*Indian Journal of Agricultural Sciences* **95** (12): 1485–1491, December 2025/Article
https://doi.org/10.56093/ijas.v95i12.161856

# Predictions and estimation of potential of rice residue management technologies in Punjab State of India

SWAPNAJA K JADHAV[1], SATISH D LANDE[2]*, K P SINGH[3], LIVLEEN SHUKLA[2], P K SAHOO[2], TAPAN KUMAR KHURA[2] and SANDEEP KUMAR[2]

*ICAR-Central Institute of Agricultural Engineering, Bhopal, Madhya Pradesh* 462 038, India

Received: 04 December 2024; Accepted: 26 November 2025

ABSTRACT

The agricultural data for the study was collected from 2010–11 to 2023–24 aimed to assess the potential of *in situ* and *ex situ* rice (*Oryza sativa* L.) residue management technologies in Punjab. The residue burning issue has intensified in the state's highly mechanized rice–wheat (*Triticum aestivum* L.) cropping system (RWCS) due to an insufficient number of Crop Residue Management (CRM) machines. The actual number of CRM machineries required to cover the total area under the RWCS were estimated in order to manage rice residues of the state completely. Based on maturity of prominent rice varieties, predicted timeframe is of only 10 days to operate CRM machines effectively. Potential area coverage of CRM machineries was estimated for selected time frames (5, 10, 15, 20, 25 and 30 days) and the possible combinations of CRM machinery were suggested based on operational time window available for both timely and delayed scenarios between rice and wheat crops. Feasibility of Super Straw management System (SMS) followed by both Happy Seeder and Super Seeder to cover total rice cultivated area were analysed and predicted. It revealed that the time window of 15, 20, 25 and 30 days to operate Happy Seeders in the state can cover only 13.22%, 27.23%, 34.03% and 40.84% of the cultivable area while Super Seeder can cover 17.17%, 34.35%, 42.94% and 51.51% area, respectively. Additionally, the *ex situ* management potential for 2024–25 was estimated at a gross residue of 21.98 MT, surplus residue of 5.71 MT, and an annual power generation potential of 994.4 MW with a CGAR of 2.04%.

**Keywords**: Crop Residue Management (CRM) machinery, Punjab, Mechanisation, Rice–wheat cropping system

The rice (*Oryza sativa* L.)–wheat (*Triticum aestivum* L.) cropping system (RWCS) approximately occupies 14 million hectares system of the Indo-Gangetic Plains (IGP) of India and generates more than 50% of total crop residues (Kaur *et al.* 2022). The rice crop alone generates more residues per unit area than wheat crop as combined harvested rice field yield about 12.5 t/ha (Singh *et al.* 2011). Punjab state has a high cropping intensity pattern with highest farm power availability of 6.0 kW/ha to meet the timeline of various farm operations of RWCS (Mehta *et al.* 2023b, Ranguwal *et al.* 2023). Timeliness in farm operations is very decisive for better yield, especially harvesting of rice and field preparation for wheat sowing. Limited time frame for the crop residue management and tillage operations after rice harvesting is the main concern responsible for field burning (Gupta *et al.* 2022). However, rice residue burning loses 5.5 kg of Nitrogen, 2.3 kg of $P_2O_5$, 25 kg of $K_2O$, 1.2 kg of Sulfur and 400 kg of carbon (Mehta *et al.* 2013a, Lohan *et al.* 2018, Dhillon 2020, Kashyap and Agarwal 2021). On-farm burning of the rice residue causes several environmental problems due to harmful emissions (Jadhav *et al.* 2024), destroys microbial activity in the soil, and reduces the nutrients and organic matter in the soil.

There are some preventive measures and corrective measures to deal with the crop residue burning problem. Preventive measures are agronomical interventions like using high yielding dwarf varieties having higher grain/straw ratio, short duration varieties or early maturing varieties so that sufficient time will be available for crop residue management. Corrective measures are mechanized crop residue management which further classified as *in situ* crop residue management and *ex situ* crop residue management which include several machineries including Happy Seeder and Super Seeder which facilitate crop residue incorporation and sowing. A conservation agriculture machinery, zero till drill is also practiced as it helps to retain moisture, nutrients, soil profile etc. (Singh *et al.* 2018, Kumar *et al.* 2024).

