	0.091822	0.119797	0.114928	0.143924	0.161723	0.133602
20	SASN	0.092332	0.098914	0.095758	0.15024	0.157589	0.136254
21	Sangrur	0.120134	0.14173	0.136714	0.191788	0.190582	0.153256
22	Tarn Taran	0.097943	0.111	0.108507	0.151237	0.168972	0.156467
Average		0.100262	0.117036	0.115252	0.162614	0.172943	0.153046

The increase in yield per acre is greater for wheat crops than rice crops because the percentage of yield increase is high for wheat crops (8.21%). The increase in yield is due to the micronutrients such as silicon, zinc, manganese etc., present in organic compost generated out of crop residues (Wang et al., 2020). Moreover, it contains enzymes and microorganisms that are not often found in inorganic fertilizers.

C. A nutrient-rich compost – The amount of compost produced per acre in 2021-22 is calculated as –

Mass of compost formed from rice straw per acre = 40 % × the mass of the surplus crop residue generated from per acre (Table 15)

As, on average 60 % mass is lost during rice straw composting (Liang et al., 2017, Dash et al., 2022).

Mass of compost formed from wheat straw per acre = 55 % × the mass of the crop surplus crop residue generated per acre (Table 15)

As, on average 45 % mass is lost during wheat straw composting (Verma et al., 2014).

For the Ferozepur district (in 2021-22) -

Compost formed per acre from rice straw = 40% × 0.320782 = 0.1283 t/acre

Compost formed per acre from wheat straw = 55% × 0.183111 = 0.1007 t/acre

Similarly, the compost formed in each district is assessed in Table 24 -

Table 24 – A nutrient-rich compost produced from crop residues (tons/acre), (year 2021-22)

Sr.No.	**Districts**	**Rice Compost (t/acre)**	**Wheat Compost (t/acre)**
1	Amritsar	0.104929	0.102591
2	Barnala	0.138286	0.105353
3	Bathinda	0.133899	0.101533
4	Faridkot	0.126676	0.105513
5	Fatehgarh S.	0.137513	0.078321
6	Fazilka	0.091459	0.098537
7	Ferozepur	0.128313	0.100711
8	Gurdaspur	0.111979	0.097229
9	Hoshiarpur	0.11055	0.083433
10	Jalandhar	0.124591	0.097307
11	Kapurthala	0.122956	0.091939
12	Ludhiana	0.14034	0.098488
13	Malerkotla	0.153098	0.099799

14	Mansa	0.133223	0.102566
15	Moga	0.138073	0.100747
16	SMS	0.1217	0.104256
17	SBSN	0.131576	0.089109
18	Pathankot	0.102405	0.084197
19	Patiala	0.125679	0.089485
20	Rupnagar	0.122801	0.083283
21	SASN	0.102254	0.085527
22	Sangrur	0.145873	0.09541
23	Tarn Taran	0.115912	0.098855
Average		0.126456	0.097146

On average, 126.456 kg of rice straw compost and 97.1 kg of wheat straw compost are prepared per acre in 2021-22. The rice residue compost produced per acre is more than wheat residue compost, as it depends on the amount of surplus residue produced per acre. The compost produced per acre is calculated only for 2021-22 year, because the market price of compost is only available for this year.

4.3 Quantitative analysis of factors involved in the burning method

4.3.1 The quantity of inputs required for the burning method -

A. Labor – As per the anecdotal information from practicing farmers, one labor is required per acre duirng the burning process of crop residues of both rice and wheat crops. This is an estimation and would remain the same for all districts of Punjab.

B. Recommended inorganic fertilizers – According to the Package of Practices of rice (Package of Practices for the crops of Punjab, 2024) and wheat crops (Package of practices for crops of Punjab, 2023-24), the amount of inorganic fertilizers required is given in Table 25.

Table 25 – Inorganic fertilizer recommended for rice and wheat crops in Punjab

Sr.No.	Crop	Inorganic Fertilizer required (kg/acre)
1.	Rice	Urea - 90 DAP- 27 MOP - 20
2.	Wheat	Urea - 110 DAP- 55 MOP - 20

These inorganic fertilizers are inputs required if crop residues are managed through burning method.

C. Farm Machinery – The farm machinery used in burning crop residues would differ from those used in the on-field composting process.

Table 26 – Farm machinery required in crop residue burning method and preparation of fields

Rice crop residue burning	**Wheat crop residue burning**
Farm Machinery	**Farm Machinery**
Reaper + tractor	Straw Chopper (trail type & combo)
Disc harrow + tractor	Disc harrow + tractor
Planker + tractor	Planker + tractor
Cultivator + tractor	Cultivator + tractor
Rotavator + tractor	Rotavator + tractor
Laser Leveler + tractor	Laser leveler + tractor
-	Tractor

(Anecdotal information from practicing farmers)

Farm machinery used here is different for rice and wheat crops. Farmers can rent the farm machinery from Custom Hiring Centres (CHC), either only farm implements or tractors and implements. The farm machinery costs less for rice crops because (Straw reaper + tractor) is used to cut stalks of crops from the ground after harvesting of rice crops. The tractor renting cost is added in wheat crop residue burning process to operate the straw chopper as renting charges of (Straw chopper + tractor) are not given. Other farm implements are used to control fire within field and prepare field for next crop.

D. Farm tools - One farm tool (Rake) is expected to be required per acre for facilitating burning crop residues.

E. Penalty – The amount of money fined to farmers for burning crop residues varies with the number of acres burnt. The National Green Tribunal (NGT) impose a fine of Rs 2,500 on crop residue burning up to two-acre land, Rs 5,000 fine to 2 to 5 acres land size, Rs 7,000 fine on land up to 10 acres, and Rs 15,000 fine on burning crop residues in fields above 10 acres (Singh & Zaffar, 2017).

4.3.2 The outcomes of burning method

Various nutrients and microorganisms gets destroyed during burning of crop residues, leading to decline in soil health, which is a significant negative output of burning crop residues. However, it is difficult to quantify the decline in soil health. In addition, other collateral damage could be possible in burning crop residues.

The emissions of GHGs in the environment is a major outcome of the burning process.

4.4 Expected Environmental Change

The difference in GHG emitted by on-field composting and burning methods in each district = GHG emitted by the burning method – GHG emitted by the on-field composting method

GHG emitted by the burning process -

The emissions of the straw-burning process in Punjab are already evaluated for the year 2017-18 (Singh, et al., 2020) in Table 27.

Table 27 **-** Emissions of various pollutants from burning of different crop residues in Punjab in 2017-18

Sr. No.	**Districts**	**$PM_{2.5}$** (in Gg)	**CO_2** (in Gg)	**CH_4** (in Gg)	**N_2O** (in Gg)
1	Amritsar	6.92	1386.81	7.95	0.57
2	Barnala	5.58	1054.03	6.45	0.43
3	Bathinda	8.04	1745.02	9.32	0.72

4	Faridkot	5.1	987.35	5.91	0.40
5	Fatehgarh S.	3.95	759.7	4.54	0.31
6	Fazilka	4.24	1064.12	4.91	0.44
7	Ferozepur	8.36	1601.31	9.69	0.66
8	Gurdaspur	6.77	1374.32	7.57	0.58
9	Hoshiarpur	3.66	927.1	3.96	0.39
10	Jalandhar	7.3	1436.17	8.31	0.60
11	Kapurthala	5.09	956.64	5.84	0.19
12	Ludhiana	12.09	2276.46	13.96	0.94
13	Mansa	5.33	1152.31	6.18	0.48
14	Moga	8.54	1597.03	9.89	0.65
15	SMS	7.17	1500.77	8.32	0.62
16	SBSN	2.96	611.82	3.36	0.25
17	Pathankot	0.98	225.43	1.09	0.09
18	Patiala	10.03	1948.65	11.59	0.80
19	Rupanagar	1.95	469.3	2.22	0.19
20	SASN	1.23	295.31	1.41	0.12
21	Sangrur	14.32	2723.24	16.53	1.12
22	Tarn Taran	7.54	1441.65	8.72	0.59
Average		6.234091	1251.57	7.169091	0.506364

(Singh, et al., 2020)

In the above table, the contributions of rice and wheat crop residues burnt among total crop residues in Punjab are 97%, of which 70% are rice and 27% are wheat (Singh, et al., 2020). Sangrur district emitted the highest CH_4 with 16.53 Gg, with CH_4 average value of 7.169 Gg for Punjab. These GHG emissions of 2017-18 are expected to remain the same for the next 3 years (2020, 2021 and 2022), as this is the latest and valuable data available on crop residue burning emissions. These emissions are combined for both rice and wheat crop residue burning in a year.

GHG emitted by the on-field composting process – Rice and wheat straw composting emissions are assumed to be similiar as that of yard waste composting emissions.

Table 28 - Yard waste composting emissions

Emission factor	**kg pollutant/kg of wet feedstock**
CH_4	2.06×10^{-3}
N_2O	4.54×10^{-5}
CO_2	1.71×10^{-1}

(Nordahl et al., 2023)

Emission factors by Nordahl et al., 2023 is applied to the combined surplus residue of rice and wheat crops for three years and yard waste emissions and difference is evaluated by comparing emissions from the burning process (Table 27) and the composting process (Table 28) for crop residue management.

For instance, for Ferozepur district, the CH_4 emissions difference in 2020 is assessed using both emissions of burning process and on-field composting process on per kg basis to differentiate them. The composting process emissions are already on per kg basis (Table 28), but we have convert burning process emission on per kg basis (Table 27).

CH_4 emitted by burning process per kg of crop residue =

CH_4 emitted in district(kg) (Table 27) ÷ Total Surplus residue produced by both rice and wheat crop in the district (kg) (Table 14)

= 9.69×10^6 (kg pollutant) ÷ 154309.5×10^3 kg feedstock (55260 (R) + 99049.5(W))

= 0.0628 kg pollutant/kg feedstock

CH_4 emitted by composting process per kg of waste = 2.06×10^{-3} kg pollutant/kg feedstock (Table 28)

Difference = CH_4 emitted per kg of feedstock by burning process - CH_4 emitted per kg of feedstock by on-field composting process

= 60.74×10^{-3} kg pollutant/kg feedstock or 9.372 Gg in Ferozepur district

The 9.372 Gg value is calculated by multiplying the 60.74×10^{-3} kg pollutant/kg feedstock value (calculated above) with total amount of surplus crop residue (rice + wheat) produced in Ferozepur district (kg) (Table 14).

In similar way, the N_2O and CO_2 emissions reduced by substituting burning with on-field composting crop residues in Gg is evaluated for each district in Table 29.

Table 29 – GHG emissions reduced by substituting the burning of crop residues with the on-field composting method (Gg)

No.	Districts	CH_4 (Gg)			N_2O (Gg)			CO_2 (Gg)		
		2020	2021	2022	2020	2021	2022	2020	2021	2022
1	Amritsar	7.546607	7.529327	7.525907	0.56111	0.560729	0.560653	1353.324	1351.89	1351.606
2	Barnala	6.127617	6.110366	6.133754	0.422895	0.422515	0.42303	1027.269	1025.837	1027.779
3	Bathinda	8.740987	8.745279	8.767629	0.707239	0.707334	0.707826	1696.956	1697.313	1699.168
4	Faridkot	5.610598	5.607761	5.6107	0.393402	0.393339	0.393404	962.4967	962.2612	962.5052
5	Fatehgarh S.	4.324547	4.296514	4.3254	0.305252	0.304634	0.30527	741.8153	739.4883	741.8861
6	Fazilka	4.406009	4.559297	4.592234	0.428893	0.432271	0.432997	1022.284	1035.008	1037.742
7	Ferozepur	9.372122	9.178658	9.208303	0.652994	0.648731	0.649384	1574.923	1558.864	1561.324
8	Gurdaspur	7.169202	7.13876	7.155529	0.571167	0.570496	0.570866	1341.05	1338.523	1339.915
9	Hoshiarpur	3.714466	3.712269	3.742294	0.384589	0.38454	0.385202	906.7183	906.5359	909.0283
10	Jalandhar	7.860127	7.83431	7.876943	0.590085	0.589516	0.590456	1398.826	1396.683	1400.222
11	Kapurthala	5.547986	5.546901	5.559888	0.183564	0.18354	0.183827	932.4	932.3099	933.388
12	Ludhiana	13.23912	13.22672	13.27539	0.924113	0.923839	0.924912	2216.62	2215.59	2219.631
13	Mansa	5.802099	5.784023	5.808236	0.471672	0.471273	0.471807	1120.941	1119.44	1121.45
14	Moga	9.382875	9.365012	9.404864	0.638824	0.63843	0.639308	1554.934	1553.451	1556.759
15	SMS	7.834771	7.788264	7.824463	0.609306	0.608281	0.609079	1460.491	1456.631	1459.636
16	SBSN	3.183564	3.178011	3.19428	0.246112	0.245989	0.246348	597.1741	596.7132	598.0636
17	Pathankot	1.024424	1.012262	1.02333	0.088555	0.088287	0.088531	219.9866	218.977	219.8958
18	Patiala	11.00796	10.95365	11.02285	0.787172	0.785976	0.787501	1900.335	1895.827	1901.571
19	Rupanagar	2.102855	2.087161	2.104459	0.187418	0.187072	0.187454	459.5758	458.2731	459.709
20	SASN	1.322881	1.327349	1.328443	0.11808	0.118178	0.118203	288.0782	288.4491	288.5399
21	Sangrur	15.6672	15.63567	15.87603	1.100985	1.10029	1.105587	2651.62	2649.002	2668.954
22	Tarn Taran	8.27555	8.250196	8.281826	0.580205	0.579646	0.580343	1404.756	1402.652	1405.277
Average		6.784708	6.766716	6.801943	0.497892	0.497496	0.498272	1219.662	1218.169	1221.093

The GHG emissions reduced by adopting on-field composting is approximately the same for all years. But there is a vast difference in the emissions of the on-field composting and burning process, and it depends on the surplus residue produced by rice and wheat crops. In addition, the Social Cost of Greenhouse Gases (SC-GHG) measures incremental additional damages expected from increase in GHG emissions.

On-field composting would reduce GHG emissions emitted in crop residue burning.

4.5 Cost Analysis

The inputs and outputs related to the on-field composting of crop residues and burning of crop residues are further evaluated in terms of cost.

4.5.1 Net Composting Costs (NCC)

The Net composting cost is calculated by adding the total input costs of on-field composting crop residues and subtracting the output revenue from composting crop residues.

Net composting cost (NCC) = Total Input Composting Cost (TICC) – Total Output Composting Revenue (TOCR)

$$NCC = TICC - TOCR$$

4.5.1.1 Total Input Composting Costs (TICC)

TICC = A decrease in yield revenue due to on-field compost pit + Labor cost + Recommended Inorganic fertilizers cost + Farm machinery cost + Farm tool cost + Gunny bag cost + Inoculants cost

Each input-related cost component is evaluated one by one.

A. <u>Decrease in yield revenue due to on-field compost pit</u> – The yield revenue decreased per acre due to the area of the compost pit is evaluated using the decrease in the yield of crop per acre and converting it into monetary units using Minimum Support Price (MSP) of crops fixed by the government.

Table 30 – Minimum Support Price for rice and wheat crops

Year	Rice (Rs/quintal)	Wheat (Rs/quintal)
2019-20	1815	1925
2020-21	1868	1975
2021-22	1940	2015

Source – website - (Minimum Support Price-2021-22 (MSP))

The MSP may change year to year, as the table above states the MSP for rice and wheat crops increased from 2019-20 to 2021-22.

A decrease in yield leads to a reduction in revenue/acre due to the area under the compost pit. Therefore,

Decrease in revenue per acre (Rs) = Decrease in crop yield/acre (Table 17) × MSP of the crop (Rs) (Table 30)

For Ferozepur district, the decrease in yield revenue per acre for wheat crop in 2020 is assessed as follows,

Decrease in yield revenue per acre (Rs) = 4.540679 kg/acre (Table 17) × Rs 1925/quintal (Table 30) or Rs. 19.25/kg = Rs. 87.40808 per acre

Similarly, the decrease in revenue of yield is assessed for all districts in Table 31.

