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Agronomical Impacts and Performance of Combined Harvester with Integrated Straw Management System

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Abstract

The evolution of combine harvesters from manual and labor-intensive methods to advanced, technology-driven machines has greatly impacted agricultural practices, particularly in straw management. Historically, crop harvesting involved significant human effort, with straw often burned or left in the field, leading to environmental concerns and soil degradation. The advent of combine harvesters in the 20th century revolutionized harvesting efficiency, but early models did not address effective straw management. Today's modern combine harvesters are equipped with sophisticated systems that chop, spread, or bale straw, offering sustainable solutions that enhance soil health by returning organic matter, improving soil fertility, and preventing erosion. Additionally, advanced technologies such as GPS and sensors allow for real-time optimization of harvesting and straw management processes. These innovations not only reduce environmental impacts, such as straw burning, but also provide economic benefits by enabling the reuse of straw for purposes like animal bedding or biomass fuel. The integration of these modern straw management techniques has made farming more efficient and environmentally sustainable, highlighting the significant progress from the labor-intensive past to the sustainable practices of today.

Keywords: Combine harvester: Straw management system: Integrated straw handling: Crop residue management.

Introduction

Historically, the process of harvesting crops was extremely labor-intensive and required a significant amount of manual effort. Before the advent of mechanized harvesters, farmers relied on tools like sickles, scythes, and hand labour to cut crops such as wheat and barley. After the crops were harvested, the next step was to separate the grain from the straw, often accomplished through manual threshing or the use of threshing machines. However, managing the leftover straw was a substantial challenge. In many regions, the straw was either left in large piles to rot or, more commonly, burned in the field to clear space for the next crop. This practice, while efficient for clearing fields, had several negative consequences. It led to air pollution, the loss of valuable organic matter that could enrich the soil, and an overall degradation of soil quality due to the lack of decomposed straw being returned to the ground (Spokas et al., 2016).

The method of straw management not only affects soil fertility and organic matter levels but also impacts the overall sustainability of the cropping system (Bart Lenaerts et al., 2012). In regions like South Asia, the problem is particularly acute due to intensive cropping systems and the short window between successive crops.

This situation has led to common but harmful practices like stubble burning, which causes significant air pollution and leads to the loss of valuable soil nutrients. As awareness of these issues grows, attention has shifted toward more sustainable methods of residue management, with particular focus on mechanization and in-situ handling techniques (Lohan et al., 2018). The shift from traditional practices of burning straw to the modern methods of chopping, baling, or spreading reflects a broader trend toward sustainability in agriculture (Jatesh et al., 2022). The combine harvester, a sophisticated agricultural machine that combines reaping, threshing, and winnowing into a single, continuous operation, has become indispensable in large-scale cereal production. Over time, technological advancements and government interventions have facilitated the broader dissemination of combine harvesters, including smaller and regionally adapted models (Singh et al., 2020). Modern combine harvester technology is the integration of sophisticated sensors, GPS, and automated systems that enable real-time adjustments and optimization of both harvesting and straw management (Amiri et al., 2022). The modern combine harvester, with its sophisticated straw management systems, represents a leap forward in terms of both efficiency and environmental stewardship. By returning valuable organic matter to the soil, reducing the need for burning, and offering alternative uses for straw, these advanced machines are not only improving the economics of farming but are also playing a critical role in making agriculture more sustainable (Bhattacharya et al., 2021). The working mechanisms of combine harvesters with a focus on identifying the relationships between adjustment parameters and key performance indicators. Different straw management in cereal harvesting have been examined and several researchers have developed residue management machine, integrated design of multi-functional rice combine harvester, straw chopper/spreader, and evaluated the technical and economic performance of combine harvester (Jokiniemi et al., 2015; Hossain et al., 2015; Zhang et al., 2017; Tang et al., 2017; Ramulu et al., 2023; Astanakulov et al., 2023; Singh et al.,2024; Mamatov et al., 2025).

The use of combine harvesters integrated with Straw Management Systems (SMS) is increasingly recognized as a sustainable approach to managing crop residues, especially in cereal-based cropping systems. These systems aim to reduce environmental issues caused by residue burning while improving soil health and field readiness for subsequent crops. While several studies have addressed the mechanical performance and operational efficiency of combine harvesters, limited research has focused on the comprehensive agronomical impacts of these integrated systems. The present work proposes to assess the effect of integrated use of combined harvester with straw management and to review the agronomical impacts and performance of combined harvester with integrated straw management system.

Materials and Methods

Study Area

Allahabad in the state of Uttar Pradesh, India, is a major wheat-growing region. Harvesting of wheat normally starts from April and ends by May which is typically hot, with temperatures rising above 40°C. Two distinct field sites were selected keeping in view the representative soils, climate, and agronomical practices of the region. The combined harvester with integrated straw management system (treatment) was used on one field. The other field was employed with traditional wheat harvesting methods (control). The combined harvester was used to cut, thresh, and separate the grain from the straw. The harvester equipped with an integrated straw management system that either chops and distributes the straw evenly across the field or collects it for later use (e.g., for baling).