Crop Residue Management (CRM) machines has become an integral part of a RWCS after combine harvesting for timely sowing of winter (*rabi*) wheat. However,

[1]ICAR-Central Institute of Agricultural Engineering, Bhopal, Madhya Pradesh; [2]ICAR-Indian Agricultural Research Institute, New Delhi; [3]Krishi Anusandhan Bhawan-II, New Delhi. *Corresponding author email: satishiari@gmail.com

insufficient number of CRM machines for both *in situ* and *ex situ* residue management turned out to be possible reasons for mishandling of crop residues by the farmers. On-farm management of rice stubbles has remained challenge for the Punjab state with limited mechanical interventions such as tillage machineries, stubble cutting/chopping machines and seeding machineries (GoI 2020a).

Currently biomass based thermal power plants are established, and coal-based plants are modified in Punjab so that rice straw in the form of bales or briquettes can be utilized. Rice straw-based compressed biogas generation plants require 1.637 MT/year, thermal power plant requires 0.876 MT/year, and biogas-based power plants require 0.20 MT/year annually summing up as 2.713 MT/year annually (Punjab Energy Development Energy 2022). Thermal power plants which were solely operated on coal are now instructed to utilize 10–20% of biomass briquettes and relatively less ash content 17% (Jadhav *et al.* 2020) than coal. Besides that, rice residue can be used for multiple purposes in such as mushroom cultivation, cushioning material in transport of fragile items, insulating blocks (Nagori *et al.* 2024).

In this study, an attempt was made to highlight issues related to rice residue management in Punjab and to estimate potential requirement of CRM machineries to satisfy demand of intensive RWCS of the region. Assessment of various crop and machine factors is essential to predict the requirements to minimise the potential rice straw burning related hazards. Several types of CRM machineries are being operated by farmers and possessions of such machineries are being increasing, however, burning events are continuing. This scenario was the motivation for this analysis of available CRM machineries, technologies over the year and additional incorporation required to reduce the burning of crop residue. Besides, potential for *ex situ* utilisation of rice residue for bio-energy production was determined as per straw availability.

## MATERIALS AND METHODS

The study was carried out during 2023–24 to estimate the actual requirement of CRM machineries to cover total cultivated area as well as potential of rice residue in power generation in Punjab.

*Data collection*: Agricultural data used in this study consisted of year wise rice production and area under rice cultivation in Punjab from year 2010–11 to 2023–24, days of maturing after transplanting or sowing of different rice varieties recommended by Punjab Government, existing CRM machineries and existing biomass energy generation plant capacity. This secondary data was referred from statistical data and survey reports of Government organisations and councils (GoI 2020a, Govt. of Punjab 2021, Kurinji and Kumar 2021, PAU 2022).

*Estimation of available timeframe for CRM in rice–wheat cropping system*: Some government recommended high yielding-early maturing varieties were selected for the estimation of duration for CRM (PAU 2002, 2025). These varieties have wide difference of days of maturing after transplanting, ranging from 93–137. The short-duration variety PR 126 matures in just 93 days, while mid-early varieties such as PR 130 and HKR 47 require 104 and 105 days. The medium duration varieties such as PR 131 matures in 110 days, PR 129 in 108 days, PR 128 in 111 days, PR 127 in 107 days, PR 122 in 117 days, PR 121 in 110 days, PR 114 in 115 days, and PR 113 in 112 days. Based on the information, variety-wise timeframe for CRM were estimated and a separate regression statistic at 95 percentiles for prediction of specific (variety-wise) and overall time frame for CRM were applied along with ANOVA and illustrated with the help of line fit plot and Normal Probability Plot. Overall time frame for CRM was calculated keeping constant as zero. The formula of the regression equation used is as below (equation 1):

$$Y = \beta_0 + \beta_1 \times X \tag{1}$$

Where Y, Timeframe for CRM (response being predicted); X, Days of maturity (factors influencing Y); $\beta_0$, Intercept (value of Y when X is zero); $\beta_1$, Regression coefficients.

*Estimated requirement of CRM machineries*: Total number of required CRM machineries to cover total rice cultivated area within available time frame for each operation were calculated by formula (equation 2) considering time frame of 5, 10, 15, 20, 25 and 30 days which will be followed by sowing of wheat. Same time frames were considered for seeders.

$$\text{Requirement of machinery} = A_{(\text{Rice cultivation})}/(FC \times T) \tag{2}$$

Where $A_{(\text{Rice cultivation})}$, Area under rice cultivation (ha); FC, Field capacity (ha/day); T, 10 h of operations to complete it within stipulated timeframe for timely sowing.

The field capacities were referred from the literature and reports (Table 1) for straw chopper cum incorporator (Ramulu *et al.* 2020), Rotavator (Maheshwari and Singh 2018), Reversible MB plough, Rice straw cutter cum spreader (Bhavya *et al.* 2020), Straw baler (Singh *et al.* 2005), Super SMS attachment Combine harvester (PAU 2022), Zero till drill (Dhruwe and Victor 2021), Happy seeder (Jat *et al.* 2013, Sidhu *et al.* 2015, Singh *et al.* 2018) and Super seeder (GoI 2020b).