Table 31 - Decrease in yield revenue on making on-field compost pit (Rs/acre)

No	**Districts**	**Year (2019-20)**		**Year (2020-21)**		**Year (2021-22)**	
		Rice (Rs/acre)	**Wheat (Rs/acre)**	**Rice (Rs/acre)**	**Wheat (Rs/acre)**	**Rice (Rs/acre)**	**Wheat (Rs/acre)**
1	Amritsar	33.17736	68.54478	34.90868	77.64414	42.1299	69.2802
2	Barnala	64.46226	92.14141	85.27687	78.96082	73.17462	73.06175
3	Bathinda	55.37035	97.96792	67.31519	84.00265	68.60531	67.8599
4	Faridkot	42.93917	103.5047	52.71344	87.9804	61.4032	**73.28289**
5	Fatehgarh S.	55.05058	64.61246	70.67426	84.20019	72.35819	40.37878
6	Fazilka	50.04184	81.18277	33.51194	77.00187	32.00761	63.91425
7	Ferozepur	22.04264	87.40808	59.56802	83.26165	63.00015	66.76523
8	Gurdaspur	40.73587	58.11685	47.3946	70.13744	47.98199	62.22855
9	Hoshiarpur	48.63138	61.38593	54.03607	58.79456	46.76457	45.82163
10	Jalandhar	50.45446	84.40287	64.80988	82.25952	59.39873	62.32758
11	Kapurthala	51.92751	72.20609	58.96384	73.07828	57.85024	55.64151
12	Ludhiana	66.44853	86.8063	74.73671	84.57729	75.36418	63.85059
13	Mansa	51.32399	97.0243	70.91126	84.40961	67.91385	69.24676
14	Moga	63.2994	95.60649	74.4045	90.70631	72.94881	66.81324
15	SMS	34.16397	99.41892	59.56271	87.36185	56.67358	71.548
16	SBSN	53.19142	86.05636	59.51728	83.63108	66.24491	52.26833
17	Pathankot	28.67329	52.0721	42.16416	64.29711	40.12796	46.66462
18	Patiala	47.39766	75.9115	62.58566	84.65295	60.44013	52.71037

19	Rupnagar	39.39142	62.66934	62.40678	69.71997	57.70406	45.65731
20	SASN	39.8455	68.18483	41.58915	65.42376	40.00985	48.15104
21	Sangrur	**67.50799**	**110.9708**	**86.70786**	**94.90276**	**81.42405**	59.92102
22	Tarn Taran	44.87452	69.02834	52.87536	75.82797	51.411	64.32704
Average		47.77051	80.69196	59.84701	79.21964	58.86077	60.07821

For rice crops, Sangrur district has a high reduction in yield revenue in all three years, and this is due to the production of the high volume of surplus residue per acre in this district, which leads to more area under compost pit. For wheat crops as well, Sangrur is the district which has a higher yield revenue reduction for the same reason in years 2019-20 and 2020-21, but Faridkot produces a high amount of surplus residue/acre which require more area under compost pit, thus led to the higher decrease in yield revenue (Rs. 73.28289) in the 2021-22 year. Whereas SASN, Amritsar and Pathankot have a minor decrease in yield revenue of rice crop per acre for 2021-22, 2020-21 and 2019-20 years respectively. Pathankot (2019-20), Hoshiarpur (2020-21) and Fatehgarh Sahib (2021-22) have a minimum decrease in yield revenue of wheat crops when making on-field compost pits. Thus, the revenue decreased in each district and year depends on the surplus residue produced per acre and the MSP of crops fixed by the government each year.

B. <u>Labor cost</u> – For the on-field composting process, we estimated that the process needs 8 labors (8 hours workday/labor) per acre for the end-to-end composting process that includes the collection of residues, pit digging, pit filling, turning and broadcasting of compost (Table 18). The labor cost is calculated using the labor wages prevailing in the districts of Punjab. The labor wage is fixed by the Punjab government in each district every year.

<u>Labor cost/ acre (Rs)</u> = Number of labors required per acre (8) × labor wage in a district(Rs)

The data related to labor wage/day is given in Table 32.

Table 32 – The labor wage (Rs/day) and total labor cost (Rs/acre) in different districts

No.	**Districts**	**(2019-20)**		**(2020-21)**		**(2021-22)**	
		Labor wage (Rs/day)	**Total Labor cost (Rs/acre)**	**Labor wage (Rs/day)**	**Total Labor cost (Rs/acre)**	**Labor wage (Rs/day)**	**Total Labor cost (Rs/acre)**
1	Amritsar	500	4000	500	4000	429.17	3433.36
2	Barnala	455	3640	455	3640	500	4000
3	Bathinda	400	3200	400	3200	416.67	3333.36
4	Faridkot	447.27	3578.16	396.67	3173.36	435.83	3486.64
5	Fatehgarh S.	388.33	3106.64	408.33	3266.64	468.29	3746.32
6	Fazilka	404.17	3233.36	400	3200	458.33	3666.64
7	Ferozepur	454.17	3633.36	433.33	3466.64	441.67	3533.36
8	Gurdaspur	450	3600	455.83	3646.64	505	4040
9	Hoshiarpur	445	3560	460	3680	490	3920
10	Jalandhar	520.83	**4166.64**	530	**4240**	420	3360
11	Kapurthala	368.33	2946.64	390	3120	409.67	3277.36
12	Ludhiana	400	3200	400	3200	441.67	3533.36
13	Mansa	300	2400	300	2400	350	2800
14	Moga	488.33	3906.64	496.67	3973.36	400	3200
15	SMS	470	3760	476.67	3813.36	535.57	**4284.56**

16	SBSN	360	2880	360	2880	379.17	3033.36
17	Pathankot	350	2800	350	2800	412.5	3300
18	Patiala	410	3280	410	3280	410	3280
19	Rupnagar	298.33	**2386.64**	300	**2400**	325	**2600**
20	SASN	450	3600	434.58	3476.64	490.5	3924
21	Sangrur	415	3320	416.25	3330	428.33	3426.64
22	Tarn Taran	410	3280	410	3280	400	3200
Average		417.489	3339.91	417.424	3339.39	433.971	3471.77

In Table 32 above, Rupanagar district have the lowest labor cost/acre in all three years: Rs. 2386.64 in 2019-20, Rs. 2400 in 2020-21 and Rs. 2600 in 2021-22. Whereas Sri Muktsar Sahib have the highest labor cost of Rs. 4284.56 in 2021-22, and Jalandhar is highest in the other two years with Rs. 4240 in 2020-21 and Rs. 4166.64 in 2019-20. This labor cost would be the same for rice and wheat crop residue for the on-field composting process.

C. Recommended Inorganic fertilizers cost – Table 19 depicts the amount of inorganic fertilizers recommended for rice and wheat crops, and the subsidized price of inorganic fertilizers is given in Table 33.

Table 33 - Subsidized Price of Inorganic Fertilizer in Punjab

Fertilizer	**Price INR (excluding taxes) (Rs)**		
	2020	**2021**	**2022**
Urea (45 kg)	266.50	266.50	266.50
DAP (50 kg)	1350	1700	1200
MOP (50 kg)	1700	900	900

(Source – As per dealer 's selling price)

Using the amount of inorganic fertilizers recommended (Table 19) and the subsidized price of inorganic fertilizers fixed by the government (Table 33), the cost of inorganic fertilizers per acre is calculated as –

Costs of recommended inorganic fertilizers/acre (Rs) = Amount of inorganic fertilizers × Subsidized price of inorganic fertilizers

The Inorganic fertilizer cost for rice and wheat crops in on-field composting method is given in Table 34.

Table 34 – Inorganic fertilizer cost/acre for rice and wheat crops in on-field composting method (Rs/acre)

Sr.No.	**Crop**	**Inorganic Fertilizer required (kg/acre)**	**Cost of fertilizers (Rs)**		
			(2020)	**(2021)**	**(2022)**
1.	Rice	Urea - 90 DAP- 27 MOP - 20	Urea – Rs. 533 DAP – Rs. 648 MOP – Rs. 360	Urea – Rs. 533 DAP – Rs. 918 MOP – Rs. 360	Urea – Rs. 533 DAP – Rs. 729 MOP – Rs. 680
Total			Rs. 1541	Rs. 1811	Rs. 1942
2.	Wheat	Urea - 110 DAP- 55 MOP - 20	Urea – Rs. 651.4 DAP – Rs. 1320 MOP – Rs. 360	Urea – Rs. 651.4 DAP – Rs. 1870 MOP – Rs. 360	Urea – Rs. 651.4 DAP – Rs. 1485 MOP – Rs. 680
Total			Rs. 2331.4	Rs. 2881.4	Rs. 2816.4

The total amount of rice and wheat inorganic fertilizers (Rs/acre) is an input cost for on-field composting costs. Wheat crops have high inorganic fertilizer costs as a higher amount of inorganic fertilizer is required for this crop in comparison to rice crops. Table 33 depicts the subsidized price of inorganic fertilizers, and Punjab farmers buy fertilizers at this rate.

However, the non-subsidized price of inorganic fertilizers (2022) is Rs 2450 for 45 kg Urea, Rs 4073 for 50 kg DAP, and Rs. 2654 for 50 kg MOP. Using the non-subsidized price of fertilizers, and the amount of inorganic fertilizers recommended per acre (Table 19), the total non-subsidized cost of recommended fertilizers (2022) is calculated as Rs.8161.02 for rice crop and Rs. 11530.79 for wheat crop.

D. Farm machinery cost– The total cost of renting farm machinery for rice and wheat crops per hour is calculated for each district as per Primary Agricultural Credit Societies (PACS) and Agro Machinery Service Centres (AMSCs). These organizations rent the machinery to farmers under the cooperative societies of Punjab, Custom Hiring Centers (CHC) and these Custom Hiring Centers fix the farm machinery renting charges in Punjab. As per assumption and anecdotal information from farmers of Punjab, the farm machinery required for the on-field composting process and field preparation for the next crop (Table 20) and the farm machinery rental charges are in Table 35.

Table 35 – Farm machinery cost of on-field composting method per acre (Rs/hr)

Composting crop residues	
Farm machinery	**Cost (Rs/ hour)**
Straw chopper	250 (+ tractor cost)
Laser Leveler + tractor	575
Disc harrow + tractor	700
Reaper + tractor	700
Cultivator + tractor	650

Rotavator + tractor	1060
Tractor	223.33
Total	**4158.33**

(Singh S., 2017),(Singh et al., 2015)

The total cost of renting farm machinery for rice or wheat crops per hour is Rs. 4158.33 per acre, assuming the same for each district (as per PACS – Primary Agricultural Credit Societies and AMSCs – Agro Machinery Service Centres).

Straw chopper charges do not include tractor-renting charges, so tractor-renting charges are added differently. A straw chopper cuts the stalks from the ground and chop them into small pieces for composting in the compost pit. The reaper + tractor rental charges are Rs.300/acre, but we need on per hour basis. So, as per anecdotal information from farmers, on average reaper can be used on 2.3 acres in one hour, so reaper rental charges would be Rs. 700/hour.

E. Farm tool cost – If one piece of farm tool is required per acre for the composting process, each spade would cost Rs 240 per acre.

F. Gunny bags cost—The government fixed the cost of each used 580 gm gunny bag at Rs 22 per bag. A new gunny bag costs Rs 55 in the wholesale market. According to the area of the compost pit, 13-14 gunny bags are required per acre.

So, the cost of bags required per acre is Rs. 770.

G. Inoculant cost—A small amount of previous compost generated could be used as an inoculant or starter to prepare the next compost. Thus, a farmer does not need to buy an inoculant for the composting process.

Adding costs of all on-field composting inputs, TICC is assessed in Table 36.

Table 36 – Total Input Composting Costs (TICC) per acre (Rs/acre)

Sr.no.	District	Rice (Rs/acre)			Wheat (Rs/acre)		
		2020	2021	2022	2020	2021	2022
1	Amritsar	10742.51	11014.24	10585.82	11568.27	12127.37	11487.37
2	Barnala	10413.79	10704.61	11183.5	11231.87	11768.69	12057.79
3	Bathinda	9964.7	10246.65	10512.3	10797.7	11333.73	11385.95
4	Faridkot	10330.43	10205.4	10658.37	11181.39	11311.07	11544.65
5	Fatehgarh S.	9871.021	10316.64	10929.01	10670.98	11400.57	11771.43
6	Fazilka	9992.732	10212.84	10808.98	10814.27	11326.73	11715.28
7	Ferozepur	10364.73	10505.54	10706.69	11220.5	11599.63	11584.86
8	Gurdaspur	10350.07	10673.36	11198.31	11157.85	11766.51	12086.96
9	Hoshiarpur	10317.96	10713.37	11077.09	11121.12	11788.52	11950.55
10	Jalandhar	**10926.42**	**11284.14**	10529.73	**11750.77**	**12371.99**	11407.06
11	Kapurthala	9707.898	10158.29	10445.54	10518.58	11242.81	11317.73
12	Ludhiana	9975.779	10254.07	10719.05	10786.54	11334.31	11581.94
13	Mansa	9160.654	9450.241	9978.244	9996.754	10534.14	10853.98
14	Moga	10679.27	11027.09	10383.28	11501.98	12113.8	11251.54
15	SMS	10503.49	10852.25	**11451.56**	11359.15	11950.45	**12340.84**
16	SBSN	9642.521	9918.847	10209.93	10465.79	11013.36	11070.36
17	Pathankot	9538.003	9821.494	10450.46	10351.8	10914.03	11331.39
18	Patiala	10036.73	10321.92	10450.77	10855.64	11414.38	11317.44
19	Rupanagar	9135.361	9441.737	9768.034	9949.039	10519.45	10630.39

20	SASN	10349.18	10497.56	11074.34	11167.91	11591.79	11956.88
21	Sangrur	10096.84	10396.04	10618.39	10930.7	11474.63	11471.29
22	Tarn Taran	10034.2	10312.21	10361.74	10848.76	11405.56	11249.06
Average		10097.01	10378.57	10640.96	10920.33	11468.34	11516.58

The average Total Input Composting Costs (TICC) for Punjab range between Rs.10,000 and Rs.11,500, with Jalandhar being the highest for rice and wheat crops in 2019-20 and 2020-21. For 2021-22, the highest TICC is of Sri Muktsar Sahib (SMS), that is, Rs.11451.56 and Rs.12340.84 for rice and wheat, respectively.

4.5.1.2 Total Output Composting Revenue (TOCR)

TOCR = Fertilizer cost reduction + Revenue due to increase in yield of crops + Pit sand taken out of pit

Or

TOCR = Selling a nutrient-rich compost directly in the market to generate revenue, if not used back into the field.

Farmers can either use compost in the field to increase the yield or can directly sell the compost in the market to generate revenue.

A. <u>Inorganic fertilizer cost reduction</u> –

   Applying compost in fields provides nutrients to the soil (Table 21) and the expenditure on inorganic fertilizers would be reduced.

Table 33 depicts the subsidized price of inorganic fertilizers, and Punjab farmers buy inorganic fertilizers at this rate.

Inorganic fertilizer cost reduction (Rs) = Quantity of inorganic fertilizer added through composting (kg/acre) (Table 22) × subsidized price of inorganic fertilizer (Rs) (Table 33)

In Table 33 all fertilizers are added, but for cost analysis, each fertilizer is multiplied separately with the respective subsidized price and later all fertilizer (Urea, DAP and MOP) prices are added and the inorganic fertilizer cost reduction through on-field composting in all districts is shown in Table 37.

Table 37 – Total Inorganic fertilizer cost reduction per acre by on-field composting method (using subsidized price) (Rs/acre)

Sr.No.	**District**	**Rice (Rs/acre)**			**Wheat (Rs/acre)**		
		2020	**2021**	**2022**	**2020**	**2021**	**2022**
1	Amritsar	175.1702	187.537	316.3301	152.9284	162.6406	267.6968
2	Barnala	244.1698	293.1136	416.894	177.308	164.0138	274.9057
3	Bathinda	226.2965	260.4215	403.6679	182.828	169.1691	264.9386
4	Faridkot	199.2811	230.4523	381.8923	187.9234	173.1281	275.3214
5	Fatehgarh S.	225.6421	266.84	414.5617	148.4769	169.3679	204.3691
6	Fazilka	215.1324	183.7469	275.7224	166.4304	161.9665	257.121
7	Ferozepur	142.7812	244.9779	386.8265	172.6938	168.4213	262.793
8	Gurdaspur	194.101	218.5168	337.5861	140.816	154.5787	253.7076
9	Hoshiarpur	212.0789	233.3255	333.2759	144.7222	141.5283	217.7078
10	Jalandhar	216.0175	255.5294	375.6072	169.6991	167.4047	253.9094

11	Kapurthala	219.1482	243.7323	370.679	156.9596	157.7861	239.9043
12	Ludhiana	247.9031	274.402	423.0852	172.0983	169.7468	256.9929
13	Mansa	217.871	267.287	401.6285	181.9454	169.5784	267.6322
14	Moga	241.9575	273.7914	416.2502	180.6111	175.7897	262.8875
15	SMS	177.7556	244.967	366.8898	184.177	172.5184	272.0429
16	SBSN	221.7992	244.8735	396.663	171.3532	168.7946	232.5187
17	Pathankot	162.8463	206.1066	308.7229	133.2918	148.0029	219.7013
18	Patiala	209.3715	251.1064	378.8856	160.9365	169.8227	233.4999
19	Rupanagar	190.871	250.7473	370.2104	146.2273	154.1179	217.3171
20	SASN	191.968	204.6965	308.2683	152.5263	149.294	223.1729
21	Sangrur	249.8715	295.5626	439.7661	194.5832	179.8101	248.9592
22	Tarn Taran	203.7226	230.8059	349.4407	153.4668	160.7272	257.9499
Average		208.4435	243.7518	371.4934	165.091	164.0094	248.4113

The total cost reduction of fertilizers (Urea + DAP + MOP) depends on the subsidized price of fertilizers fixed by the Punjab government and surplus rice and wheat residues that would add nutrients to the soil. In most districts, the cost reduction of inorganic fertilizers increases with the year for both rice and wheat residues. The average surplus residue of wheat crops per acre is lowest in 2022, but the MSP of inorganic fertilizers is higher in 2022, thus making the inorganic fertilizer cost reduction high in 2022. Sangrur and Faridkot districts have the highest inorganic fertilizer cost reduction in 2022 for on-field composting rice and wheat residues, respectively.

And the non-subsidized price of inorganic fertilizers (2022) is Rs 2450 for Urea, Rs 4073 for DAP, and Rs. 2654 for MOP. Using this non-subsidized price of fertilizers, the cost reduction of inorganic fertilizers is assessed and shown in Table 38.

