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Design, Development, and Performance Evaluation of an Agriculture Crop Residue Collection Machine (CRCM) for Sustainable Farming

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Abstract—Post-harvest crop residue management remains one of the most pressing environmental and agricultural challenges in India, where approximately 500–620 million tonnes of residue are generated annually, of which around 140 million tonnes are openly burned. Open-field burning causes severe air pollution, greenhouse gas emissions, and soil fertility degradation. This paper presents the design, development, and performance evaluation of a tractor-mounted Crop Residue Collection Machine (CRCM) that automates the process of cutting, collecting, conveying, and storing crop residue. The machine integrates a sickle-bar cutter, rod-type chain conveyor, bevel gear power transmission, and a V-belt pulley system driven by the tractor's Power Take-Off (PTO) shaft at 540 RPM with a gear ratio of 2:1. The prototype, fabricated predominantly from mild steel and high-carbon steel at a cost of ₹25,795, demonstrated a field capacity exceeding 0.5 ha/hr and a collection efficiency greater than 85%, significantly outperforming manual collection methods. The machine reduces labor requirement by approximately 80% and eliminates the need for residue burning, thereby supporting climate-smart agriculture. A design patent was granted by the Government of India (Design No. 439135-001, dated 05/11/2025).

Keywords: Crop Residue Management, Straw Collecting Machine, Sustainable Agriculture, PTO-driven Mechanism, Climate-Smart Farming, Air Pollution Reduction, Residue Burning

1. Introduction

Agriculture forms the backbone of India's economy, with millions of farmers engaged in cereal crop production, particularly rice and wheat, which together generate the largest share of post-harvest residue. After harvesting, vast amounts of straw, stubble, and biomass are left in the field. The sheer volume of this residue, combined with the narrow window between crop cycles, creates immense pressure on farmers to clear fields quickly and inexpensively [1, 2].

Open-field burning has historically served as the default solution due to its speed and zero direct cost to the farmer. However, the environmental consequences are severe. Studies have documented Air Quality Index (AQI) values exceeding 487 in Delhi and 493 in Ghaziabad during the peak burning season of November, directly attributed to paddy straw combustion in neighboring states [3]. The burning releases carbon dioxide (CO_2), carbon monoxide (CO), particulate matter ($PM_{2.5}$), nitrogen oxides (NOx), and black carbon, all of which contribute to climate change and respiratory disease [4, 5].

Beyond air quality, residue burning destroys soil microbial biomass, reduces organic carbon, and disrupts nutrient cycling. Chen et al. (2020) demonstrated that while burning produces a temporary spike in phosphorus and potassium through ash deposition, it leads to long-term declines in cation exchange capacity (CEC) and soil fertility [6]. Kaur et al. (2021) confirmed that significant proportions of soil nitrogen are lost as NOx and N_2O during burning, exacerbating soil degradation [7].

The root cause of this persistent problem is the absence of affordable, efficient, and farmer-accessible mechanized residue management solutions. Manual collection is labor-intensive, requiring 8–12 workers per hectare, and is increasingly unviable given rural labor shortages [8]. Existing commercial balers and rakers are either too expensive for smallholder farmers or incompatible with local tractor models.

This paper addresses this gap by presenting the Crop Residue Collection Machine (CRCM), a tractor-mounted, PTO-driven prototype designed to automate residue cutting, pickup, conveying, and storage. The machine is engineered for compatibility with standard Indian tractors, ease of operation, low maintenance, and affordability. This work further reports on design calculations, material selection, fabrication processes, performance evaluation, and economic impact analysis.

2. Literature Review

A systematic review of 34 peer-reviewed papers published between 2020 and 2025 was conducted across four thematic clusters: (i) the need for residue waste collection, (ii) challenges in residue management, (iii) environmental and soil sustainability impacts, and (iv) waste management strategies. Figure 3 presents the year-wise distribution of reviewed literature.