*Area covered using existing machineries*: Based on this information collected, area covered by existing CRM machineries was calculated using formula (equation 3) for six timeframes (5, 10, 15, 20, 25 and 30 days). Recent information of number of existing Super SMS (5,972), Happy Seeder (13,316) and Super Seeders (17,697) was referred for the further calculation (Kurinji and Kumar 2021).

$$A_{(\text{Rice cultivation})}/(FC \times T) = \text{Number of CRM of machineries} \tag{3}$$

Where $A_{(\text{Rice cultivation})}$, Covered area under rice cultivation for specific combination of CRM machineries and T, Time frame available for CRM and tillage operation.

*Gross crop residue (MT/y)*: Estimation of gross, surplus and bioenergy potential of rice residue in Punjab based on the rice production using residue production ratio (RPR) of 1.5 as a measure (Venkatramanan *et al.* 2021) is given formula (equation 4):

Gross Crop residue (MT/y) = A(Rice production)×Y×RPR (4)

Where A, Area under rice production (ha); Y, Yield of rice (kg/ha); RPR, Residue Production Ratio.

*Surplus Residue Potential (MT/y)*: Surplus residue potential (SRP) was estimated using the surplus residue fraction (SRF) of 0.26 (Jain *et al.* 2018) as given in formula (equation 5).

SRP (MT/y) = Gross crop residue × SRF (5)

*Annual power generation potential*: Power generation potential was estimated for steam-based power plant considering operating hours as 24 for 300 days per year using formula (equation 6).

Annual power generation potential (MW) = (0.278 × SRP × H × Ec)/T operating (6)

Where H, Heating value of rice residue, MJ/kg (15.5 MJ/kg) (Hiloidhari *et al.* 2014); $E_c$, Conversion efficiency which is 29% (Maguyon-Detras *et al.* 2020, Chandra *et al.* 2016); $T_{Operating}$, Operating hours of power plant/year.

Gross crop residue, surplus residue potential and energy generation potential based on above formulae were calculated considering year wise yield of the biomass and Compound annual growth rate (CAGR%) was calculated using standard formula.

## RESULTS AND DISCUSSION

*Estimation of time frame available for the CRM*: Based on the data, Fig. 1 illustrates the variety-wise operational calendar for major rice varieties recommended in Punjab, highlighting the distinct periods for transplanting, crop growth, harvesting, CRM, and subsequent sowing of wheat. Considering harvesting and sowing operations been done properly (15 days for each), the duration left for CRM and soil preparation for wheat sowing ranges between 2–22 days depending on the rice variety. That also means total duration for harvesting, CRM and soil preparation and wheat sowing is in the range of 32–52 days for recommended varieties.

*Prediction of time frame available for the CRM*: Based on the information of the prominent high yielding and short duration varieties of rice, available duration for CRM (Variety-wise) was estimated and a regression statistic ($R^2$ =0.93) was illustrated with the help of line fit plot and normal probability plot in Fig. 2. The ANOVA was drawn showing the significance F (*p*-value)< 0.05, showing that the regression model for variety-wise timeframe for CRM is statistically significant as shown below (equation 7).

Predicted specific time frame for CRM = 102.6 – 0.856 × Days to maturity (7)

However, overall timeframe for CRM in Punjab was predicted considering all the varieties was about10 days at ($R^2$ =0.71; $p$<0.05) and can be given as below (equation 8).

Predicted overall timeframe for CRM in Punjab = 0.087 × Days to maturity (8)

However, with the help of line fit plot analysis, predicted time frame for CRM as shown in Fig. 2.

*Requirement of CRM machinery to cover rice cultivated area*: CRM machineries are used in a whole crop cycle like Straw Baler, Super SMS, Happy Seeder, Super Seeder, zero