Table 38- The cost reduction of inorganic fertilizers per acre by using non-subsidized prices of inorganic fertilizers (Rs/acre)

No.	District	Rice (Rs/acre)				Wheat (Rs/acre)			
		Urea	DAP	MOP	Total	Urea	DAP	MOP	Total
1	Amritsar	245.2869	91.51752	404.837	741.6414	132.4674	14.86487	387.7348	535.0671
2	Barnala	323.2655	120.6117	533.5379	977.4151	136.0346	15.26516	398.1762	549.4759
3	Bathinda	313.0098	116.7852	516.6113	946.4064	131.1025	14.71171	383.7398	529.554
4	Faridkot	296.1247	110.4853	488.743	895.353	136.2403	15.28825	398.7783	550.3069
5	Fatehgarh S.	321.457	119.9369	530.5531	971.9471	101.1302	11.34836	296.0103	408.4889
6	Fazilka	213.799	79.76928	352.8675	646.4358	127.234	14.2776	372.4166	513.9282
7	Ferozepur	299.9507	111.9128	495.0577	906.9212	130.0408	14.59256	380.6321	525.2654
8	Gurdaspur	261.769	97.66708	432.0402	791.4763	125.5449	14.08806	367.4727	507.1057
9	Hoshiarpur	258.4268	96.4201	426.5241	781.371	107.7307	12.08904	315.3301	435.1499
10	Jalandhar	291.2512	108.667	480.6994	880.6176	125.6448	14.09927	367.765	507.509
11	Kapurthala	287.4297	107.2412	474.3923	869.0632	118.7145	13.32158	347.4799	479.516
12	Ludhiana	328.0663	122.4029	541.4614	991.9306	127.1706	14.27049	372.2311	513.6722
13	Mansa	311.4284	116.1952	514.0013	941.6249	132.4354	14.86128	387.6412	534.9379
14	Moga	322.7663	120.4254	532.714	975.9058	130.0875	14.59781	380.7689	525.4542
15	SMS	284.4916	106.145	469.543	860.1795	134.618	15.1062	394.0297	543.7539
16	SBSN	307.5781	114.7586	507.6464	929.9831	115.0598	12.91147	336.7825	464.7538
17	Pathankot	239.3881	89.31668	395.1014	723.8062	108.7172	12.19973	318.2175	439.1345

18	Patiala	293.7932	109.6154	484.895	888.3037	115.5453	12.96595	338.2036	466.7149
19	Rupanagar	287.0664	107.1056	473.7926	867.9645	107.5374	12.06734	314.7643	434.369
20	SASN	239.0356	89.18514	394.5195	722.7402	110.4351	12.39251	323.2459	446.0735
21	Sangrur	341.0008	127.2288	562.8095	1031.039	123.1952	13.82439	360.5951	497.6147
22	Tarn Taran	270.9612	101.0967	447.2116	**819.2696**	127.6442	14.32363	373.6173	**515.5852**

On average, the cost reduction of fertilizers for rice and wheat residue on-field composting would be Rs. 833.10/acre and Rs. 474.93/acre, respectively. It is analyzed that inorganic fertilizers cost reduction using non- subsidized price is 57% more for rice residues and 50 % more for wheat residues if compared with inorganic fertilizer cost reduction using subsidized price (Table 37). Thus, if the Punjab government removes subsidies on inorganic fertilizers in future, the farmers would benefit even more if on-field composting is used as a crop residue management method.

B. Revenue based on the increase in crop yield - Table 23 shows the increase in crop yield, and Table 30 shows the Minimum Support Price of crops, which are used to assess farmers' revenue based on increased crop yields by using crop residue compost as organic fertilizer in fields.

Revenue based on increase in crop yield (Rs) = Increase in crop yield × MSP of crop(Rs)

For Ferozepur district,

Revenue generated on the increase in rice yield in 2020 (Rs) = 0.0686 t/acre ×1815 (Rs/quintal) = Rs 1245/acre

Similarly, it is assessed for all districts of Punjab as shown in Table 39.

Table 39 – Revenue generated per acre by increased yield of crops by using crop residue compost fertilizer (Rs/acre)

No.	District	Rice (Rs/acre)			Wheat (Rs/acre)		
		2020	2021	2022	2020	2021	2022
1	Amritsar	1527.686	1690.409	1891.945	2898.512	3368.935	3262.637
2	Barnala	2134.131	2625.463	2522.164	3359.203	3433.998	3348.459
3	Bathinda	1976.733	2338.915	2429.193	3467.977	3541.631	3250.312
4	Faridkot	1740.636	2066.321	2287.653	3563.954	3628.491	3371.448
5	Fatehgarh S.	1972.104	2391.024	2491.981	2815.332	3493.222	2569.797
6	Fazilka	1879.517	1679.87	1663.639	3154.452	3377.364	3149.484
7	Ferozepur	1245.296	2158.082	2318.398	3276.023	3512.333	3221.068
8	Gurdaspur	1694.343	1963.265	2028.553	2668.167	3198.545	3094.32
9	Hoshiarpur	1851.741	2102.113	2012.897	2744.949	2948.99	2671.558
10	Jalandhar	1884.146	2290.031	2267.653	3218.436	3487.788	3118.547
11	Kapurthala	1911.922	2191.776	2231.535	2975.294	3283.497	2947.39
12	Ludhiana	2166.537	2470.335	2546.652	3263.226	3537.514	3162.898
13	Mansa	1902.664	2391.286	2417.775	3448.782	3553.143	3278.067
14	Moga	2110.985	2461.968	2506.519	3423.188	3669.152	3234.203
15	SMS	1550.833	2177.893	2210.834	3493.571	3609.434	3336.363
16	SBSN	1935.069	2202.806	2380.702	3250.429	3516.742	2886.555
17	Pathankot	1421.211	1840.735	1857.247	2527.4	3055.394	3370.327
18	Patiala	1828.594	2248.312	2279.768	3052.076	3519.728	2893.503

19	Rupanagar	1666.567	2237.807	2229.599	2770.543	3194.039	2692.084
20	SASN	1675.826	1847.715	1857.703	2892.114	3112.373	2745.522
21	Sangrur	2180.425	2647.523	2652.26	3691.924	3764	3088.103
22	Tarn Taran	1777.671	2073.487	2105.04	2911.309	3337.189	3152.816
Average		1819.756	2186.233	2235.896	3130.312	3415.614	3083.885

Due to the high MSP of crops and increased crop yield, wheat crops generate more revenue per acre than rice crops. This revenue seems to increase yearly for most districts, but in year 2021 there is high revenue for wheat crops due to the high amount of surplus wheat residue produced this year in most of the districts of Punjab. Revenue related to yield increases yearly for rice crops. Sangrur has higher yield revenue for rice and wheat crops, except for wheat crops in the year 2022, for which Faridkot district shows a yield revenue of Rs. 3371.48/acre.

C. Sand - It can be used as filler for various purposes, such as fields, households and gardening, but it is not evaluated in terms of costs.

Adding revenues of these outputs of the on-field composting process from Table 37 and Table 39, TOCR is assessed in Table 40.

Table 40– Total Output Composting Revenue (TOCR) per acre (Rs/acre)

Sr.no.	**District**	**Rice**			**Wheat**		
		2020	**2021**	**2022**	**2020**	**2021**	**2022**
1	Amritsar	1702.856	1877.946	2208.275	3051.441	3531.575	3530.334
2	Barnala	2378.301	2918.577	2939.058	3536.511	3598.012	3623.365

3	Bathinda	2203.03	2599.336	2832.861	3650.805	3710.8	3515.251
4	Faridkot	1939.918	2296.774	2669.546	3751.878	3801.62	**3646.769**
5	Fatehgarh S.	2197.746	2657.864	2906.542	2963.809	3662.59	2774.166
6	Fazilka	2094.649	1863.617	1939.361	3320.882	3539.33	3406.605
7	Ferozepur	1388.077	2403.059	2705.224	3448.716	3680.754	3483.861
8	Gurdaspur	1888.444	2181.781	2366.139	2808.983	3353.123	3348.027
9	Hoshiarpur	2063.82	2335.438	2346.173	2889.671	3090.518	2889.266
10	Jalandhar	2100.164	2545.56	2643.26	3388.135	3655.193	3372.457
11	Kapurthala	2131.071	2435.509	2602.214	3132.254	3441.283	3187.294
12	Ludhiana	2414.44	2744.737	2969.737	3435.324	3707.26	3419.891
13	Mansa	2120.535	2658.573	2819.404	3630.727	3722.722	3545.699
14	Moga	2352.942	2735.76	2922.769	3603.799	3844.941	3497.091
15	SMS	1728.589	2422.859	2577.724	3677.748	3781.952	3608.406
16	SBSN	2156.868	2447.68	2777.365	3421.782	3685.536	3119.074
17	Pathankot	1584.057	2046.842	2165.97	2660.692	3203.397	3590.028
18	Patiala	2037.966	2499.419	2658.654	3213.012	3689.551	3127.003
19	Rupanagar	1857.438	2488.554	2599.809	2916.77	3348.157	2909.401
20	SASN	1867.794	2052.411	2165.972	3044.64	3261.667	2968.695
21	Sangrur	**2430.296**	**2943.086**	**3092.026**	**3886.507**	**3943.81**	3337.062
22	Tarn Taran	1981.394	2304.293	2454.48	3064.776	3497.916	3410.766
Average		1940.017	2324.334	2606.972	3152.124	3423.987	3313.504

Sangrur district has high TOCR for rice residues for all three years and wheat residues in 2020 and 2021. For 2022, the Faridkot district has a high TOCR with Rs. 3646.769, and Fatehgarh Sahib has the lowest with Rs. 2774.166 per acre. There is an increase in TOCR every year for rice crops, and the year 2021 depicts a high TOCR in wheat crops.

TOCR is higher for wheat crops because of the increased revenue based on the yield of crops (high MSP) and the inorganic fertilizer cost reduction is less (due to less percent of nutrient present in wheat straw in comparison to rice straw).

Revenue generation by selling nutrient-rich compost to market –

Table 24 depicts the amount of compost produced by crop residues of rice and wheat crops per acre in 2021-22 at the market rate of Rs 40/kg is based on the website - https://rur.cleantech-mart.com/index.php/product/natural-compost-cost-rs-40-kg/. So, farmers have an option to sell compost in the market instead of using it in their fields.

Compost price per acre (Rs) = Amount of compost produced × Price of compost

For instance, the rice compost price for the Ferozepur district

= 0.128313 t/acre (Table 24) × Rs 40/kg = Rs 5132.5

Similarly, calculations are made for each district of Punjab in Table 41.

Table 41 – The revenue generated per acre by farmers by selling compost in the market for each district in the year 2021-22 (Rs/acre)

Sr.no.	Districts	Revenue (Rs/acre)	
		Rice	Wheat
1	Amritsar	4197.146	4103.621
2	Barnala	5531.452	4214.128
3	Bathinda	5355.965	4061.339
4	Faridkot	5067.04	4220.501
5	Fatehgarh S.	5500.507	3132.847
6	Fazilka	3658.352	3941.5
7	Ferozepur	5132.508	4028.449
8	Gurdaspur	4479.175	3889.175
9	Hoshiarpur	4421.986	3337.321
10	Jalandhar	4983.649	3892.269
11	Kapurthala	4918.26	3677.58
12	Ludhiana	5613.599	3939.536
13	Malerkotla	6123.919	3991.948
14	Mansa	5328.906	4102.631
15	Moga	5522.91	4029.897
16	SMS	4867.984	4170.243
17	SBSN	5263.021	3564.363
18	Pathankot	4096.212	3367.88

19	Patiala	5027.147	3579.404
20	Rupnagar	4912.042	3331.331
21	SASN	4090.179	3421.098
22	Sangrur	5834.924	3816.386
23	Tarn Taran	4636.464	3954.207
Average		5058.225	3885.855

On average, rice residue compost revenue is Rs. 5058.225, while wheat residue produces compost which costs Rs. 3885.855 per acre.

So, even if farmers do not want to use crop residue compost in their fields, they have the option to sell it in the market directly and earn revenue per acre. TOCR is found to be lower than a farmer's revenue per acre on selling nutrient-rich compost in the market.

But, if a farmer chooses to sell the compost in the market, the input costs of on-field composting will not be the same as studied earlier because input costs may include transporting costs, storage and maintenance costs to carry compost from the field to the market. Therefore, market revenue based assessment is not considered to assess the Net composting cost.

So, to calculate Net Composting Costs,

$$NCC = TICC - TOCR$$

Therefore, NCC is calculated using Table 36 and Table 40 and is shown in Table 42.

Table 42 – Net Composting Cost (NCC) per acre for rice and wheat crop residues

Sr.No.	Districts	Rice (Rs/acre)			Wheat (Rs/acre)		
		2020	2021	2022	2020	2021	2022
1	Amritsar	**9039.651**	**9136.293**	8377.545	**8516.834**	8595.799	7957.036
2	Barnala	8035.491	7786.03	8244.447	7695.361	8170.679	8434.427
3	Bathinda	7761.67	7647.309	7679.434	7146.893	7622.933	7870.699
4	Faridkot	8390.512	7908.63	7988.828	7429.517	7509.451	7897.884
5	Fatehgarh S.	7673.274	7658.78	8022.466	7707.174	7737.981	8997.263
6	Fazilka	7898.082	8349.225	8869.616	7493.391	7787.402	8308.68
7	Ferozepur	8976.656	8102.479	8001.466	7771.782	7918.878	8100.994
8	Gurdaspur	8461.622	8491.583	8832.173	8348.864	8413.384	8738.931
9	Hoshiarpur	8254.142	8377.928	8730.922	8231.445	8698.007	**9061.286**
10	Jalandhar	8826.261	8738.58	7886.469	8362.637	**8716.797**	8034.601
11	Kapurthala	7576.827	7722.785	7843.326	7386.323	7801.525	8130.437
12	Ludhiana	7561.339	7509.33	7749.317	7351.212	7627.047	8162.049
13	Mansa	7040.119	6791.668	7158.84	6366.027	6811.418	7308.277
14	Moga	8326.327	8291.335	7460.51	7898.178	8268.855	7754.452
15	SMS	8774.905	8429.393	8873.84	7681.401	8168.5	8732.432
16	SBSN	7485.653	7471.167	7432.57	7044.004	7327.825	7951.284
17	Pathankot	7953.946	7774.653	8284.488	7691.11	7710.63	7741.366
18	Patiala	7998.762	7822.497	7792.117	7642.629	7724.832	8190.437
19	Rupanagar	7277.924	6953.183	7168.225	7032.269	7171.293	7720.986

20	SASN	8481.382	8445.148	**8908.368**	8123.275	8330.126	8988.186
21	Sangrur	7666.542	7452.952	7526.368	7044.194	7530.823	8134.229
22	Tarn Taran	8052.811	8007.912	7907.261	7783.982	7907.642	7838.291
Average		7717.996	7602.994	7684.287	7293.413	7545.732	7828.445

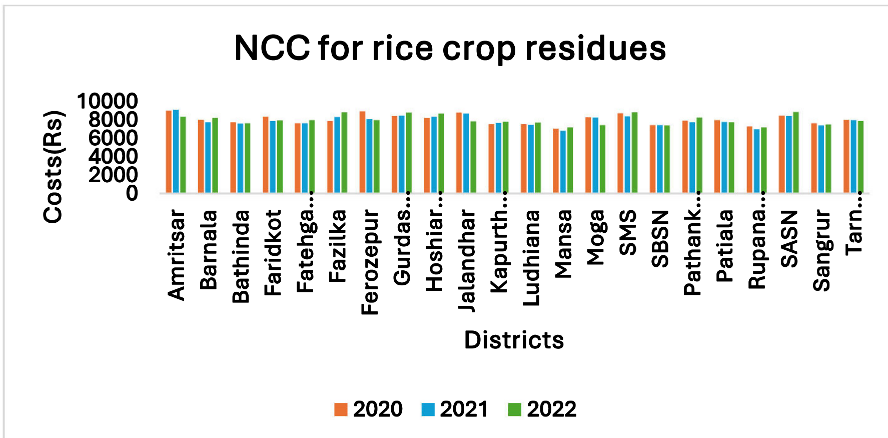


Figure 7 - The Total Cost of Composting rice crop residues for 3 years

<u>NCC for rice crop residues</u> – On an average basis, the NCC of rice residues is approximately the same for all years and the values remain between Rs 7600 – Rs 7800. The Amritsar district has high NCC in 2020 and 2021, while for 2022 year, SASN has high on-field composting costs (Rs.8908.368). Mansa district has the lowest NCC in all 3 years.

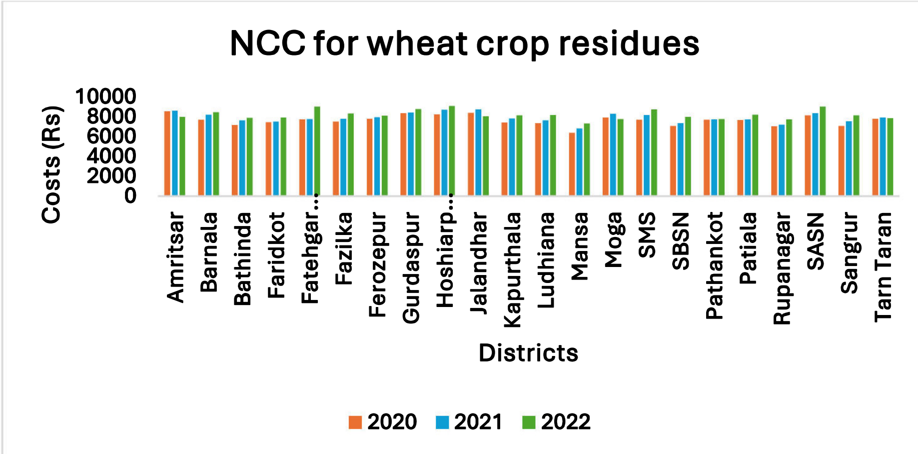


Figure 8 - The Total Cost of Composting wheat crop residues for 3 years

<u>NCC for wheat crop residues</u> - Meanwhile, 17 (more than half) districts of Punjab have high on-field composting costs for wheat residues in 2022, with the Hoshiarpur district being the highest, with Rs. 9061.286. The Amritsar district in 2020 and Jalandhar district in the 2021 year have high on-field composting costs of Rs. 8516.834 and Rs. 8716.797, respectively. Mansa district has the lowest on-field composting cost for wheat residues for all three years. The average values of NCC increase with the upcoming year and these values range between Rs 7200 – Rs 7850.