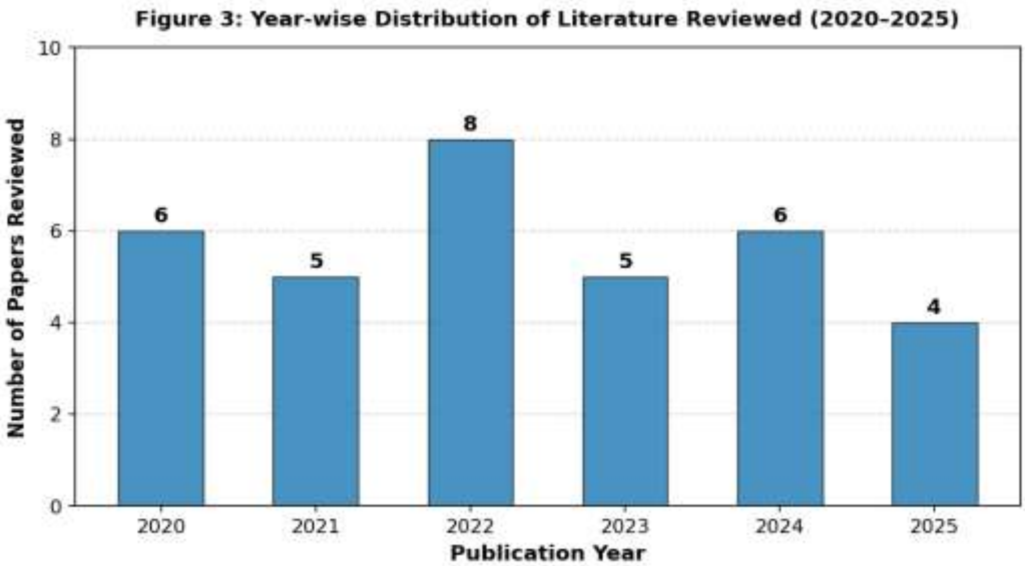

Figure 3: Year-wise distribution of reviewed literature (2020–2025), N = 34 papers

2.1 Need for Residue Collection

Abdurrahman et al. (2020) quantified the public health crisis triggered by crop burning, linking the seasonal AQI spikes in northern India to large-scale paddy straw combustion [3]. Dutta et al. (2020) identified three primary drivers of burning: short inter-crop intervals, inaccessibility of residue management equipment, and absence of cost-effective alternatives, and proposed composting, bioenergy generation, and manure production as viable substitutes [9].

2.2 Challenges in Residue Management

Rattan Lal (2020) highlighted the prohibitive cost of mechanized collectors, balers, and spreaders as the foremost barrier to adoption among smallholder farmers who lack capital for investment [10]. Downing et al. (2020, 2022) explored conventional valorization pathways including bioenergy, compost, paper pulping, and plywood manufacturing, but identified logistical bottlenecks in collection, transportation, and processing as critical economic constraints at the farm level [11, 12].

2.3 Environmental Impact

Chen et al. (2020) and Kaur et al. (2021) collectively established that residue burning depletes soil organic carbon, microbial biomass, and CEC while releasing greenhouse gases [6, 7]. In contrast, Bin Fu et al. (2022) demonstrated through a systematic review that residue retention or incorporation significantly improves soil physicochemical properties including water-holding capacity, porosity, and nutrient content [13]. Nwakaire and Ugwuishiwu (2023) proposed a structured five-stage waste management framework—production, collection, transfer, storage, treatment, and utilization—as a systematic pathway for sustainable residue management [14].

2.4 Residue Management Strategies

Marjanovic (2020) demonstrated the agronomic benefits of in-situ residue management, including improved moisture retention and reduced chemical fertilizer dependence [15]. Prasad et al. (2020) reviewed the energy potential of crop residues for biogas and biofuel production [16]. Gatkal et al. (2024) analyzed sustainable residue management strategies specific to India, underscoring the need for localized, scalable mechanized solutions [17].

The literature collectively supports the urgent development of affordable, tractor-compatible residue collection machines that can be adopted by India's predominantly small and marginal farming community.

3. Materials and Methods

3.1 Design Approach and Material Selection

The CRCM was designed following a user-centered engineering approach. A structured field survey of 35 farmers was conducted to capture operational requirements, preferred features, and existing challenges. Key farmer priorities included tractor compatibility, low maintenance, simple operation, and affordability. Based on these inputs and literature benchmarks, the machine was designed around a mild steel frame with modular subsystems for cutting, conveying, and storage.

Table 1 presents the material selection with mechanical properties and selection rationale for each major component.

Table 1: Material Selection for CRCM Components

Part	Material	Yield Str. (MPa)	Tensile Str. (MPa)	Reason
Frame	Mild Steel IS 2062 E250	250	400–550	Weldability, cost, availability
Sprocket	Carbon Steel C45	600–900	800–1200	High strength, wear resistance
Residue Cutter	High-Carbon Steel AISI 1045	350–500	570–700	Wear resistance, machinability
Conveyor Rod	Carbon Steel AISI 1018	370	440	Easy to weld, good machinability
Storage Bin	Mild Steel	250	400–550	Strength, weldability, cost

3.2 System Architecture and Design Calculations

The CRCM is a tractor-mounted, PTO-driven machine composed of five integrated subsystems: (1) Power Transmission, (2) Sickle-Bar Cutter, (3) Chain Conveyor, (4) Storage Bin, and (5) Frame. Table 2 summarizes the key design specifications and calculated values.