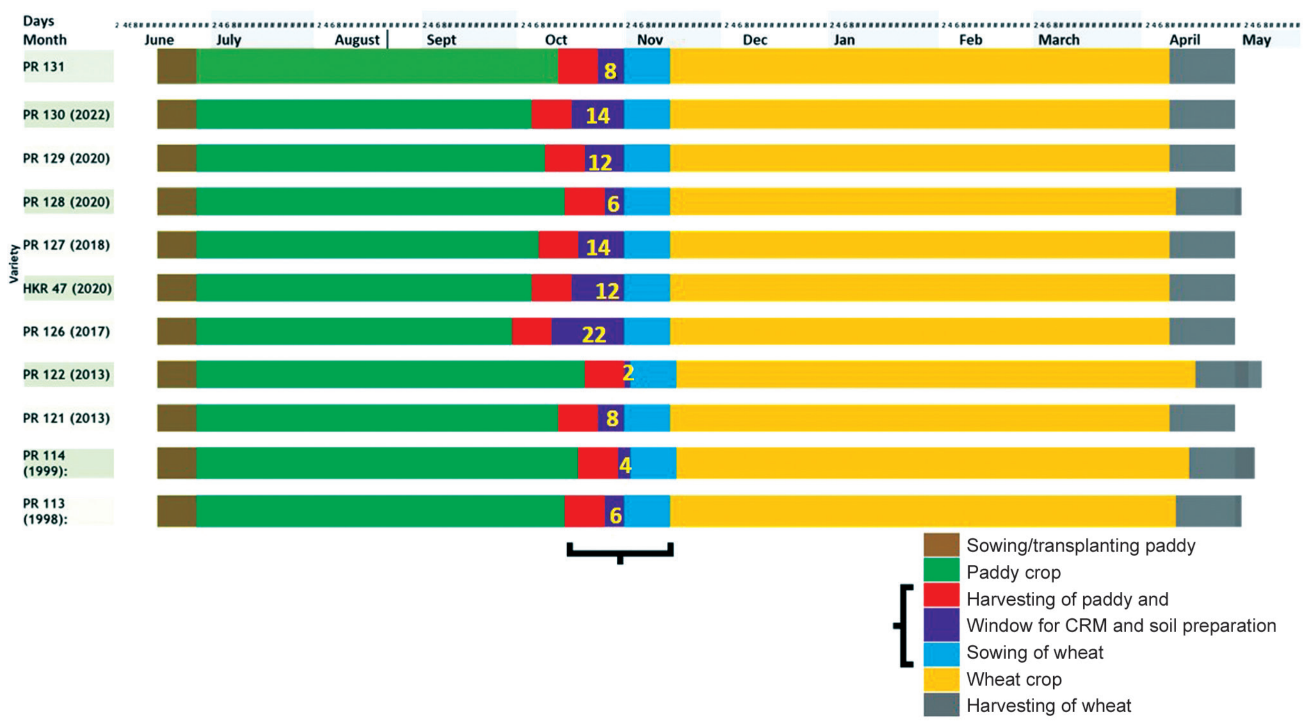


Fig. 1 Variety-wise operation cycle in rice-wheat cropping system in Punjab.

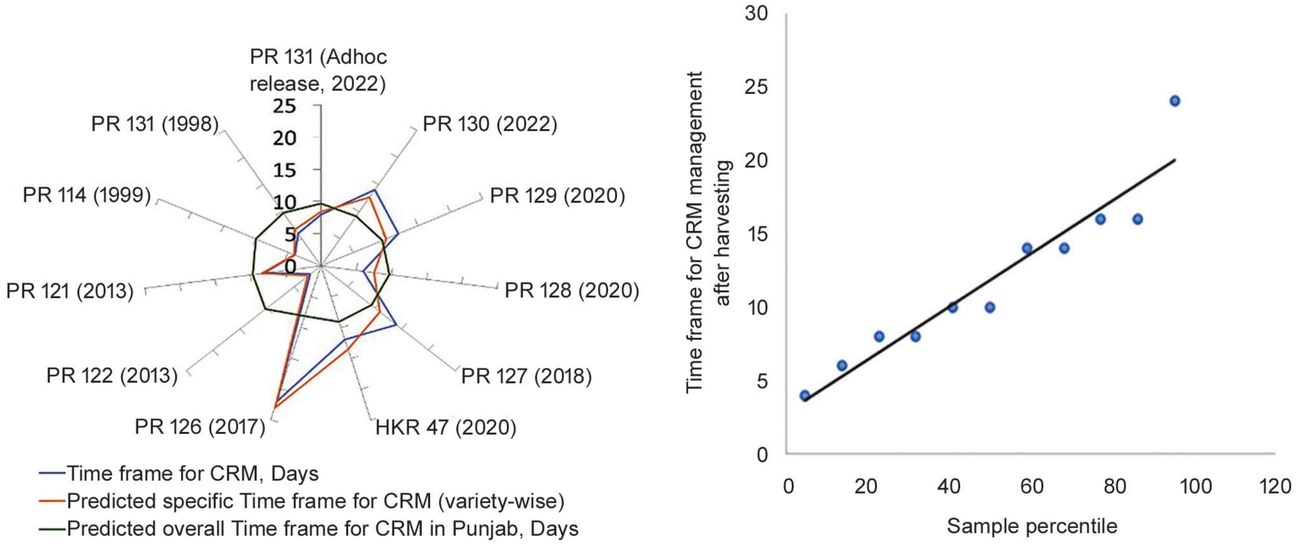


Fig. 2 a) Specific and overall time frame for CRM Line Fit Plot, b) Normal Probability Plot of time frame for CRM management.