The difference in NCC of rice and wheat crop residues is due to the amount of surplus residue produced by them, as it directly or indirectly affects the input and output costs of these crop residues. Moreover, the values of the MSP of crops and the recommended amount of inorganic fertilizers differ for both crops which makes a huge difference in the Net Composting Costs of both crop residues. NCC differs within districts due to prevailing labor wages, and different amounts of the surplus residue produced by crops within districts of Punjab. Even nutrient-rich compost prices differ in districts, and this is due to the compost produced by different amounts of surplus crop residues generated.

What if, in a scenario, a farmer sells the compost made up of these crop residues into the market instead of using it in the field? Outputs such as cost reduction of fertilizers and an increase in crop yield would not be achieved. However, the farmers would generate more revenue from selling the compost in the market (depending on the market demand). However, the positive effects, such as enrichment and improving soil's physical, biological, and chemical properties of soil, would not be achieved. Moreover, selling compost into the market would depend on the demand for compost and would include other inputs than those mentioned above in TICC, such as transport, storage and maintenance of compost.

4.5.2 Net Burning Costs (NBC)

The Net Burning Costs are assessed by adding the inputs to the crop residue burning process and subtracting the total outcomes of burning crop residues.

Net Burning Costs = Total Input Burning Costs(TIBC) – Total Outcome Burning Costs(TOBC)

$$NBC = TIBC - TOBC$$

4.5.2.1 Total Outcome Burning Costs (TOBC)

Total Outcome Burning Cost (TOBC) = Nutrient loss + Collateral damage

TOBC could not be evaluated in terms of costs but it can make a huge difference as an outcome of the burning method, if all the required data could be available.

$$\text{So,} \qquad NBC = TIBC - TOBC$$

As the total outcomes of the burning process are not evaluated in terms of cost.

$$\text{So, } NBC = TIBC$$

4.5.2.2 Total Input Burning Costs (TIBC)

Total Input Burning Costs (TIBC) = Labor cost + Recommended inorganic fertilizer cost + Farm machinery cost + Farm tool cost + Penalty cost related to crop residue burning

A. Labor cost—Only one labor is expected to be required per acre for burning crop residues so the labor costs are the same as the labor wage per day in all districts of Punjab.

For burning method,

Labor cost/acre (Rs) = Labor wage/day in a district (Rs)

Table 43 shows labor cost per acre in the district of Punjab.

Table 43 – The labor cost of burning rice and wheat crop residues per acre in different districts

No.	Districts	(2019-20) Labor wage (Rs/day)	(2020-21) Labor wage (Rs/day)	(2021-22) Labor wage (Rs/day)
1	Amritsar	500	500	429.17
2	Barnala	455	455	500
3	Bathinda	400	400	416.67
4	Faridkot	447.27	396.67	435.83
5	Fatehgarh S.	388.33	408.33	468.29
6	Fazilka	404.17	400	458.33
7	Ferozepur	454.17	433.33	441.67
8	Gurdaspur	450	455.83	505
9	Hoshiarpur	445	460	490
10	Jalandhar	520.83	530	420
11	Kapurthala	368.33	390	409.67
12	Ludhiana	400	400	441.67

13	Mansa	300	300	350
14	Moga	488.33	496.67	400
15	SMS	470	476.67	535.57
16	SBSN	360	360	379.17
17	Pathankot	350	350	412.5
18	Patiala	410	410	410
19	Rupnagar	298.33	300	325
20	SASN	450	434.58	490.5
21	Sangrur	415	416.25	428.33
22	Tarn Taran	410	410	400
Average		417.489	417.424	433.971

The above table depicted that Rupanagar district has the lowest labor wage in all three years, with Rs. 298.33/day in 2019-20, Rs. 300/day in 2020-21 and Rs. 325/day in 2021-22. The variation in labor wages in districts over the years varies, as some districts show an increase in wages while others show a decline. In Patiala district, it remains constant. This cost is added as an input cost in the burning method of residue management, which is relatively low compared to the composting method's labour cost.

B. Recommended inorganic fertilizers cost – As per Table 34, the total cost of using the recommended fertilizer for rice crops per acre is Rs. 1541, Rs. 1811, and Rs. 1942 for 2019-20, 2020-21, and 2021-22, respectively (Package of Practices for the crops of Punjab, 2024). The total cost of using recommended inorganic fertilizer for wheat crops per acre is Rs. 2331.4, Rs. 2881.4, and Rs. 2816.4 for 2019-20, 2020-21, and 2021-22 respectively (Package of practices for crops of Punjab, 2023-24). The input costs of recommended inorganic fertilizers applied in the burning process of crop residues are the same as those required for composting crop residues. High amounts of inorganic fertilizers are recommended for wheat crops, raising their cost compared to rice crops.

C. Farm machinery cost – Custom Hiring Centers rent farm machinery to farmers to use it in their fields. The total cost related to renting farm machinery for burning of crop residues is given in Table 44.

Table 44 – Farm machinery costs of burning method and preparation of fields per acre (Rs/hour)

Rice crop residue burning (per hour basis)		**Wheat crop residue burning (per hour basis)**	
Farm machinery	**Cost (Rs/hour)**	**Farm machinery**	**Cost (Rs/hour)**
Straw reaper + tractor	700	Straw Chopper (trail type & combo)	250 (+ tractor cost)
Disc harrow + tractor	700	Disc harrow + tractor	700
Planker + tractor	300	Reaper + tractor	700
Cultivator + tractor	650	Cultivator + tractor	650
Rotavator + tractor	1060	Rotavator + tractor	1060
Laser Leveler + tractor	575	Laser leveler + tractor	575
Tractor	-	Tractor	223.33
Total	**3985**	Total	**4158.33**

(Singh S., 2017), (Singh et al., 2015)

The farm machinery related cost per hour after rice and wheat residue burning is Rs. 3985 and Rs. 4158.33, respectively. These costs are subsidized rates under the cooperative societies of Punjab (Custom Hiring Centers—CHC). The farm machinery costs are less for rice crops because (Straw reaper + tractor) is used to cut stalks of crops from the ground after harvesting of rice crops. Farmers do not gain any revenue from chopping and collecting rice straw. They directly burn rice crops remains, so straw chopper is not required after rice crop harvesting. The straw chopper used in wheat crops does not include tractor-renting charges, so tractor-renting charges are added differently. Straw reaper is Rs. 300/acre or Rs. 700/hour, as it is used in 2.3 acres approx. in one hour.

D. Farm tool cost– The cost of one Rake is Rs. 250, which is added to the total input cost of burning.

E. Penalty cost – The legal penalty depends on the number of acres a farmer burns to manage crop residues. So, to assess TIBC Rs. 2500 per acre is used as penalty cost. However, the legal penalty varies with the acres burnt as it is shown in Table 45.

Table 45 – Penalty cost on burning crop residues by Punjab government

Land size under burning process	**Legal Penalty (Rs)**
Up to 2 acres	2500
2 -5 acres	5000
Up to 10 acres	7000
Above 10 acres	15000

(Singh & Zaffar, 2017)

TIBC or NBC per acre is assessed by adding input costs related to burning and is shown in Table 46.

Table 46 – Net Burning Costs (NBC) per acre (Rs/acre)

Sr.no.	Districts	Rice			Wheat		
		2020	**2021**	**2022**	**2020**	**2021**	**2022**
1	Amritsar	8776	9046	9106.17	9739.73	10289.73	10153.9
2	Barnala	8731	9001	9177	9694.73	10244.73	10224.73
3	Bathinda	8676	8946	9093.67	9639.73	10189.73	10141.4
4	Faridkot	8723.27	8942.67	9112.83	9687	10186.4	10160.56
5	Fatehgarh S.	8664.33	8954.33	9145.29	9628.06	10198.06	10193.02
6	Fazilka	8680.17	8946	9135.33	9643.9	10189.73	10183.06
7	Ferozepur	8730.17	8979.33	9118.67	9693.9	10223.06	10166.4
8	Gurdaspur	8726	9001.83	9182	9689.73	10245.56	10229.73
9	Hoshiarpur	8721	9006	9167	9684.73	10249.73	10214.73
10	Jalandhar	**8796.83**	**9076**	9097	**9760.56**	**10319.73**	10144.73
11	Kapurthala	8644.33	8936	9086.67	9608.06	10179.73	10134.4
12	Ludhiana	8676	8946	9118.67	9639.73	10189.73	10166.4
13	Malerkotla	8276	8546	8677	9239.73	9789.73	9724.73
14	Mansa	8576	8846	9027	9539.73	10089.73	10074.73
15	Moga	8764.33	9042.67	9077	9728.06	10286.4	10124.73
16	SMS	8746	9022.67	**9212.57**	9709.73	10266.4	**10260.3**
17	SBSN	8636	8906	9056.17	9599.73	10149.73	10103.9
18	Pathankot	8626	8896	9089.5	9589.73	10139.73	10137.23

19	Patiala	8686	8956	9087	9649.73	10199.73	10134.73
20	Rupanagar	8574.33	8846	9002	9538.06	10089.73	10049.73
21	SASN	8726	8980.58	9167.5	9689.73	10224.31	10215.23
22	Sangrur	8691	8962.25	9105.33	9654.73	10205.98	10153.06
23	Tarn Taran	8686	8956	9077	9649.73	10199.73	10124.73
Average		8675.337	8945.275	9092.103	9639.067	10189.01	10139.83

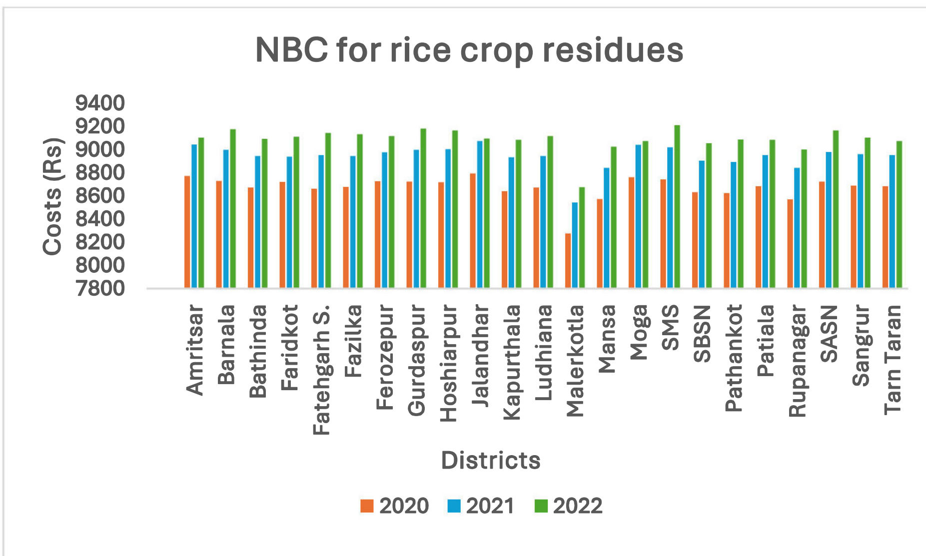


Figure 9 – The net cost related to burning rice crop residues over 3 years

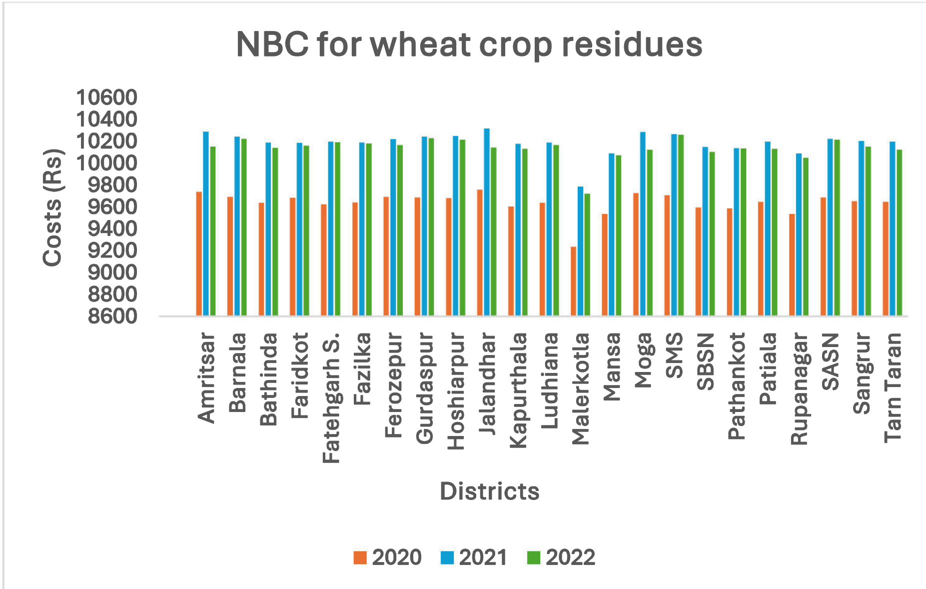


Figure 10 – The net cost related to burning wheat crop residues over 3 years

The costs of burning rice crop residues are lowest in all districts of Punjab for the year 2019-20 and increased for the next two years. On the other hand, burning costs for wheat crop residues are high in 2021 and the lowest in 2020. This trend is due to the significant impact of the change in total inorganic fertilizer costs of rice and wheat crops, as inorganic fertilizer costs keep increasing from 2020 to 2022 in the case of rice crops and highest in 2021 for wheat crops. Sri Muktsar Sahib district has the highest burning cost of rice and wheat crop residues in 2022 followed by Gurdaspur district, while this cost is high in Jalandhar district for 2021 and 2020. Within districts, the variation in burning costs is due to the prevailing labor wages. NBC is high for wheat crop residues in comparison to rice crop residues as farm machinery cost is high for managing wheat crop residues, and more amount of inorganic fertilizer is recommended for wheat crops, making it more cost driven.

4.5.3 Comparison between on-field composting and on-field burning costs per acre

4.5.3.1 Net Composting Costs vs Net Burning Costs of rice crop residues

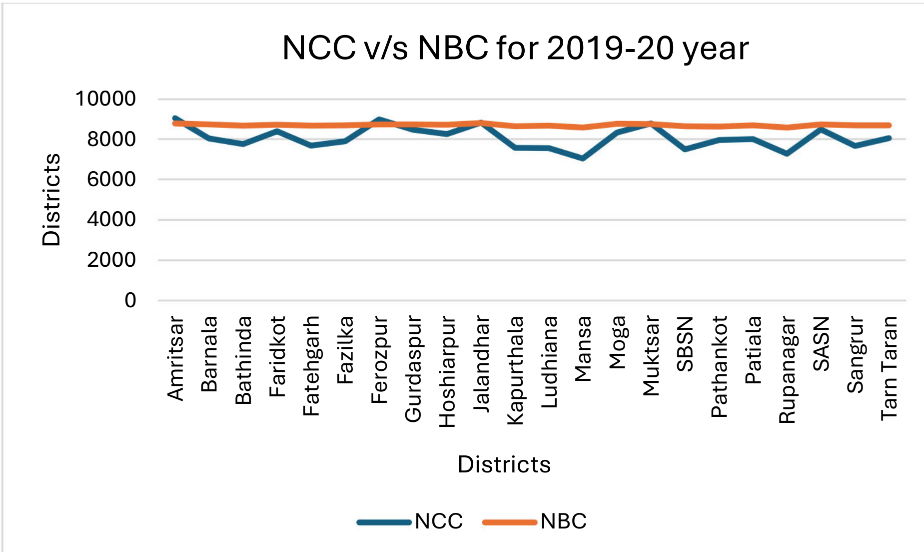


Figure 11 – Net costs of on-field composting v/s on-field burning of rice crop residues in the year 2019-20

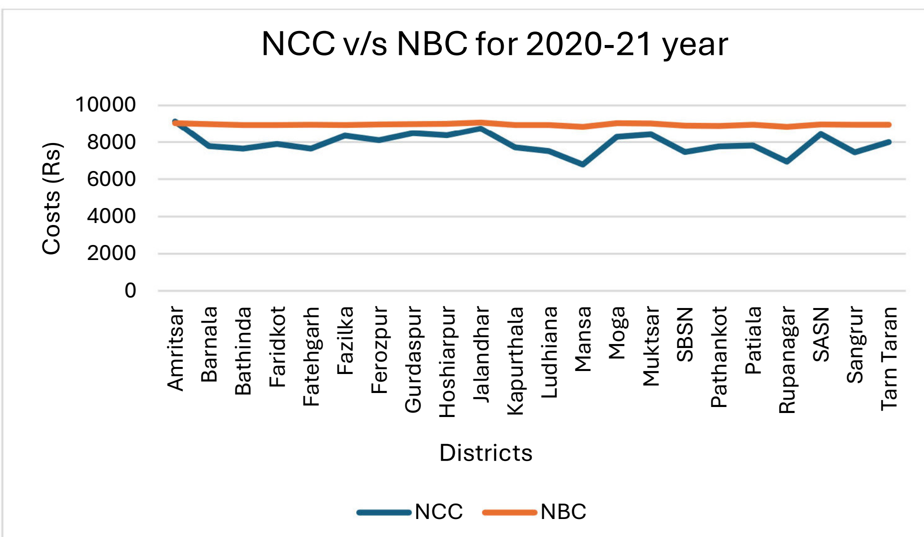


Figure 12- Net Costs of on-field composting v/s on-field burning of rice crop residues in the year 2020-21

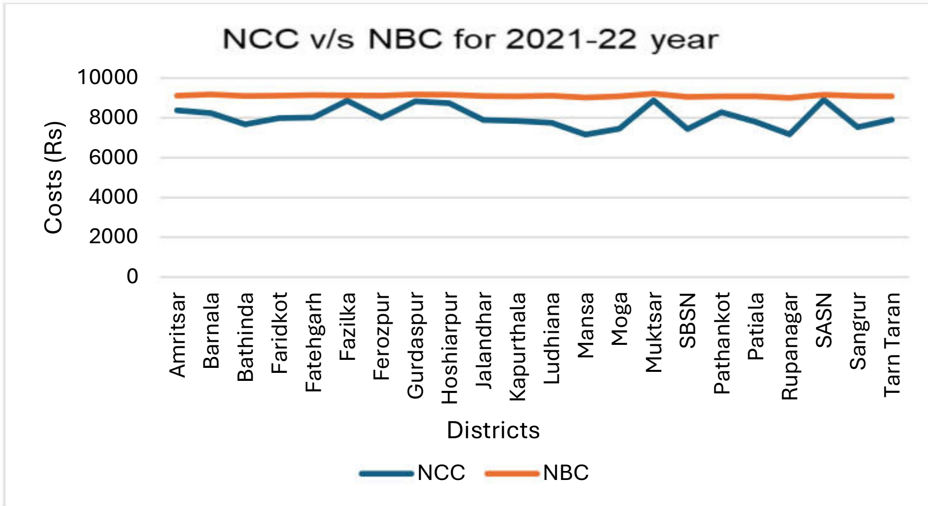


Figure 13 – Net Costs of on-field composting v/s on-field burning of rice crop residues in the year 2021-22

For rice residues, burning costs remained almost the same or with minor differences in each district for all years, and this constant value of burning costs increased each year. Only labor wages affected the overall burning costs of rice residues within districts to some extent. However, the on-field composting costs were quite different for each district. They reflected different labor wages and surplus crop residues produced in each district.