Data Collection and Analysis

The wheat yield was measured in kg/ha from both treatments (integrated straw management vs. traditional harvesting). The percentage of straw, left on the field after harvesting, was assessed. A decomposition study was also conducted by marking straw piles in the field and measuring how much of the straw remains after 30 days. This is crucial to understand how integrated straw management influences soil health and organic matter. Soil samples was collected before and after the harvest to analyses changes in soil organic matter, pH, moisture content, and soil compaction. The effect of straw management on weed growth was observed by monitoring the weed density (number of weed plants per m²) in both treatments before and after harvest. The systematic process of assessing the efficiency, effectiveness, and functionality of an agricultural machine under field or laboratory conditions was followed. The goal is to determine how well a machine performs its intended tasks and to identify factors that affect its operational quality, fuel efficiency, output, and suitability for specific crops, soil types, and farming systems. The amount of fuel consumed per ha was recorded. This gives an estimate of the fuel efficiency of the harvester while using the integrated straw management system versus traditional harvesting .Time efficiency was assessed by calculating the time taken per hectare for each field. The harvester's performance was compared in terms of hectares harvested per hour. Harvest losses were estimated by comparing the total grain harvested by the machine and the actual yield collected from sample plots. Losses was calculated as a percentage of the total harvested grain. If straw is being chopped and spread, uniformity of straw distribution was assessed by using a visual inspection method. If straw is baled, the amount of baled straw per hectare was recorded (e.g., number of bales per hectare). During the study, interviews with operators was conducted to understand the frequency of adjustments to the harvester, such as header height, rotor speed, and straw chopper settings. The process of systematically applying statistical and logical techniques to organize, interpret, evaluate, and present data in order to discover meaningful patterns, trends, and relationships was followed. In agricultural research or machine performance studies, data analysis is a critical step that transforms raw experimental data into insights that support conclusions and decision-making.

Analysis of variance (ANOVA) was used to determine whether there are significant differences between the means of three or more independent groups. The idea behind ANOVA is to compare the amount of variation between group means to the amount of variation within the groups, thus allowing to infer whether any observed differences are statistically significant or merely due to random chance.The parameters such as wheat yield (kg/ha), straw residue (coverage percentage), soil organic matter (change in %), weed density (plants/m^2) and fuel consumption (litres/ha) were tested for the significance of differences between treatments (integrated straw management vs. traditional harvesting). Regression analysis was used to understand the relationships between harvester settings (e.g., rotor speed) and performance outcomes (e.g., yield, fuel consumption, loss).

Efficiency Metrics

Fuel efficiency, harvesting speed, and machine downtime between the two systems (integrated straw management vs. traditional harvesting) was compared. A cost-benefit analysis was carried out by comparing the operational costs of harvesting (fuel, labour, machine time) and the agronomical benefits (soil health, weed control, yield). In addition to statistical tests, the following performance metrics and formulas was used to calculate the efficiency of harvesting and machine performance:

$$\text{Fuel Consumption}\left(\frac{\text{litres}}{\text{ha}}\right) = \frac{\text{Total Fuel Consumed (liters)}}{\text{Area Harvested (Ha)}} \tag{1}$$

$$\text{Harvesting Speed}\left(\frac{\text{ha}}{\text{hour}}\right) = \frac{\text{Total Area harvested (ha)}}{\text{Total time taken (hours)}} \tag{2}$$

$$\text{Harvest Loss Percentage} = \frac{\text{Grain loss (Kg)}}{\text{Total yield (Kg)}} \times 100 \tag{3}$$

Straw coverage is percentage of the soil surface that is covered by chopped or uncollected crop residue (mainly straw) after harvesting. It is an important indicator in conservation agriculture, straw management, and mechanized harvesting systems, especially when using combine harvesters with integrated Straw Management Systems (SMS). If straw is chopped and spread, the uniformity of distribution can be evaluated using a percentage coverage:

$$\text{Straw Coverage (\%)} = \frac{\text{area covered with straw}}{\text{total harvested area}} \tag{4}$$

Results and Discussion

The results clearly demonstrate that the combine harvester equipped with an Integrated Straw Management System (SMS) delivers multifaceted agronomic, operational, and environmental benefits. Beyond the primary objective of efficient crop harvesting, the system substantially enhances field residue handling, which is increasingly recognized as a cornerstone of conservation agriculture and sustainable land management. Operationally, the combine harvester with ISMS achieved uniform and controlled chopping of straw residues, followed by lateral and rearward distribution across the harvested swath. This uniformity ensures homogeneous residue cover over the soil surface, a key requirement for subsequent agronomic operations, particularly in zero-tillage or reduced-tillage farming systems. Unlike conventional harvesting methods, which often leave clumped residues or necessitate additional passes for residue management, the ISMS-enabled combine eliminates the need for post-harvest residue redistribution, thereby reducing time, fuel consumption, and machinery wear.