till drill etc. since their function is exclusively required for crop residue management. To ensure timely completion of operations, these machineries can be used in the various combinations. If the operations need to be done without disturbing the soil, then operation of straw cutter cum spreader followed by straw baler and then by zero till drill with enhanced efficiency of sowing operation and collection of rice residue for *ex situ* utilisation is possible. Super SMS attached with combine harvester enhances the efficiency of the CRM cum sowing operations along with residue incorporations. Otherwise, Happy Seeder and Super Seeder can be used after combine harvesting. Based on the timeframe available for different operations, requirement of number of machineries to cover cultivated area (3.13 ha) can be drawn (Table 1). Available CRM machinery machineries can be used in various combinations to manage rice effectively in the state.

*Potential area covered by existing CRM machinery*: Rice cultivated area covered by the existing CRM machineries like happy seeder and super seeder after the combine harvesting, was estimated considering time frame of operation (for CRM and sowing) as 15, 20, 25 and 30 days (Table 2). From this estimation it can be stated that, sowing operations using both Happy Seeder and Super Seeder has potential to cover the 30.85% of area within 15 days and up to 92.24% of area within 30 days of time frame. However, farmers' preference towards use of machinery plays a major role in overall CRM.

Based on the quantity of existing Super SMS attached combine harvester, Happy Seeder and Super Seeder, additional requirement of machines was estimated to cover total rice cultivated area as shown in Table 2. For timely wheat sowing, predicted duration for harvesting, CRM and sowing collectively is of 40 days. Therefore, 20 days

Table 1 Estimated requirement of CRM machineries to cover total rice cultivated area of Punjab in case of individual operation

| CRM operation | Implement and combination | Field capacity (ha/h) | Days available for CRM operation | | | | | |
|---|---|---|---|---|---|---|---|---|
| | | | 5 | 10 | 15 | 20 | 25 | 30 |
| | | | No. of machines required to cover rice cultivated area | | | | | |
| Residue incorporation | Straw chopper cum incorporator | 3.6 | 174056 | 87028 | 58019 | 43514 | 34811 | 29009 |
| | Rotavator | 3.24 | 193395 | 96698 | 64465 | 48349 | 38679 | 32233 |
| Chopping | Rice straw cutter + spreader (RSCS) | 2.9 | 139244 | 69622 | 46415 | 34811 | 27849 | 36011 |
| Collection | Straw baler | 4.5 | 174056 | 87028 | 58019 | 43514 | 34811 | 23207 |
| Pulverising | Reversible MB plough | 3.2 | 113514 | 56757 | 37838 | 28379 | 22703 | 29009 |
| | Super SMS | 5.52 | 216069 | 108034 | 72023 | 54017 | 43214 | 18919 |
| CRM and Seeding operation | Zero till drill | 3.33 | 188168 | 94084 | 62723 | 47042 | 37634 | 33153 |
| | Happy seeder | 3.15 | 198921 | 99460 | 66307 | 49730 | 39784 | 34129 |
| | Super seeder | 3.04 | 206082 | 103041 | 68694 | 51520 | 41216 | 31562 |

*The number of machines will change in proportion to the future changes in the rice cultivated area of Punjab.

Table 2 Estimated area covered by existing CRM machinery used for sowing in different time frame

| CRM machinery for sowing | Estimated area covered by existing machinery (mha) (% of total rice cultivated area) | | | | Required machinery to cover rice cultivated area in 20 days of CRM and sowing | Existing machinery (% of required machineries) | Additional requirement of machines in 20 days off CRM and sowing (% of required machineries) |
|---|---|---|---|---|---|---|---|
| | Time frame for operation (days) | | | | | | |
| | 15 | 20 | 25 | 30 | | | |
| Happy seeder | 0.43 (13.22) | 0.85 (27.23) | 1.07 (34.03) | 1.28 (40.84) | 49730 | 13540 (27.22) | 37653 (65.97) |
| Super seeder | 0.54 (17.17) | 1.08 (34.35) | 1.35 (42.94) | 1.61 (51.51) | 51520 | 17697 (34.35) | 33823 (57.06) |
| (Happy seeder + Super seeder)* | 0.97 (30.85) | 1.93 (61.60) | 2.42 (77.24) | 2.89 (92.24) | 50,625 | 31237 (61.70) | 19388 (38.29) |
| Super SMS attached combine harvester | 0.33 (10.52) | 0.66 (21.04) | 0.82 (26.31) | 0.99 (31.57) | 28351 | 5972 (26.31) | 22407 (73.69) |