The on-field composting costs are higher than the burning costs for the Amritsar district for both 2020 and 2021, while Ferozepur, Jalandhar and SMS have higher compost costs than burning costs only in 2020. The rest of the districts of Punjab have on-field composting costs lower than burning costs for residue management.

4.5.3.2 Net Composting Costs vs Net Burning Costs of wheat crop residues

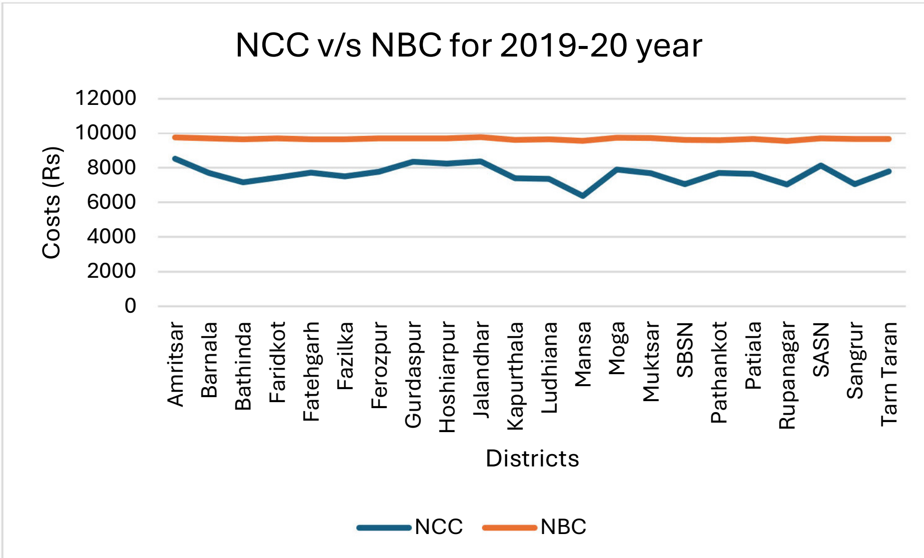


Figure 14- Net Costs of on-field composting v/s on-field burning of wheat crop residues in the year 2019-20

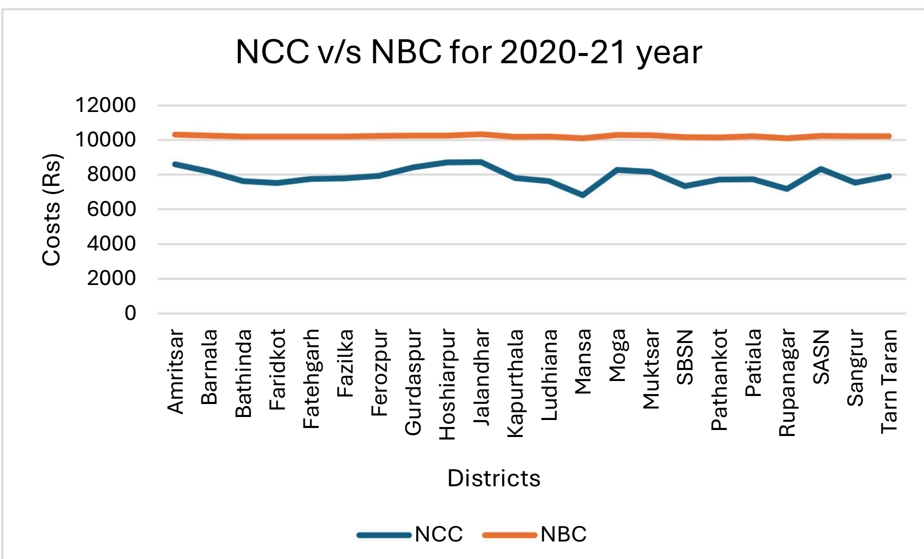


Figure 15 – Net Costs of on-field composting v/s on-field burning of wheat crop residues in the year 2020-21

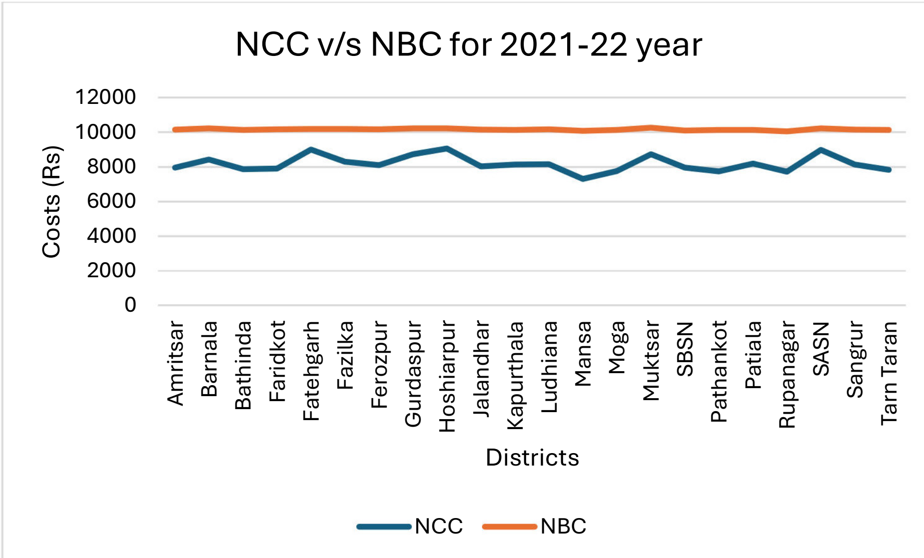


Figure 16 – Net Costs of on-field composting v/s on-field burning of wheat crop residues in the year 2021-22

The above figures depict that the cost of on-field composting wheat crop residues is lower than the burning method of wheat crop residue management in all three years. The burning costs of wheat crop residues have a minor difference over the years, but the on-field composting costs are low for the 2020-21 year due to high surplus residue this year.

4.5.3.3 Cost savings by the on-field composting of crop residues

Cost savings are the savings that farmers of different districts of Punjab can make by substituting crop residue burning with the on-field composting method for crop residue management.

$$\text{Cost Savings} = \text{Net Burning Costs} - \text{Net composting cost}$$

$$\text{Cost Savings} = \text{NBC} - \text{NCC}$$

The cost savings are shown in Table 47.

Table 47 – Cost Savings per acre by substituting crop residue burning (with penalty) method with on-field composting method

Sr.No.	Districts	Rice (Rs/acre)			Wheat (Rs/acre)		
		2020	2021	2022	2020	2021	2022
1	Amritsar	-263.651	-90.2925	728.6249	1222.896	1693.931	2196.864
2	Barnala	695.5089	1214.97	932.5535	1999.369	2074.051	1790.303
3	Bathinda	914.3296	1298.691	1414.236	2492.837	2566.797	2270.701
4	Faridkot	332.7583	1034.04	1124.002	2257.483	2676.949	2262.676
5	Fatehgarh S.	991.0556	1295.55	1122.824	1920.886	2460.079	1195.757
6	Fazilka	782.0876	596.775	265.7137	2150.509	2402.328	1874.38
7	Ferozepur	-246.486	876.8514	1117.204	1922.118	2304.182	2065.406
8	Gurdaspur	264.378	510.2467	349.8275	1340.866	1832.176	1490.799
9	Hoshiarpur	466.8584	628.072	436.0784	1453.285	1551.723	1153.444
10	Jalandhar	-29.4306	337.4201	1210.531	1397.923	1602.933	2110.129
11	Kapurthala	1067.503	1213.215	1243.344	2221.737	2378.205	2003.963
12	Ludhiana	1114.661	1436.67	1369.353	2288.518	2562.683	2004.351
13	Mansa	1535.881	2054.332	1868.16	3173.703	3278.312	2766.453
14	Moga	438.0027	751.3353	1616.49	1829.882	2017.545	2370.278
15	SMS	-28.9053	593.2768	338.7305	2028.329	2097.9	1527.868
16	SBSN	1150.347	1434.833	1623.6	2555.726	2821.905	2152.616
17	Pathankot	672.0542	1121.347	805.0116	1898.62	2429.1	2395.864
18	Patiala	687.238	1133.503	1294.883	2007.101	2474.898	1944.293
19	Rupanagar	1296.406	1892.817	1833.775	2505.791	2918.437	2328.744

20	SASN	244.618	535.4323	259.1317	1566.455	1894.184	1227.044
21	Sangrur	1024.458	1509.298	1578.962	2610.536	2675.157	2018.831
22	Tarn Taran	633.1893	948.0878	1169.739	1865.748	2292.088	2286.439
Average		624.6756	1014.84	1077.399	2032.287	2318.435	1974.418

The cost difference between implementing on-field composting and burning methods for rice residue management in Punjab is significant, with an average of Rs. 624.6756 in 2019-20 and increased by 38.44 % to Rs. 1014.84 in 2020-21 and further increased by 5.8% to Rs.1077.399 in 2021-22. The cost difference for wheat residues was even higher than rice residues, with Rs. 2032.287 in 2019-20, Rs. 2318.435 in 2020-21, and Rs. 1974.418 in 2021-22. These figures demonstrate the potential savings per acre achieved by adopting the on-field composting method over burning for crop residue management. In all three years, Mansa district has the highest cost difference of Rs. 1535.881 in 2021-22, Rs 2054.332 in 2020-21, Rs. 1868.16 in 2019-20 for rice management, and Rs. 3173.703 for 2021-22, Rs. 3278.312 for 2020-21 and Rs. 2766.453 for 2019-20 for wheat management.

However, Amritsar district has a negative cost difference (composting cost is high) in 2020 for rice, which is Rs. -263.651 and Rs.1222.896 for wheat crop residue management. In 2021, Amritsar (Rs -90.295) and Hoshiarpur (Rs. 1551.723) have the lowest compost savings for rice and wheat crop residue management respectively. SASN and Hoshiarpur districts have the lowest cost savings in the year 2022 of Rs. 259.1317 and Rs. 1153.444 for rice and wheat residue management, respectively. Within three years, 11 districts out of 22 districts (50%) show an increasing pattern of cost difference in rice crop residue management from 2020 to 2022. While in wheat crop residue management, in most districts, 2021 year has the highest cost savings on composting, followed by 2020, and the least in 2022.

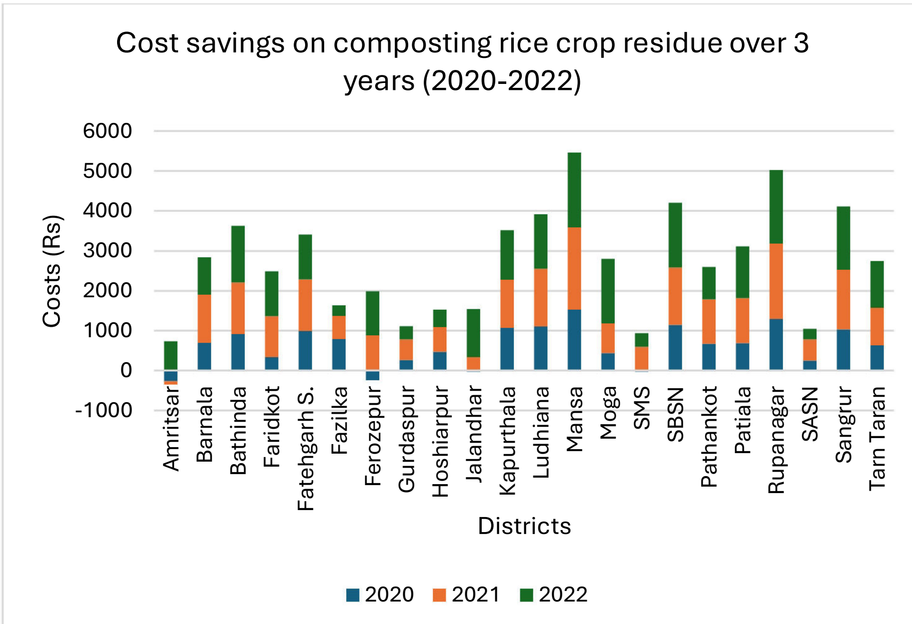


Figure 17 – Total cost savings on composting rice crop residues per acre over 3 years (Rs/acre)

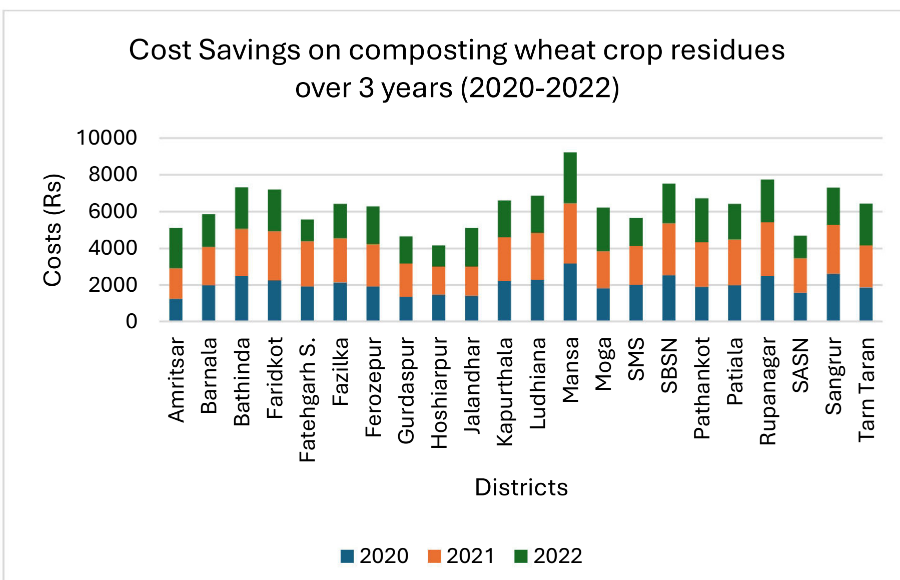


Figure 18 - Total cost savings on composting wheat crop residues per acre over 3 years (Rs/acre)

Cost Savings on composting crop residues (without Penalty) –

As farmers who burn crop residues are at risk of Penalty if regulatory agencies find it out and register a case against them. However, most of the farmers take this risk as regulatory agencies do not have enough resources to enforce the regulations.

Therefore, without adding a penalty as an input cost, the cost savings on composting crop residues are shown in Table 48.

Table 48 – Cost Savings per acre by substituting crop residue burning (without penalty) with on-field composting method

Sr.No.	**Districts**	**Rice**			**Wheat**		
		2020	**2021**	**2022**	**2020**	**2021**	**2022**
1	Amritsar	**-2763.65**	-2590.29	-1771.38	-1277.1	-806.069	-303.136
2	Barnala	**-1804.49**	-1285.03	-1567.45	-500.631	-425.949	-709.697
3	Bathinda	**-1585.67**	-1201.31	-1085.76	-7.16276	66.79742	-229.299
4	Faridkot	**-2167.24**	-1465.96	-1376	-242.517	176.9492	-237.324
5	Fatehgarh S.	-1508.94	-1204.45	-1377.18	-579.114	-39.9206	-1304.24
6	Fazilka	**-1717.91**	-1903.22	-2234.29	-349.491	-97.6716	-625.62
7	Ferozepur	**-2746.49**	-1623.15	-1382.8	-577.882	-195.818	-434.594
8	Gurdaspur	**-2235.62**	-1989.75	-2150.17	-1159.13	-667.824	-1009.2
9	Hoshiarpur	**-2033.14**	-1871.93	-2063.92	-1046.72	-948.277	-1346.56
10	Jalandhar	**-2529.43**	-2162.58	-1289.47	-1102.08	-897.067	-389.871
11	Kapurthala	-1432.5	-1286.79	-1256.66	-278.263	-121.795	-496.037
12	Ludhiana	-1385.34	-1063.33	-1130.65	-211.482	62.68305	-495.649

13	Mansa	-964.119	-445.668	-631.84	673.7028	778.3122	266.4527
14	Moga	**-2062**	-1748.66	-883.51	-670.118	-482.455	-129.722
15	SMS	**-2528.91**	-1906.72	-2161.27	-471.671	-402.1	-972.132
16	SBSN	-1349.65	-1065.17	-876.4	55.72563	321.9051	-347.384
17	Pathankot	**-1827.95**	-1378.65	-1694.99	-601.38	-70.9002	-104.136
18	Patiala	**-1812.76**	-1366.5	-1205.12	-492.899	-25.1024	-555.707
19	Rupanagar	-1203.59	-607.183	-666.225	5.790546	418.4365	-171.256
20	SASN	**-2255.38**	-1964.57	-2240.87	-933.545	-605.816	-1272.96
21	Sangrur	-1475.54	-990.702	-921.038	110.5363	175.1568	-481.169
22	Tarn Taran	**-1866.81**	-1551.91	-1330.26	-634.252	-207.912	-213.561
Average		-1875.32	-1485.16	-1422.6	-467.713	-181.565	-525.582

If a penalty is not considered as an input of burning costs, the above table depicts the cost difference between the on-field composting and burning processes. For rice crop residues, all districts will have more composting costs than burning costs for all three years. Amritsar district shows the highest negative savings on composting for 2020 (Rs. -2763.65) and 2021(-2590.29), while the SASN district in the 2022 year (Rs -2240.87) (see Figure 19).