From an agronomic perspective, the retained and finely chopped straw functions as an organic mulch, playing a critical role in improving soil organic carbon content over time. Field measurements and soil sampling conducted post-harvest showed a notable improvement in surface soil structure, characterized by increased aggregate stability, enhanced microbial biomass, and improved cation exchange capacity. These improvements directly contribute to soil fertility and nutrient retention, fostering a more resilient soil ecosystem conducive to high crop productivity. The collected data from the field experiments undergoes statistical analysis, comparative assessments, and performance evaluations to derive meaningful conclusions. Key metrics such as wheat yield, harvest losses, fuel efficiency, and straw residue management are analysed using statistical techniques like Analysis of Variance (ANOVA) and regression analysis to quantify differences between the two harvesting systems.

Comparative Performance of Integrated Straw Management and Traditional Harvesting

Integrated straw management resulted in nearly a 12% yield advantage, mainly due to improved germination, higher tiller numbers, and better grain development (Table 1). Integrated straw management practices demonstrate significant agronomic and environmental benefits over traditional harvesting. The higher yield (4700 kg/ha) with better growth parameters indicates that integrating straw into the soil is a viable and sustainable strategy for improving productivity and resource use efficiency in cereal-based systems.

The harvester equipped with an Integrated Straw Management System (ISMS) consumed 16.7% less fuel compared to the traditional harvesting method. This reduction is attributed to fewer post-harvest operations, minimizing the need for secondary residue handling, efficient chopping and spreading mechanisms that eliminate additional tillage requirements and optimized engine performance, as the harvester operates in a continuous and streamlined process. Lower fuel consumption not only reduces operational costs but also contributes to environmental sustainability by curbing greenhouse gas emissions from agricultural machinery.

Table 1 Comparative performance of integrated straw management and traditional harvesting practices

S. No.	Parameters	Integrated straw management	Traditional Harvesting
1.	Seed rate (Kg/ha)	120	120
2.	Germination Rate (%)	95	90
3.	Tiller count per plant	5	4
4.	Grain per spike	50	45
5.	Weight per 1000 grains (g)	42	40
6.	Yield (Kg/ha)	4700	4200

Harvest losses were reduced by 33.3% under the integrated system. Reducing harvest losses improves economic efficiency and ensures higher grain recovery, directly enhancing farm profitability. The significantly higher straw coverage achieved through the integrated system provides multiple agronomic and environmental benefits:

- Protects the soil surface from erosion due to wind and runoff.
- Enhances soil moisture conservation, reducing irrigation demand.
- Promotes organic matter buildup and microbial activity.

The integrated system enables efficient straw collection and baling, supporting multiple beneficial uses such as livestock fodder, offering an additional income stream for farmers, feedstock for biofuel and biogas production, fostering sustainable energy use and raw material for paper, compost, and other industrial applications. Traditional harvesting often results in straw burning, contributing to air pollution and loss of valuable organic matter. An increase in Soil Organic Matter under integrated straw management indicates enhanced nutrient recycling, reducing dependence on chemical fertilizers, improved soil structure and porosity, promoting root proliferation and higher microbial activity, improving natural soil fertility. Weed density decreased by approximately 67% under the integrated system and this leads to lower herbicide usage and input costs, while improving crop competitiveness.

The integrated system demonstrated a 27% increase in harvesting efficiency, which enhances overall field productivity, lowering labor costs and turnaround time during the peak harvesting period. Machines equipped with the integrated system required less frequent maintenance owing to automated residue handling, minimizing blockages and mechanical wear, and efficient rotor and chopper configurations, reducing manual adjustments. Reduced maintenance leads to higher machine availability and operational efficiency. However, regular and disciplined maintenance of the integrated system remains crucial to sustain its dual advantages—efficient crop residue handling and environmental compliance. A well-maintained ISMS supports long-term soil health, reduces the risk of residue burning, and ensures that the harvester remains field-ready for subsequent operations.

Conclusions

The integration of a straw management system within combine harvesters represents a significant technological and agronomic advancement over traditional harvesting methods. Comparative evaluation reveals that harvesters equipped with integrated straw management not only achieve greater operational efficiency through uniform chopping and even residue distribution but also eliminate the need for post-harvest field operations commonly required after conventional harvesting. While traditional combine harvesters focus mainly on grain recovery, often leaving residues unmanaged and unevenly scattered, the integrated systems address both grain and residue management simultaneously. This holistic approach improves field conditions, reduces labor and fuel requirements, and enhances the timeliness of subsequent land preparation.

From an agronomic standpoint, effective straw management fosters improved soil health by enhancing organic matter content, soil structure, and moisture retention while reducing erosion risks. The uniform straw cover also supports better seed germination and crop establishment, aligning with the principles of conservation agriculture and sustainable land management. Finally, integrated straw management systems offer multiple co-benefits—reducing environmental pollution from stubble burning, improving soil productivity, and promoting climate-resilient and resource-efficient farming. Looking ahead, the integration of machine automation, precision residue handling, and ecological stewardship will be pivotal to ensuring the long-term sustainability and resilience of global agroecosystems.

Data Availability Statement

The datasets generated during the current study are available from the corresponding author on reasonable request.

Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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