*Values considering use of happy seeder and super seeder together during 20 days.

each were considered for harvesting cum CRM operation using Super SMS attached combine harvester followed by wheat sowing using both Happy Seeder and Super Seeder. Existing Happy Seeder, Super Seeder and Super SMS are 27.22%, 34.35% and 26.31% of the number of respective machinery required to cover rice cultivated within 20 days. For seeding, if existing Happy Seeder and Super Seeder used together, it can cover 61.70% rice cultivated area.

*Rice residue-based power generation potential*: Year wise gross crop residue (rice straw) generation based on the yield of the rice in Punjab was estimated using the rice production and area under rice cultivation. Surplus crop residue and potential power generation from the surplus rice residue was estimated. The CGAR calculated for the gross crop residue for year 2024–25 is 2.04% and similar for and the power generation as shown in Table 3. Estimated gross crop residue (rice residue) is 21.98 MT, while estimated surplus residue of 5.71 MT has the annual power generation potential of 991 MW for year 2024–25.

However, as reported (PEDA 2024), the total biomass utilisation across existing power plants, biogas plants, and bioethanol plants is 3.23 MT, with individual contributions of 0.8765, 2.15, and 0.2 MT, respectively and hence 2.37 MT rice residue remained unutilized in year 2023–24 having potential of producing additional annual power generation of 411.6 MW.

There are several factors responsible for non-utilisation of the rice residue through *ex situ* management. Major

Table 3 Year wise rice residue generation and its power generation potential in Punjab

| Year | Rice production (MT) | Gross crop residue (GCR), (MT) | Potential Annual Power Generation from GCR (MW) | Surplus residue potential (SRP), (MT) | Potential Annual Power Generation from SRP, (MW) |
|---|---|---|---|---|---|
| 2010–11 | 10.819 | 16.23 | 2814.32 | 4.22 | 732 |
| 2011–12 | 10.54 | 15.81 | 2741.74 | 4.11 | 713 |
| 2012–13 | 10.54 | 15.81 | 2741.74 | 4.11 | 713 |
| 2013–14 | 11.111 | 16.67 | 2890.27 | 4.33 | 751 |
| 2014–15 | 11.121 | 16.68 | 2892.88 | 4.34 | 752 |
| 2015–16 | 11.803 | 17.70 | 3070.28 | 4.60 | 798 |
| 2016–17 | 12.638 | 18.96 | 3287.49 | 4.93 | 855 |
| 2017–18 | 13.377 | 20.07 | 3479.72 | 5.22 | 905 |
| 2018–19 | 12.818 | 19.23 | 3334.31 | 5.00 | 867 |
| 2019–20 | 12.675 | 19.01 | 3297.11 | 4.94 | 857 |
| 2020–21 | 12.78 | 19.17 | 3324.43 | 4.98 | 864 |
| 2021–22 | 12.89 | 19.34 | 3353.04 | 5.03 | 872 |
| 2022–23 | 13.15 | 19.73 | 3420.67 | 5.13 | 889 |
| 2023–24 | 14.36 | 21.54 | 3735.43 | 5.60 | 971 |
| Estimated 2024–25 | 14.65 | 21.98 | 3811.74 | 5.71 | 991.05 |
| CGAR, % Potential Annual Power Generation from SRP and GCR, MW | | | 2.04 | | |

reason comes down to the raw material availability which directs towards the inability to collect the rice residue during the limited time frame, requirement of the straw balers, collection, and transportation cost due to increased fossil fuel prices, are of rice residue collection catchment, storage infrastructure etc. A well strategic, mechanized CRM ensures rice residue supply which may increase the capacity of the biomass-based energy generation of the Punjab state.

The effective operational window for Crop Residue Management (CRM) is approximately 10 days based on the maturity period of the major rice varieties grown in the highly mechanized Punjab state. Promoting short to mid-early maturing rice varieties effectively enhance the available duration for CRM practices by up to three times compared to longer-duration varieties. There is need of additional CRM machineries to cover remaining 40% cultivated area within 20 days.

However, certain short-duration, varieties are location-specific, highlighting the need for developing more adaptable ones to increase the operational window for CRM. A well-coordinated integration of *in situ* and *ex situ* rice residue management practices, supported by collaborative efforts from farmers, private industries, and policymakers, can ensure effective residue management without on-field burning thereby promoting timely farm operations and enhancing power generation in the state.