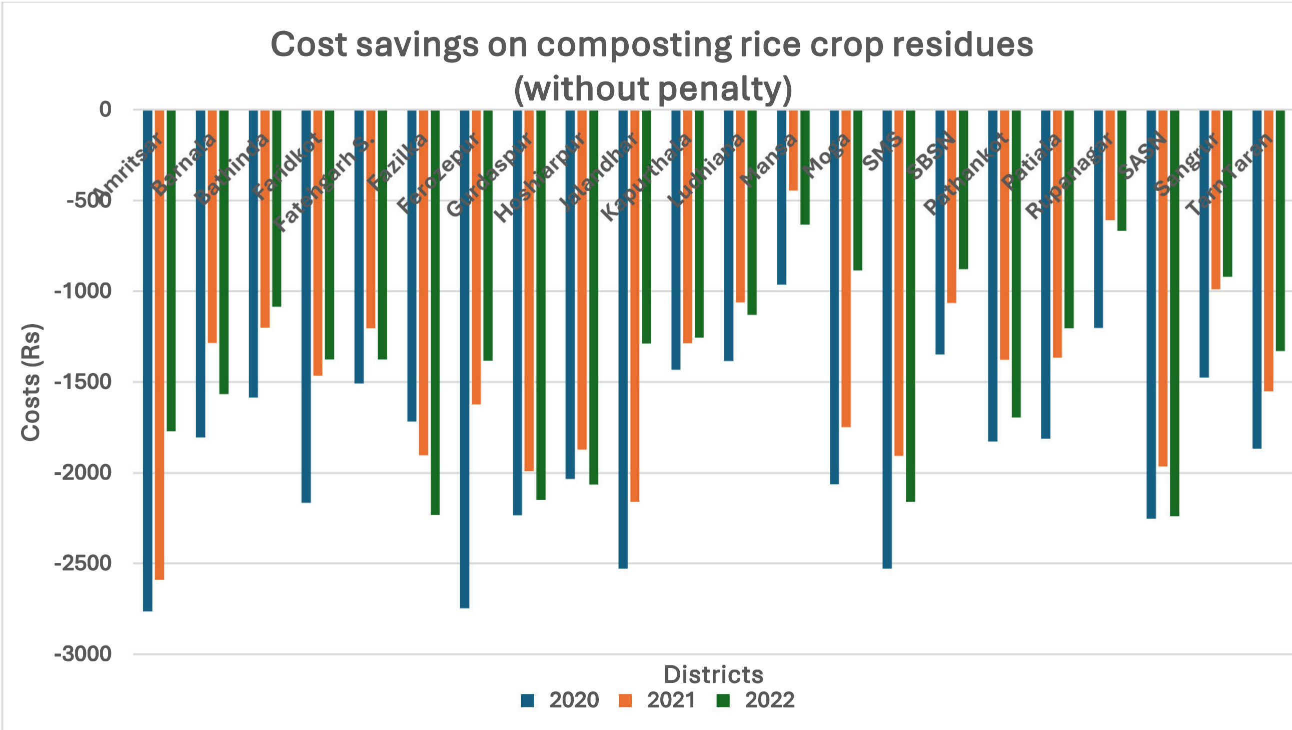


Figure 19 – Cost Savings on composting rice crop residues (without penalty)

Cost savings per acre on composting crop residues are less negative for wheat crop residues, as the cost difference is still positive for Mansa district for all three years, and SBSN, Rupanagar and Sangrur district still shows positive savings in 2020 and 2021 years, even if penalty input cost is excluded from Net Burning Cost (NBC). Bathinda, Faridkot, and Ludhiana districts have positive cost savings only in the 2021 year. On average, 2021 has the highest savings or least expenditures for composting wheat residues, followed by 2020 and 2022 year (see Figure 20).

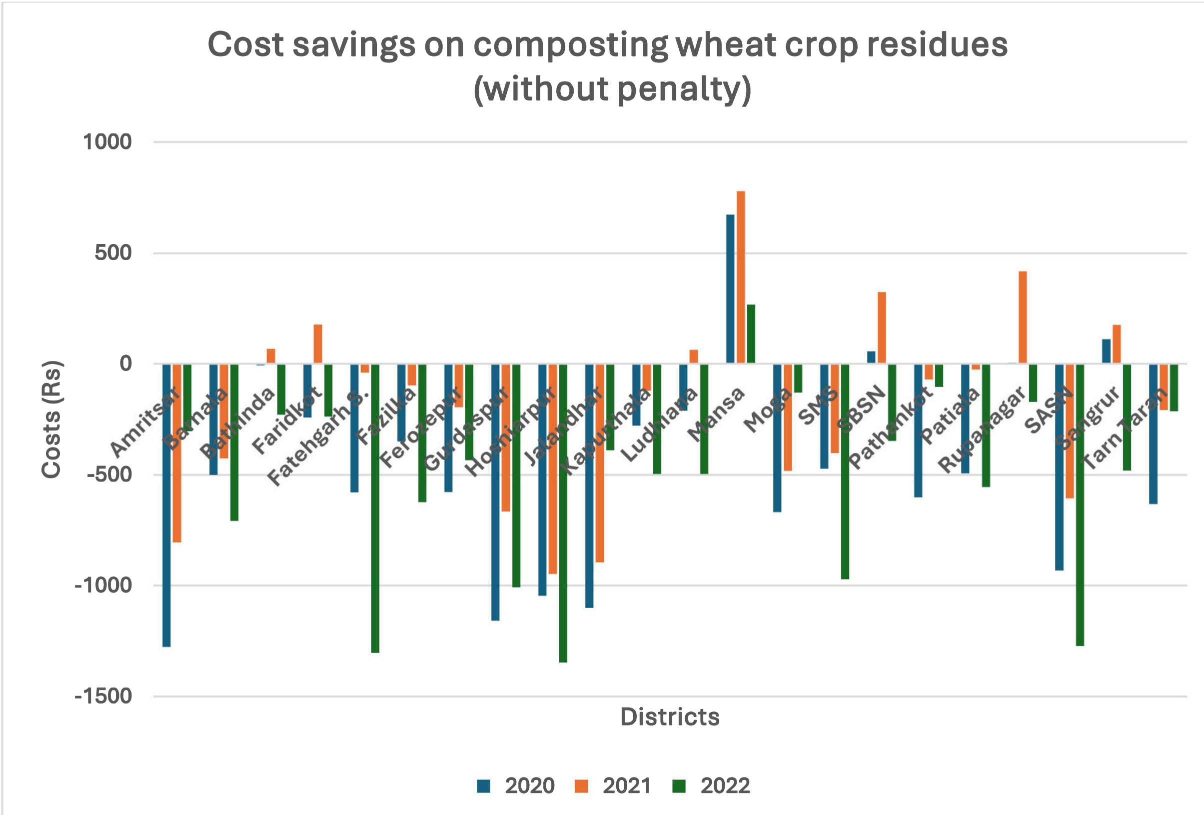


Figure 20- Cost Savings per acre on composting wheat crop residues (without penalty)

4.5.4 The Effect of farmer’s landholding size on the On-field composting costs /acre

On further studying the on-field composting costs for four on-field composting models. Farmers with one acre, four acres, eight acres, and sixteen acres may not have the same on-field composting costs per acre. Labor and machinery costs influence farmers' on-field composting costs per acre. The equations are developed using the percentage of labor hired and machinery rented by different categories of farmers based on the size of land owned by them.

1) **For the on-field one-acre model–**

- **Labor cost (Rs/acre) -**

As, 67.6 % of total farmers that do not have contract labors (99.4%), even do not hire casual labors, so the labor cost for this percent of farmers is zero. While 32.4 % of farmers who do not have contract labors (99.4%) do hire casual labors when needed, so these will hire the number of labors required in on-field composting process. The 0.40 % of total farmers have one contract labor, so they hire one labor less than the number required for the on-field composting process. The 0.20 % of total labors have 2 contract labors, so needed 2 labors less than the number required for the on-field composting process of residue management.

= [67.6% × 99.4% (× 0) + 32.4 % × 99.4% (xy)] + 0.40% ((x-1) y) + 0.20% ((x-2) y)

$$= 0 + \frac{3220.56}{10000} xy + \frac{0.60}{100} xy - \frac{0.8}{100} y$$

$$= \; y(32.8x - 0.8) * 10^{-2} \qquad \text{Equation 1}$$

Here, x = number of labors required per acre for on-field composting

y = labor wage/day prevailing in the district of Punjab

Equation 1 calculates the labor cost of an on-field composting process for farmers with one acre.

For instance, the labor cost per acre in the Patiala district in the year 2019-20, if eight labors are required is as -

Here, x = 8,

y = Rs. 500 (Table 32),

Using Equation 1,

Total labor cost per acre per crop is Rs. 1308.

- **Farm machinery cost (Rs/acre) –**

The farmers having one acre do not own tractors, so they need to rent farm implements along with tractors from hiring centers. So, the farm machinery cost will be the combined rent of farm implements + tractor, which is higher than the rent cost if a farmer would pay for renting only farm implements.

Fam machinery costs = (t+a) + (t+b) + (t+c)+ (t+d)+ (t+e)+……., Equation 2

where (t+a), (t+b), (t+c), (t+d), (t+e), …. etc., are the rent-out charges of various tractors and implements (rented together) used in on-field composting. This is the total rental cost of the tractor and associated implements, and it is higher than the rental costs if farm implements are rented without tractors.

For instance, the farm machinery cost per acre in Patiala district for a farmer with one acre in the year 2019-20 would be –

= (t+a), (t+b), (t+c), (t+d), (t+e) …….

= (Tractor + Straw chopper) + (Tractor + laser leveler) + (Tractor + disc harrow) + (Tractor + Reaper) + (Tractor + Cultivator) + (Tractor + Rotavator)

Using Farm machinery renting cost (Table 35),

= 250 + 575 +700 + 700 + 650 + 1060 + 223.33 = Rs. 4158.33 hr^{-1} per acre

2) **For on-field four-acre model -**

- **Labor cost (Rs/acre) –**

As, 38.32 % of total farmers that do not have contract labors (92.5%), even do not hire casual labors, so the labor cost for this percent of farmers is zero. While 61.68 % of farmers that do not have contract labors (92.5%) do hire casual labors in the on-field composting process. The 6.51 percent of total farmers have one contract labor, so they hire one labor less than the number required for the on-field composting process. 0.36 % of total labors have 2 contract labors, so needed 2 labors less than the number required for the on-field composting process of crop residue management. Similarly, 0.18% of farmers owning 4 acres have 3 contract labors, so does hire 3 labors less than the number of labors required for on-field composting.

$$= [38.32\% \times 92.5\% (\times 0) + 61.68\,\% \times 92.5\% (xy)] + 6.51\% ((x\text{-}1)\,y) + 0.36\% ((x\text{-}2)\,y) + 0.18\% ((x\text{-}3)\,y)$$

$$= 0 + \frac{57.054}{100}xy + \frac{6.51}{100}xy - \frac{6.51}{100}y + \frac{0.36}{100}xy - \frac{0.72}{100}y + \frac{0.18}{100}xy - \frac{0.54}{100}y$$

$$= y(64.104x - 7.77) * 10^{-2} \qquad \text{Equation 3}$$

Here, x = number of labors required per acre for on-field composting

y = labor wage/day prevailing in the district of Punjab

For instance, in Patiala district in the year 2019-20, if eight labors are required per acre, then a farmer with 4 acres would have a labor cost/acre is as follows -

Here, x = 8

y = Rs.500, (Table 32), using Equation 3, Total labor cost per acre per crop is Rs. 2525.31

- **Farm machinery cost (Rs/acre) –**

65.21% of total farmers having four acres do not own tractors, so they need to rent farm implements along with tractors from hiring centers. So, the farm machinery cost will be combined rent of farm implement + tractor, which is higher than a farmer's rental cost for renting only farm implements. While 34.79% of farmers having 4 acres own tractors, they rent farm implements without tractors.

$$= \frac{65.21}{100}\big((\mathrm{t}+\mathrm{a}) + (\mathrm{t}+\mathrm{b}) + (\mathrm{t}+\mathrm{c}) + (\mathrm{t}+\mathrm{d}) + (\mathrm{t}+\mathrm{e}) + \cdots\big) + \frac{34.79}{100}(a+b+c+d+e+\cdots) \qquad \text{Equation 4}$$

where (t+a), (t+b), (t+c), (t+d), (t+e), …. etc., are the hire-out charges of various tractors and implements (hired together) used in composting, t = tractor hire-out charges, and a, b, c, d, e = hire-out charges of various farm implements.

For instance, the farm machinery cost/acre in Patiala district for a farmer with four acres in the year 2019-20 would be –

$$= \frac{65.22}{100}\big((\text{Tractor + Straw chopper}) + (\text{Tractor + laser leveler}) + (\text{Tractor + disc harrow}) + (\text{Tractor + Reaper}) + (\text{Tractor + Cultivator}) + (\text{Tractor + Rotavator})\big) + \frac{34.78}{100}(\text{Straw chopper} + \text{laser leveler} + \text{disc harrow} + \text{Reaper} + \text{Cultivator} + \text{Rotavator})$$

Using values from Table 35 and Table 11,

$$= \frac{65.22}{100}(4158.33) + \frac{34.78}{100}(250 + 351.67 + 50 + 150 + 62.5 + 250)$$

= 2712.06 + 387.50

= Rs 3099.56 hr^{-1} per acre

3) **For the on-field eight-acre model_-**

   - **Labor cost (Rs/acre) –**

As, 56.16 % of total farmers that do not have contract labors (78.68%), even do not hire casual labors, so the labor cost for this percent of farmers is zero. While 43.84 % of farmers that do not have contract labors (78.68%) do hire casual labors when needed. The 20.62 % of total farmers have one contract labor, so they hire one labor less than the number required for the on-field composting process. The 0.35 % of total labors have 2 contract labors, so they need 2 labors less than the number required for the composting process of crop residue management. Similarly, 0.35% of farmers owning 4 acres have 3 contract labors, so does hire 3 labors less than the number of labors required for on-field composting process.

$$= [56.16\% \times 78.68\% (\times 0) + 43.84\% \times 78.68\% (xy)] + 20.62\% ((x\text{-}1)y) + 0.35\% ((x\text{-}2)y) + 0.35\% ((x\text{-}3)y)$$

$$= 0 + \frac{34.49}{100}xy + \frac{20.62}{100}xy - \frac{20.62}{100}y + \frac{0.35}{100}xy - \frac{0.7}{100}y + \frac{0.35}{100}xy - \frac{1.05}{100}y$$

$$= y(55.81x - 22.37) * 10^{-2} \qquad \text{Equation 5}$$

Here, x = number of labors required per acre for on-field composting

y = labor wage/day prevailing in the district of Punjab

For instance, in Patiala district in the year 2019-20, if eight labors are required per acre, then a farmer with 8 acres would have a labor cost/acre as follows -

Here, x = 8,

y = Rs. 500 (Table 32),

Using Equation 5,

Total labor cost per acre per crop is Rs. 2120.55.

- **Farm machinery cost (Rs/acre) -**

The 18 % of farmers having eight acres do not own tractors, so they need to rent farm machinery along with tractors from hiring centers. So, the farm machinery cost will be combined rent of farm implement + tractor, which is higher than the rent cost a farmer pay for renting only farm implements. While 82 % of farmers own tractors, they rent farm implements without tractors.

$$= \frac{18}{100}\left((\mathrm{t}+\mathrm{a})+(\mathrm{t}+\mathrm{b})+(\mathrm{t}+\mathrm{c})+(\mathrm{t}+\mathrm{d})+(\mathrm{t}+\mathrm{e})+\cdots\right)+\frac{82}{100}(a+b+c+d+e+\cdots) \qquad \text{Equation 6}$$

where (t+a), (t+b), (t+c), (t+d), (t+e), …. etc., are the hire-out charges of various tractors and implements (hired together) used in composting, t = tractor hire-out charges, and a, b, c, d, e = hire-out charges of various farm implements.

- For instance, the farm machinery cost/acre in Patiala district for a farmer with eight acres in the year 2019-20 is as–

$$= \frac{18}{100}\big((\text{Tractor + Straw chopper}) + (\text{Tractor + laser leveler}) + (\text{Tractor + disc harrow}) + (\text{Tractor + Reaper}) + (\text{Tractor + Cultivator}) + (\text{Tractor + Rotavator})\big) + \frac{82}{100}(\text{Straw chopper} + \text{laser leveler} + \text{disc harrow} + \text{Reaper} + \text{Cultivator} + \text{Rotavator})$$

Using values from Table 35 and Table 11,

$$= \frac{18}{100}(4158.33) + \frac{82}{100}(250 + 351.67 + 50 + 150 + 62.5 + 250)$$

= 748.49 + 913.62

= Rs 1662.11 hr^{-1} per acre.