## REFERENCES

Bhavya B, Lendra S, Veerangouda M, Palled V and Yadalli G S. 2020. Performance evaluation of straw chopper cum spreader for rice crop. *International Journal of Current Microbiology and Applied Sciences* **9**(4): 3209–15. https://doi.org/10.20546/ijcmas.2020.904.373

Chandra R, Vijay V K, Subbarao P M V, Nagpal S, Trivedi A, Jha B and Vijay V. 2016. Rice straw-based power generation from biogas: Fazilka District in Punjab leading the way. *Energy Future- The Complete Energy Magazine* **4**: 52–56.

Dhillon B. 2020. Agricultural mechanisation for *in situ* management of crop residue in Punjab. *Just Agriculture e-Newsletter* **1**(1): 139–46.

Dhruwe N K and Victor V M. 2021. Performance evaluation of Happy Seeder for wheat sowing in combine harvested rice field. *International Journal of Current Microbiology and Applied Sciences* **10**(01): 2542–47. https://doi.org/10.20546/ijcmas.2021.1001.294

Govt. of India. 2020a. Central Sector Scheme on Promotion of Agricultural Mechanisation for *in situ* Management of Crop Residue in the States of Punjab, Haryana, Uttar Pradesh and NCT of Delhi.

Govt. of India. 2020b. *Vishal Eco-FL Super Seeder (Tractor Mounted),* Commercial Test Report. Northern Region Farm Machinery Training and Testing Institute, Department of Agriculture, Cooperation and Farmers Welfare, Government of India.

Govt. of Punjab. 2021. Punjab Economic Survey. Retrieved on 10th February 2025: www.esopb.gov.in

Gupta R K, Kaur J, Kang J S, Singh H, Kaur S, Sayed S, Gaber A and Hossain A. 2022. Tillage in combination with rice straw retention in a rice-wheat system improves the productivity and quality of wheat grain through improving the soil physio-chemical properties. *Land* **11**(10): 1693. https://doi.org/10.3390/land11101693

Hiloidhari M, Das D and Baruah D C. 2014. Bioenergy potential from crop residue biomass in India. *Renewable and Sustainable Energy Reviews* **32**: 504–12. https://doi.org/10.1016/j.rser.2014.01.025

Jadhav S K, T N Aruna, Yadav S K, Kumari S and Nagori. A. 2024. Black carbon aerosols from crop residue burning: Sources, measurement techniques, challenges and mitigation. *International Journal of Advanced Biochemistry Research* **8**(2): 750–56. DOI: 10.33545/26174693.2024.v8.i2i.4184

Jadhav S K, Wakudkar H, Bhardwaj M and Soni R. 2020. Effect of torrefaction on physio-chemical properties of rice straw and its size reduction. *International Journal of Current Microbiology and Applied Sciences* **9**(1): 7–18. https://doi.org/10.20546/ijcmas.2020.901.002

Jain N, Sehgal, V K, Singh S and Kaushik N. 2018. Estimation of surplus crop residue in India for biofuel production. Technology Information, Forecasting and Assessment Council (TIFAC), New Delhi.

Jat M, Kapil Kamboj B, Sidhu H, Singh M, Bana A, Bishnoi D, Gathala M, Saharawat Y, Kumar V, Kumar A, Jat H, Jat R, Sharma P, Sharma R, Singh R, Sapkota T, Malik R and Gupta R. 2013. *Operational manual for Turbo Happy Seeder Technology for managing crop residues with environmental stewardship*, pp. 28. International Maize and Wheat Improvement Centre (CIMMYT), Indian Council of Agricultural Research (ICAR), New Delhi.

Kashyap D and Agarwal T. 2021. Carbon footprint and water footprint of rice and wheat production in Punjab, India. *Agricultural Systems* **186**: 102959. https://doi.org/10.1016/j.agsy.2020.102959

Kaur M, Malik D P, Malhi G S, Sardana V, Bolan, N S, Lal R and Siddique K H M. 2022. Rice residue management in the Indo-Gangetic Plains for climate and food security. A review. *Agronomy for Sustainable Development* **42**(92). https://doi.org/10.1007/s13593-022-00817-0

Kumar R, Rao K K, Mondal S, Choudhary J S, Kumar S, Jat S L, Mishra J S, Singh A K, Upadhyay P K, Das A, Singh V K, Kumar S, Jadhav S K, Sharma N K, Bhatt B P, Rakshit S and Chaudhari S K. 2024. A comprehensive analysis of resource conservation strategies: Impacts on productivity, energetics, and environmental footprints in rice-based systems of the eastern Indo-Gangetic Plains. *Current Research in Environmental Sustainability* **8**: 100271.

Kurinji L S and Kumar S. 2021. Is *ex situ* Crop Residue Management a Scalable Solution to Stubble Burning? A Punjab Case Study. Retrieved on 10th October 2024. https://www.ceew.in/publications/ex-situ-crop-residue-management-scalable-solution-stubble-burning

Lohan S K, Jat H S, Yadav A K, Sidhu H S, Jat M L, Choudhary M, Peter J K and Sharma P C. 2018. Burning issues of rice residue management in north-west states of India. *Renewable and Sustainable Energy Reviews* **81**: 693–706. https://doi.org/10.1016/j.rser.2017.08.057

Maguyon-Detras M C, Migo M V P, Van Hung N and Gummert M. 2020. Thermochemical Conversion of Rice Straw. *(In) Sustainable Rice Straw Management*, pp. 43–64. Gummert M, Hung N, Chivenge P and Douthwaite B. (Eds). Springer, Cham. https://doi.org/10.1007/978-3-030-32373-8_4

Maheshwari T K and Singh U V. 2018. Tractor Drawn Rotavator – A Comparative Study. *International Journal of Current*

*Microbiology and Applied Sciences* **7**(04): 2373–80. https://doi.org/10.20546/ijcmas.2018.704.272

Mehta C R, Sharma S, Nair R and Singh K P. 2013a. Impact of crop residue burning on environment and human health. *Indian Farming* **63**(8): 34–35.

Mehta C R, Bangale R A, Chandel N S and Kumar M. 2023b. Farm mechanisation in India: Status and way forward. *Agricultural Mechanisation in Asia, Africa and Latin America* **54**(2): 75–88.

Nagori A, Jadhav S K, Guru P, Gajendra S, Gangil S, and Rawat M. 2024. Development and performance evaluation of rice straw based insulating block composite for low temperature storage application. *Energy Building* **317**: 114379. https://doi.org/10.1016/j.enbuild.2024.114379

PAU. 2022. *Package of Practices for Crops of Punjab Kharif*. Punjab Agricultural University, Ludhiana, Punjab. https://www.pau.edu/content/ccil/pf/pp_kharif.pdf

PAU. 2025. *Package of Practices for Crops of Punjab KHARIF*. Punjab Agricultural University, Ludhiana, Punjab. ISSN 2278-3725.

Punjab Energy Development Energy (PEDA). 2024. Biomass power projects. https://www.peda.gov.in/biomass-power-projects

Ramulu C, Pateriya R N and Naik M A. 2020. Comparison of straw chopper cum incorporator with existing rice residue management technologies in combine harvested rice field at north western region of India. *Current Journal of Applied Science and Technology* **39**(40): 31–40. https://doi.org/10.9734/cjast/2020/v39i1430694

Ranguwal S, Sidana B K, Singh J, Sachdeva J, Kumar S, Sharma R K and Dhillon J. 2023. Quantifying the energy use efficiency and greenhouse gas emissions in Punjab (India) agriculture. *Energy Nexus* **11**: 1–8.

Sidhu H S, Singh M, Singh Y, Blackwell J, Lohan S K, Humphreys E, Jat M L, Singh V and Singh S. 2015. Development and evaluation of the Turbo Happy Seeder for sowing wheat into heavy rice residues in NW India. *Field Crops Research* **184**: 201–12. https://doi.org/10.1016/j.fcr.2015.07.025

Singh A, Dhaliwal I S and Dixit A. 2011. Performance evaluation of tractor mounded straw chopper cum spreader for rice straw management. *Indian Journal of Agricultural Research* **45**(1): 21–29.

Singh M, Singh R, Singh J, Dhillon B, Singh R, Singh J, Grover J, Singh A, Kumar R, Marwaha B, Chandel R, Chhina R S, Sharma K, Sharma A, Kumar A, Murai A S, Lohan S K and Singh M. 2018. *Manual on Happy Seeder (Technology for In Situ Management of Paddy Residue)*. ICAR-Agricultural Technology Application Research Institute, Zone-1, Punjab Agricultural University, Ludhiana, Punjab. https://www.mendeley.com/reference-manager/reader/7fb560b8-aa19-3275-95f7-b31c2e1497f8/76f02057-cfc2-1adf-2c16-8057d753d4ba

Singh S, Mehta V and Sharda A. 2005. Economics of using straw baler for rice straw management. *Journal of Research* **42**: 78–82.

Venkatramanan V, Shah S, Prasad S, Singh A and Prasad R. 2021. Assessment of bioenergy generation potential of agricultural crop residues in India. *Circular Economy and Sustainability* **1**(4): 1335–48.