4) **For on-field sixteen-acre model –**

   - **Labor cost (Rs/acre) –**

100 % of total farmers that do not have contract labors (36.57%) do not hire casual labors. The 39.8 % of total farmers have one contract labor, so they hire one labor less than the number required for the composting process. The 13.92 % of total labors have 2 contract labors, so needed 2 labors less than the number required for the on-field composting process of crop residue management. Similarly, 10.3 % of farmers owning 16 acres have 3 contract labors, so does hire 3 labors than the required for composting.

$$= 100\% \times 36.57\% (\times 0) + 39.8\% ((x-1)\ y) + 13.92\% ((x-2)\ y) + 10.03\% ((x-3)\ y)$$

$$= 0 + \frac{39.8}{100}xy - \frac{39.8}{100}y + \frac{13.92}{100}xy - \frac{27.84}{100}y + \frac{10.03}{100}xy - \frac{30.09}{100}y$$

$$= y(63.75x - 97.73) * 10^{-2} \qquad \text{Equation 7}$$

Here, x = number of labors required per acre for on-field composting

y = labor wage/day prevailing in the district of Punjab

For instance, the labor cost in Patiala district in the year 2019-20, if eight labors are required per acre, then a farmer with 16 acres would have a labor cost as following -

Here, x = 8,

y = Rs. 500 (Table 32),

Using Equation 7,

Total labor cost per acre per crop is Rs. 2061.35

- **Farm Machinery cost (Rs/acre) –**

3.85 % of farmers who have sixteen acres do not own tractors, so they need to rent farm implements along with tractors from hiring centers. So, the farm machinery cost will be combined rent of farm implements + tractor, which is higher than a farmer's rent cost for renting only farm implements. While 96.15% of farmers having 16 acres own tractors, they rent farm machinery without tractors and pay the operating charges of the tractor.

$$= \frac{3.85}{100}\left((\mathrm{t}+\mathrm{a})+(\mathrm{t}+\mathrm{b})+(\mathrm{t}+\mathrm{c})+(\mathrm{t}+\mathrm{d})+(\mathrm{t}+\mathrm{e})+\cdots\right)+\frac{96.15}{100}(a+b+c+d+e+\cdots) \text{ ....Equation 8}$$

where (t+a), (t+b), (t+c), (t+d), (t+e), …. etc., are the hire-out charges of various tractors and implements (hired together) used in composting, t = tractor hire-out charges, and a, b, c, d, e = hire-out charges of various farm machinery.

For instance, the farm machinery cost in Patiala district for a farmer with sixteen acre in the year 2019-20 is–

$$= \frac{3.85}{100}\big(\text{(Tractor + Straw chopper) + (Tractor + laser leveler) + (Tractor + disc harrow) + (Tractor + Reaper) + (Tractor + Cultivator) + (Tractor + Rotavator)}\big) + \frac{96.15}{100}(\text{Straw chopper} + \text{laser leveler} + \text{disc harrow} + \text{Reaper} + \text{Cultivator} + \text{Rotavator})$$

Using values from Table 35 and Table 11,

$$= \frac{3.85}{100}(4158.33) + \frac{96.15}{100}(250 + 351.67 + 50 + 150 + 62.5 + 250)$$

$$= 160.09 + 1071.27$$

= Rs 1231.36 hr^{-1} per acre.

Depending on the number of contract (attached) labors or hired seasonal labors, the labor costs per acre for on-field composting process differ for each land size holding category of a farmer in Punjab. As, in the above example of Patiala district, keeping x (no. of labors/acre) and y (labor wage/day) variables constant, using the above equations. The labor costs per acre can be estimated by filling the labor wage/day in a particular district and the number of labors required per acre in the on-field composting process. The labor cost per acre is the least (Rs. 1308 per acre) for a farmer having one acre of land, then would be high for farmer having 4 acres (Rs. 2525.31 per acre) and decreases later after an increase in the number of acres.

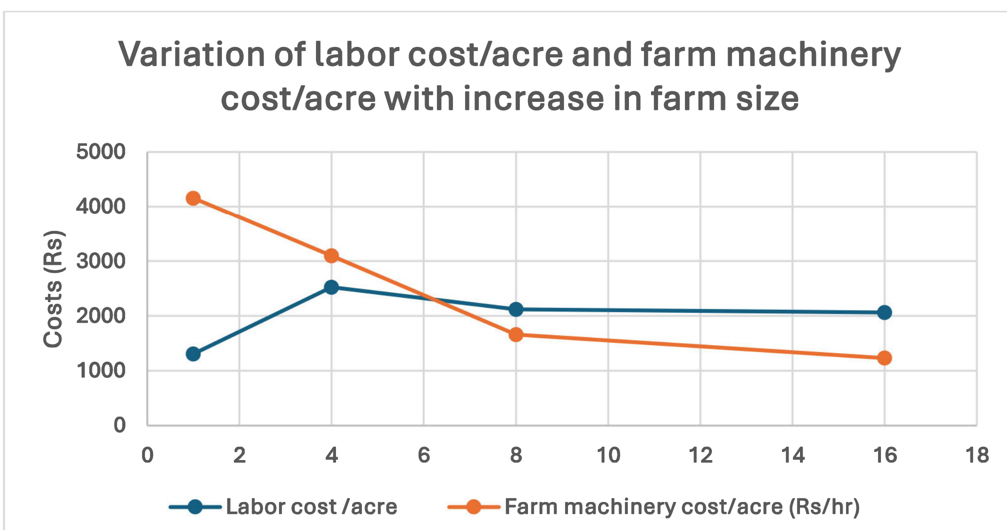


Figure 21– Variation in labor cost/acre in different on-field composting models

To calculate the farm machinery costs per acre in each on-field composting model the renting charge for a single implement (a, b, c, d…) and the renting charge of a tractor-implement combined ((t+a), (t+b), (t+c), (t+d)…) are filled in the above equations of farm machinery costs per acre.

Summarizing labor and farm machinery costs per acre for Patiala district in 2019-20 year, if 8 labors are required per acre for the on-field composting process.

Table 49 – Variation of labor and farm machinery costs per acre of Patiala district in different on field composting models

On-field composting Models	Casual Labor cost/acre (Rs)	Farm machinery cost/acre (Rs/hr)
1. One-acre model	1308	4158.33
2. Four-acre model	2525.31	3099.56
3. Eight-acre model	2120.55	1662.11
4. Sixteen-acre model	2061.35	1231.36

Similarly, labor and farm machinery costs/acre can be calculated for various districts of Punjab based on on-field composting models. So, if x and y values are kept constant, the variation of labor costs in different on-field composting models will remain the same.

Table 49 shows that labor costs /acre firstly increase and later start decreasing with the increasing farm size because the farmers with large landholding have more contract-based labors and even have farm machinery to replace labor in the field operations. While farm machinery costs per acre decrease with an increase in the number of acres a farmer owns (economy of scale).

4.5.5 Costs of environmental change

The reduced GHG emissions by substituting the burning process with the on-field composting process for crop residue management calculated earlier (Table 29) is multiplied by the social cost of GHG (Table 12) to calculate the environmental savings.

Environmental savings (\$) per district = Reduced GHG emissions per district (Table 29) × Social cost-GHG(\$) (Table 12, Year 2020)

For instance, for the Ferozepur district, the environmental cost savings for **CH_4** in year 2020 is evaluated as,

Environmental savings (\$) for **CH_4** = 9.372122 Gg (Table 29, year 2020) × \$2107/ton (SC- CH_4 in 2020, Table 12)

= $\$19.7471 \times 10^6$ per district (Ferozepur)

Environmental savings (\$) per acre = Environmental savings (\$) per district / number of acres under (rice + wheat) crops per district{Appendix A (year – 2019-20)}

Environmental savings (\$) per acre of Ferozepur district = $\$19.7471 \times 10^6$ per district / (281694 + 462077) acres

= \$ 26.54992 per acre of Ferozepur district

Similarly, Table 50 evaluates the Social Cost of all emissions per district and per acre of the district.

Table 50 – Social Cost -GHG benefitted (profits) by using the on-field composting method for crop residue management for the year 2019-20

No.	Districts	CH_4 (10^6 \$)	N_2O (10^6 \$)	CO_2 (10^6 \$)	CH_4/acre (\$)	N_20/acre (\$)	CO_2/acre (\$)
1	Amritsar	15.9007	38.8456	334.271	17.43882	42.60327	366.6061
2	Barnala	12.9109	29.277	253.736	22.91652	51.966	450.3743
3	Bathinda	18.4173	48.9622	419.148	17.13417	45.55108	389.947
4	Faridkot	11.8215	27.2352	237.737	20.62115	47.50832	414.7014
5	Fatehgarh S.	9.11182	21.1326	183.228	21.56435	50.01306	433.6346
6	Fazilka	9.28346	29.6922	252.504	9.463387	30.26772	257.398
7	Ferozepur	19.7471	45.2068	389.006	26.54992	60.78054	523.0185
8	Gurdaspur	15.1055	39.5419	331.239	17.02818	44.57487	373.4003
9	Hoshiarpur	7.82638	26.6251	223.959	14.39678	48.97737	411.9779
10	Jalandhar	16.5613	40.8516	345.51	19.25937	47.50695	401.7989
11	Kapurthala	11.6896	12.7082	230.303	20.65817	22.45817	406.9968
12	Ludhiana	27.8948	63.9763	547.505	22.17854	50.86613	435.309
13	Mansa	12.225	32.6538	276.872	17.05999	45.56834	386.3748
14	Moga	19.7697	44.2258	384.069	22.41091	50.13423	435.3794
15	SMS	16.5079	42.1823	360.741	16.53624	42.25477	361.3614
16	SBSN	6.70777	17.0383	147.502	19.81458	50.3307	435.7171
17	Pathankot	**2.15846**	**6.13065**	**54.3367**	12.84584	36.48587	323.3787
18	Patiala	23.1938	54.496	469.383	20.01362	47.0239	405.0247
19	Rupanagar	4.43072	12.975	113.515	16.45033	48.17338	421.4585

20	SASN	2.78731	8.17468	71.1553	14.27859	41.87654	364.5084
21	Sangrur	**33.0108**	**76.2212**	**654.95**	23.03325	53.18326	456.9907
22	Tarn Taran	17.4366	40.1676	346.975	18.96905	43.69784	377.4698
Average		14.2954	34.4691	301.257	18.66463	45.53647	401.4921

Sangrur district benefits more from all kinds of GHGs, while Pathankot has the lowest environmental savings on the district level. On average, 14.29538 million dollars on CH_4, 34.46908 million on N_2O, and 301.2566 million on CO_2 could be savedby substituting the burning method with the on-field composting method to manage both rice and wheat crop residues.

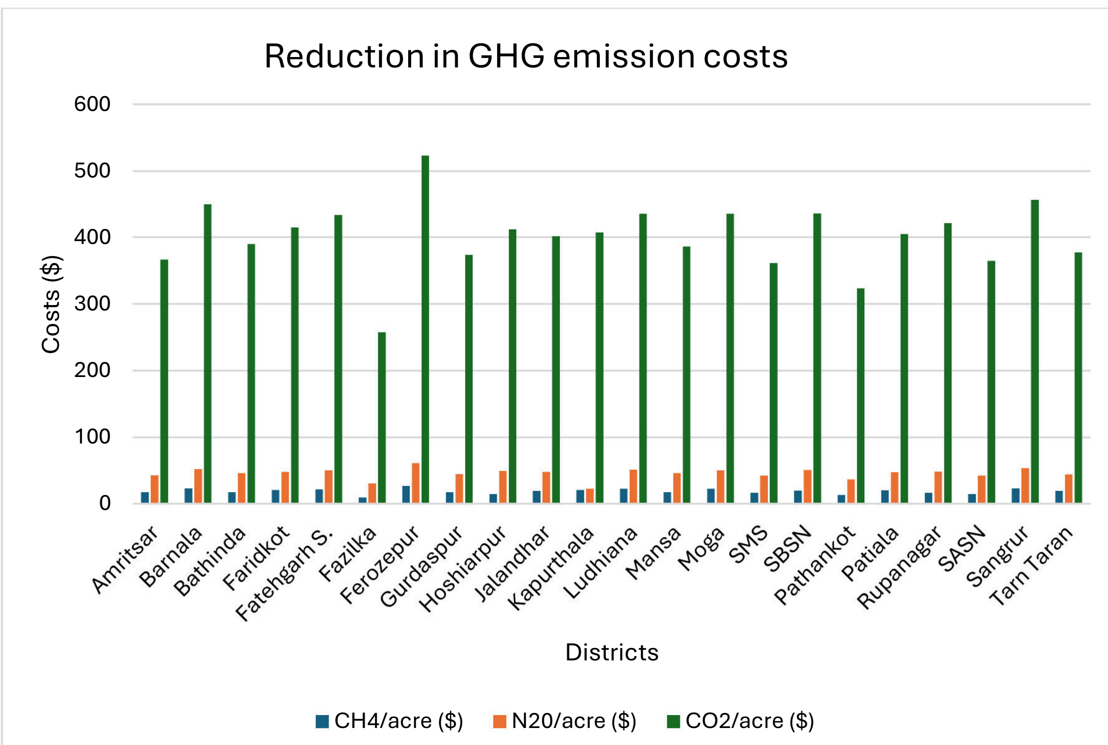


Figure 22– GHG emission costs reduced on composting crop residues

There is a reduction in GHG emissions by using an alternative to burning crop residues: on-field composting. On-field composting emissions are far less than burning crop waste, and these reduced emissions when converted into the cost as per the Canadian government. Each district would make a massive profit (million dollars) from managing crop residues with the on-field composting process. The amount of GHG emissions and the cost-benefit of reducing these emissions depend on the surplus residue produced by the crop. Farmers individually could save a minimum of 9.46 dollars/acre on reducing CH_4 emissions (Fazilka district), 22.46 dollars/acre on N_2O emissions (Kapurthala district) and 257.40 dollars/acre on CO_2 emissions (Fazilka district) and a maximum of 26.55 dollars/acre on reducing CH_4 emissions, 60.78 dollars/acre on N_2O emissions and 523.02 dollars/acre in the Ferozepur district by implementing the on-field composting method for rice residue management for both rice and wheat crops.

Chapter 5: DISCUSSION

5.1 On-field composting costs v/s burning costs of crop residues

5.1.1 Burning costs including penalty cost

The outcomes of this study have provided insight into significant differences between on-field composting and burning costs. The Net Burning Costs of crop residues (including penalty charges) seem higher than the total on-field composting costs in most districts of Punjab. The cost savings (Net Burning Costs – Net Composting Costs) by on-field composting of rice crop residues are relatively less than on-field composting of wheat crop residues. This is due to the lower NCC of wheat crop residues and lower on-field composting costs are due to the high amount of surplus residue generated from wheat crops. High surplus residues of wheat crops ultimately lead to the high amount of compost generated, further reducing the amount of inorganic fertilizer for the next crop. No doubt, the high surplus residue also leads to more reduction in the area under production for making compost pits, but the revenue decrease is quite low. Moreover, the percentage value of the yield increased on using compost as organic fertilizer in fields is higher for wheat crops than rice crops, so the revenue generated in the on-field composting process is higher for wheat crops. Other costs such as farm machinery costs, labor costs, gunny bag costs and farm tools costs are more or less the same for rice and wheat crop residues. The burning costs of wheat crop residues seem higher due to higher farm machinery costs and inorganic fertilizer requirement-related costs (as per recommendations of the Package of Practices).

Overall, farmers can save more money by on-field composting of wheat crop residues than rice crop residues.

5.1.2 Burning costs without penalty cost

If on-field burning penalty costs are not added to the total burning-related costs, then the burning costs are quite less than the on-field composting costs and the cost savings (Net Burning Costs – Net Composting Costs) values are negative for rice and wheat crops in most of the districts. The difference in on-field composting costs and burning costs is lower or less negative for wheat crop residues than for rice crop residues because wheat crops have less Net on-field Composting Costs and high Net Burning Costs. In other words, rice crop residues on-field composting will cost more to farmers than wheat crop residues. These on-field composting costs per acre would be way more than burning crop residue costs (if penalty costs are not included) and perhaps, this is the reason that farmers are tempted to go for the burning method for crop residue management. The penalty imposed by the government for burning crop residues is a kind of risk taken by farmers of Punjab for burning crop residues. All the farmers committing the activity of burning crop residues are not penalized by government officials because regulatory agencies do not have enough resources to go after every farmer who burns crop residues in their fields. Moreover, government officials cannot reach every village and farmer in Punjab during a short period of crop residue burning. It is very difficult for government officials to fine every farmer in Punjab for performing this activity. Even if officials reach out to some of the farms in a short period, then in most of the cases officials let them escape by accepting bribes.

Overall, most of the farmers escape from the penalty cost of burning, and that leads to less amount of burning costs in comparison to on-field composting costs of crop residues.

Labor costs constitute almost half of the on-field composting costs, followed by farm machinery costs. Labor costs are minimal in the burning method, but machinery costs for burning crop residues are almost equal to those of the on-field composting method.

5.2 Variation of costs of on-field composting method

5.2.1 Variation of on-field composting costs within districts

Within districts of Punjab, the costs of on-field composting positively relate to the surplus residue produced. The amount of surplus residue produced per acre in a district depends on the area under crop production and the yield of crops in the district. The amount of surplus residue generated in the district directly reflects the costs of the on-field composting method per acre such as a decrease in revenue generated on reduction in area under production (by making on-field compost pit), reduction in inorganic fertilizer cost (on adding compost (organic fertilizer), gunny bag costs etc. Other costs such as machinery costs, labor costs of the on-field composting process depend on the machinery rental charges and labor wages prevailing in the district of Punjab.

The Mansa district should have the highest cost savings per acre if farmers would substitute crop residue burning with crop residue on-field composting. The Amritsar district is the only district with negative cost savings value in rice crops, even if the penalty is added to the burning costs (due to relatively high total composting costs than total burning costs).

The burning costs are almost similar for all districts, only labor wages prevailing in districts make difference to some extent.

5.2.2 Variation of on-field composting costs within years

Within three consecutive years, the surplus residue produced per acre, subsidized inorganic fertilizer prices, MSP (Minimum Support Price) of rice and wheat crops and labor wages every year greatly impact the on-field composting and burning costs of crop residues. In the case of rice crop residue management through on-field composting, 11 districts out of total of 22 districts (50%) or the average value of all districts of Punjab show an increasing pattern of cost difference. Whereas, for wheat crop residue on-field composting, the highest cost savings on composting are in 2021 for most of the districts followed by 2020 and least in 2022. This pattern is highly influenced by the amount of surplus residue generated each year.

5.3 Variation of on-field composting costs per acre in different on-field composting models

5.3.1 Labor costs of on-field composting method

The burning and on-field compositing costs calculated are on a per-acre basis, and these costs change depending on the size of landholdings owned by farmers. On-field composting models of 1 acre, 4 acres, 8 acres, and 16 acres showed that labor and farm machinery costs per acre do not multiply with an increase in the number of acres. The equations are evaluated to calculate the labor costs/acre of the on-field composting method based on the number of acres a farmer owns. The labor costs per acre are calculated by filling out the number of labors required per acre and the labor wage/day prevailing in the district. Labor costs of on-field composting crop residues per acre form an inverted U-shaped relation with an increase in the number of acres, as large farmers replace farm labor with farm machinery and even the number of contract labors increases with increase in landholding size. The labor costs per acre are lowest for farmers owing up to 2.5 acres (one-acre model) as most of them use family labor and it is highest for farmers owing 2.5 to 5 acres (four-acre model). Further, farmers owning above 5 acres (eight-acre and sixteen-acre model) replace casual farm labor with farm machinery, so casual labor costs per acre decrease in these cases.

5.3.2 Farm machinery costs of on-field composting method

The farm machinery costs per acre decrease with an increase in the number of acres due to the economy of scale, as costs per unit (acre) go down with the increase in the number of acres. Further, equations are evaluated which could be used to calculate farm machinery costs per acre for different on-field models depending on landholding size with farmers.

5.4 Reduction in the amount of GHG released into the environment

Substituting burning with the on-field composting method would significantly impact the environment, as an incredible amount of GHGs is reduced by managing crop residues by on-field composting method. The savings on the Social Cost of burning crop residues is very high. On average, the social cost of \$18.66 (CH_4), \$45.54 (N_2O) and \$401.49 (CO_2) (Table 50) per acre can be saved in Punjab by switching from crop residue burning to on-field composting for crop residue management in year 2020.

5.5 Government policy to promote on-field composting of crop residues

The on-field composting costs are higher than the burning costs of crop residues if penalty cost is not considered. This is the reason farmers take the risk of going for the burning method over the on-field composting method. However, the Punjab and Indian governments could encourage the farmers to adopt on-field composting methods instead of burning methods to manage crop residues by providing incentives for composting and penalties for burning methods.

- For example, the on-average net cost of on-field composting is Rs.7684.287 for rice (Table 42) and Rs.7828.445 (Table 42) for wheat per acre in 2022 year and it is difficult for farmers to spend this amount of money for on-field composting methods, especially the farmers with marginal and small landholdings. If the government could share some percentage of the costs of on-field composting then farmers can be encouraged to apply the on-field composting method on their fields and may substitute the burning method with the on-field composting method to manage crop residues.
- There are many benefits of on-field composting to farmers such as soil enrichment, an increase in quality and quantity of yield of crops etc., but it would also benefit the society and government. On performing on-field composting of crop residues, a huge amount of GHG emissions-related social costs could be reduced. Moreover, amount of inorganic fertilizers could also be reduced by applying organic compost in fields. The various kind of input expenditures, energy and resources spent on the production of inorganic fertilizers could also be saved by the government and used for other purposes.

5.6 Limitations of the study

The results of the study are interpreted with caution due to the limitations of the current research. There are at least five potential limitations related to the results of this study.

1) The first limitation is that the use of farm machinery and labor costs are on an hourly basis and this data is estimated as per anecdotal information from practicing farmers, as the exact number of labor or farm machinery required per acre and the number of hours each will be engaged during the on-field composting process might differ.

2) The second potential limitation is the percentage increase in the yield of crops (as it is estimated from previous research sources). When crop residue compost is applied to the fields, its effect may differ depending on other factors, such as the type of soil, and climatic conditions of the area.
3) The third limitation is the amount of nutrients present in rice and wheat crop residues is estimated to be transferred as a whole to the compost generated from them due to low nitrogenous emissions (high C:N ratio) and leaching of nutrients will deposit the nutrients within the field.
4) In addition, the killing of soil biodiversity, loss of micronutrients from soil, other collateral damage and health impacts on animals and humans due to burning crop residues are not evaluated or calculated in this research.
5) Last but not least is the assumption of yard waste composting emissions as the crop residue composting emissions, as the GHG emissions on crop residue composting are unknown.

Despite these above limitations, the present study has helped to enhance our understanding of the costs of on-field composting of rice and wheat crop residues in Punjab.

Chapter 6: CONCLUSION

In conclusion, on-field composting is a sustainable method, as it helps to **R**euse crop residues, **R**educe inorganic fertilizers and **R**ecycle soil nutrients. Punjab farmers will benefit economically and environmentally sustainable way from on-field composting of rice-wheat crop residues instead of burning them in the field. Moreover, the farm machinery costs and labor costs per acre of the on-field composting method vary with an increase in landholding size.

Future research directions -

1. The present study has provided clear support for on-site composting of rice and wheat residues on cost analysis, but the generality of current results must be established by future research (practical implication).
2. This research does not include quantity and cost analysis of collateral damage, effect on soil health and human and animal health hazards caused by burning crop residues and this could be a topic for future research.
3. Even the amount of energy and resources that could be reduced by decreasing the use of inorganic fertilizers by applying organic compost is not evaluated in this research. This could be an interesting topic for research in the future.
4. As water is an input for on-field composting of the crop residues, but the use of water is not included as an input cost to farmers because it is free of cost for agricultural purposes. But somehow, water use is a cost to society and detailed research on this topic could be done in future.

5. The effect of different climatic and soil conditions prevailing in different regions of Punjab on the on-field composting process of crop residues and its input and output costs could be an interesting topic of future research.

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Appendix A

Total crop area and production of rice and wheat in various districts

1. Year (2019-20)

No.	District	Area (acres)		Production (tons)		Yield (tons/acre)	
		Rice	Wheat	Rice	Wheat	Rice	Wheat
1	Amritsar	447251	464548	598000	852000	1.337057	1.834041
2	Barnala	281694	281694	525000	599000	1.863724	2.126421
3	Bathinda	442309	632576	764000	1387000	1.727299	2.192622
4	Faridkot	286636	286636	436000	646000	1.521093	2.253729
5	Fatehgarh	212506	210035	366000	374000	1.722304	1.780656
6	Fazilka	471961	509026	775000	1016000	1.642085	1.995969
7	Ferozepur	281694	462077	307000	957000	1.089835	2.071083
8	Gurdaspur	429954	457135	637000	772000	1.481554	1.688779
9	Hoshiarpur	192738	350882	312000	609000	1.618778	1.735626
10	Jalandhar	432425	427483	713000	870000	1.648841	2.035169
11	Kapurthala	296520	269339	496000	507000	1.672737	1.882386
12	Ludhiana	639989	617750	1211000	1275000	1.89222	2.063942
13	Mansa	294049	422541	489000	922000	1.662988	2.182037
14	Moga	447251	434896	826000	942000	1.846838	2.166035
15	SMS	469490	528794	637000	1168000	1.356791	2.2088
16	SBSN	148260	190267	251000	391000	1.692972	2.055007
17	Pathankot	69188	98840	86000	158000	1.24299	1.598543
18	Patiala	580685	578214	928000	1116000	1.598113	1.930081

19	Rupnagar	98840	170499	144000	299000	1.4569	1.753676
20	SASN	71659	123550	105000	226000	1.465273	1.829219
21	Sangrur	714119	719061	1362000	1678000	1.907245	2.333599
22	Tarn Taran	454664	464548	707000	855000	1.554994	1.840499
	Average	7763882	8700391	12675000	17619000	1.63256	2.025081

Revised from- https://data.desagri.gov.in/website/crops-apy-report-web.

2. Year (2020-2021)

No.	District	Agricultural Area (acres)		Agricultural Production(t)		Yield (t/acre)	
		Rice	**Wheat**	**Rice**	**Wheat**	**Rice**	**Wheat**
1	Amritsar	456393.7	467019	617000	900000	1.351903	1.927116
2	Barnala	284906.3	280952.7	602000	546000	2.112975	1.943388
3	Bathinda	437861.2	631587.6	822000	1266000	1.877307	2.004473
4	Faridkot	287130.2	286636	477000	588000	1.661267	2.051382
5	Fatehgarh	215224.1	210282.1	414000	422000	1.923576	2.006828
6	Fazilka	286883.1	512732.5	380000	984000	1.324581	1.919129
7	Ferozepur	466030.6	484563.1	823000	967000	1.765978	1.995612
8	Gurdaspur	431683.7	458617.6	680000	840000	1.575227	1.831591
9	Hoshiarpur	196197.4	350634.9	330000	588000	1.681979	1.676958
10	Jalandhar	432672.1	426000.4	797000	845000	1.842042	1.983566
11	Kapurthala	290836.7	259949.2	511000	486000	1.757	1.869596
12	Ludhiana	639000.6	617008.7	1264000	1241000	1.978089	2.011317
13	Mansa	299979.4	424023.6	578000	852000	1.926799	2.009322
14	Moga	451945.9	437367	892000	911000	1.973688	2.082919

15	SMS	458123.4	531759.2	809000	1087000	1.7659	2.044158
16	SBSN	152954.9	191996.7	270000	384000	1.765226	2.000034
17	Pathankot	70670.6	103782	105000	182000	1.485766	1.753676
18	Patiala	578955.3	577472.7	1048000	1162000	1.810157	2.012216
19	Rupanagar	99581.3	169757.7	180000	310000	1.807568	1.826132
20	SASN	68446.7	119843.5	101000	212000	1.475601	1.768974
21	Sangrur	718566.8	719061	1531000	1532000	2.13063	2.130556
22	Tarn Taran	457382.1	462077	761000	880000	1.663817	1.904444
	Average	7781426	8723124	13992000	17185000	1.798128	1.970051

Revised from- https://www.indistatdistricts.com/.

3. Year (2021-2022)

No.	Districts	Agricultural area (acres)		Agricultural Production (t)		Yield (t/acre)	
		Rice	Wheat	Rice	Wheat	Rice	Wheat
1	Amritsar	452193	467760.3	659000	843000	1.457342	1.802205
2	Barnala	286883.1	283670.8	551000	525000	1.920643	1.850737
3	Bathinda	445768.4	644189.7	829000	1149000	1.85971	1.783636
4	Faridkot	285894.7	285400.5	503000	529000	1.759389	1.853536
5	Fatehgarh S.	215718.3	210776.3	412000	290000	1.909898	1.375866
6	Fazilka	279470.1	504331.1	355000	873000	1.270261	1.731006
7	Ferozepur	464053.8	464053.8	827000	821000	1.782121	1.769191
8	Gurdaspur	431436.6	454911.1	671000	777000	1.555269	1.708026
9	Hoshiarpur	189525.7	351376.2	291000	515000	1.535412	1.465666

10	Jalandhar	431683.7	428224.3	747000	732000	1.730434	1.709385
11	Kapurthala	294543.2	271810	503000	439000	1.707729	1.615099
12	Ludhiana	639247.7	603418.2	1246000	1044000	1.949166	1.730143
13	Mansa	303191.7	426247.5	561000	768000	1.850315	1.80177
14	Moga	448980.7	439590.9	861000	778000	1.917677	1.769827
15	SMS	453181.4	541643.2	766000	992000	1.690272	1.831464
16	SBSN	150483.9	191008.3	275000	299000	1.827438	1.565377
17	Pathankot	68199.6	97357.4	97000	144000	1.422296	1.479086
18	Patiala	577472.7	576978.5	1008000	907000	1.745537	1.571982
19	Rupanagar	99087.1	169510.6	169000	248000	1.70557	1.463035
20	SASN	79566.2	123797.1	113000	186000	1.420201	1.502458
21	Sangrur	589827.7	590074.8	1195000	989000	2.026015	1.676059
22	Tarn Taran	449722	458370.5	724000	796000	1.609883	1.736586
	Average	7767341.4	8713981.5	13642000	14871000	1.756328	1.706568

Revised from- https://www.indistatdistricts.com/.

Appendix B

Volume of crop residues generated

No.	District	2019-20		2020-21		2021-22	
		Rice	Wheat	Rice	Wheat	Rice	Wheat
1	Amritsar	5.532649	7.856922	5.594081	8.255652	6.030382	7.720539
2	Barnala	7.711963	9.10946	8.743346	8.325357	7.947488	7.928446
3	Bathinda	7.147445	9.393062	7.768168	8.587041	7.695352	7.640991
4	Faridkot	6.294178	9.654843	6.874209	8.787999	7.28023	7.940436
5	Fatehgarh	7.126776	7.628222	7.959626	8.597131	7.903027	5.894129
6	Fazilka	6.794834	8.550611	5.481026	8.221436	5.256253	7.415525
7	Ferozepur	4.509662	8.872398	7.307497	8.549083	7.374294	7.579111
8	Gurdaspur	6.130568	7.234629	6.518182	7.846428	6.435596	7.317082
9	Hoshiarpur	6.698391	7.435319	6.959915	7.183988	6.353428	6.278824
10	Jalandhar	6.82279	8.718541	7.622241	8.497479	7.160415	7.322902
11	Kapurthala	6.921671	8.06403	7.270344	8.009238	7.066465	6.918987
12	Ludhiana	7.829876	8.841803	8.185195	8.616362	8.065515	7.411831
13	Mansa	6.88133	9.347715	7.972961	8.607816	7.656474	7.718676
14	Moga	7.642087	9.279165	8.166983	8.923101	7.935216	7.581835
15	SMS	5.614309	9.462366	7.307171	8.757052	6.994231	7.845882
16	SBSN	7.005401	8.803527	7.304384	8.568028	7.561812	6.705982
17	Pathankot	5.143407	6.848063	6.147999	7.512643	5.885362	6.336318
18	Patiala	6.61288	8.268353	7.490305	8.620215	7.222912	6.734279
19	Rupanagar	6.028552	7.512643	7.479593	7.823041	7.057532	6.267556
20	SASN	6.063199	7.836265	6.105934	7.578178	5.876694	6.436442

21	Sangrur	7.892049	9.996999	8.8164	9.127177	8.383512	7.180136
22	Tarn Taran	6.43446	7.884587	6.884759	8.158527	6.661587	7.439433
Average		6.755419	8.675328	7.44053	8.439581	7.267565	7.310835

Appendix C

End use of Rice-wheat crop residues by a few districts of Punjab in 1998

Districts	End use in different districts (% of total residue produced by farmers)									
	Fodder		Incorp		Burned		Sold		Misc	
	RS	WS	RS	WS	RS	WS	RS	WS	RS	WS
Amritsar	18.2	39.9	0.0	0.0	**49.4**	**54.2**	19.6	5.9	9.4	0.0
Bathinda	0.0	41.1	0.0	0.0	**100.0**	**33.4**	0.0	25.5	0.0	0.0
Faridkot	0.4	54.6	0.0	0.0	**97.6**	**40.1**	0.8	5.3	1.3	0.0
Fatehgarh S.	8.1	28.4	0.0	0.0	**78.0**	**45.2**	12.3	26.4	1.6	0.0
Ferozepur	3.3	25.4	8.8	0.0	**68.1**	**69.2**	1.0	0.0	18.8	5.4
Gurdaspur	12.9	49.1	1.7	2.4	**62.5**	**48.5**	1.7	0.0	20.6	0.0
Jalandhar	3.2	35.6	0.0	0.0	**88.4**	**64.4**	2.8	0.0	4.7	0.0
Kapurthala	5.7	43.5	1.7	0.0	**88.0**	**53.7**	0.0	2.8	4.4	0.0
Ludhiana	1.9	54.3	0.0	0.0	**94.9**	**37.5**	0.5	6.1	2.7	2.1
Patiala	11.7	38.7	0.0	0.0	**81.5**	**43.6**	5.9	15.3	0.9	2.4
Sangrur	0.4	48.0	0.0	0.0	**94.8**	**39.5**	1.9	11.6	2.8	0.9
Area surveyed	6.5	42.6	0.9	0.2	**81.4**	**48.2**	4.8	8.1	5.8	1.0

(Sidhu et al., 1998)

Appendix D

Operational Holdings in Punjab (1995-96 to 2015-16)

	1995-96			**2010-11**			**2015-16**		
	Area (%)	**Number (%)**	**Size of holding (ha)**	**Area (%)**	**Number (%)**	**Size of holding (ha)**	**Area (%)**	**Number (%)**	**Size of holding (ha)**
Marginal	2.95	18.65	0.6	2.55	15.62	0.61	2.36	14.13	0.60
Small	5.78	16.78	1.31	6.78	18.57	1.38	7.33	18.98	1.40
Semi-medium	20.08	29.31	2.6	21.56	30.83	2.64	24.87	33.67	2.67
Medium	42.29	27.98	5.74	43.18	28.35	5.74	43.75	27.93	5.67
Large	28.89	7.28	15.05	25.93	6.62	14.75	21.65	5.28	14.85
All classes	100	100	3.79	100	100	3.77	100	100	3.62

(Agricultural Census 2015-16, 2018)