Table 2: Design Specifications and Calculated Parameters

Component	Specification	Calculated Value
Power Source (PTO)	30 HP Tractor	22.37 kW
PTO Input Speed	Standard	540 RPM
Output Speed (After Bevel Gear)	Reduction GR = 2	270 RPM
Driver Pulley Diameter (D_1)	Assumed	100 mm
Driven Pulley Diameter (D_2)	Speed ratio = 2	200 mm
Belt Length	C = 250 mm	981.23 mm
Conveyor Speed	Target 1 m/s	1 m/sec
Frame Dimensions	Mild Steel 2.5×2.5 in	1524×914×914 mm
Bevel Gear Pitch Cone Dist.	zp=25, zg=50, m=4	111.80 mm

3.3 Power Transmission System

Power is drawn from the tractor PTO at 540 RPM (22.37 kW for a 30 HP tractor). A bevel gear pair ($z_p = 25$, $z^g = 50$, module m = 4 mm) achieves a gear ratio GR = 2, reducing the output shaft speed to 270 RPM. The pitch cone distance is calculated as $A\_C = \sqrt{[(D\_P/2)^2 + (D\_G/2)^2]} = 111.80$ mm. The pitch cone angles are $\gamma_p = 26.56°$ and $\gamma^g = 63.43°$.

A V-belt and pulley system (D_1 = 100 mm, D_2 = 200 mm, center distance C = 250 mm) further distributes power to the cutter and conveyor subsystems. The calculated belt length is L = 981.23 mm. Wrap angles are 156.92° (small pulley) and 203.07° (large pulley).

3.4 Sickle-Bar Cutter Mechanism

The cutting mechanism employs a sickle-bar cutter comprising a series of sharp triangular blades mounted on a horizontal reciprocating bar. Operating close to the ground, the blades cut crop residue at the base, ensuring a clean, uniform cut with minimal soil disturbance. The cutter blade material is AISI 1045 high-carbon steel (tensile strength 570–700 MPa), selected for its superior wear resistance and machinability.

3.5 Chain Conveyor

A rod-type chain conveyor transports the cut residue from the cutter unit to the storage bin. Metal rods interconnected by roller chains on both sides form an open-gap conveyor bed that allows soil and fine particles to fall through, delivering cleaner biomass to the storage unit. The conveyor is driven at 96 RPM with a sprocket diameter of 200 mm, producing a conveyor speed of 1 m/s: $v = r\omega = 0.1 \times (2\pi \times 96/60) = 1$ m/s.

3.6 Frame and Storage Bin

The structural frame is fabricated from 2.5 × 2.5 inch mild steel (IS 2062 E250) square hollow sections, designed to support a load capacity of 300 kg. Frame dimensions are 1524 mm (L) × 914.4 mm (W) × 914.4 mm (H). Pedestal bearings (Bearing No. P20, ID 25 mm, OD 35 mm) are deployed at all rotating shaft supports.

3.7 Fabrication Processes

Fabrication involved the following sequential manufacturing operations:

- Cutting: Abrasive wheel cutting machine for mild steel sections and high-carbon cutter blades
- Drilling: SSC-4 drill press (32 mm capacity, 75–2070 RPM) for shaft and fastener holes
- Boring: Single-point boring bar for precision shaft seat enlargement and alignment
- Arc Welding: SMAW (Shielded Metal Arc Welding) at ~20 V for structural frame assembly
- Grinding: Abrasive flap wheel (20–50 m/s) for weld bead smoothing and surface finishing

- Hydraulic Press: Pascal's Law-based press for component forming and press-fitting of bearings

4. Results and Discussion

4.1 Performance Comparison

Field trials under dry, level conditions confirmed that the CRCM substantially outperforms manual residue collection across all key performance indicators. Table 3 and Figure 1 present the comparative analysis.

Table 3: Performance Comparison — Manual Collection vs. CRCM

Parameter	Manual Collection	CRCM	Improvement
Field Capacity (ha/hr)	0.05–0.10	> 0.50	~8×
Collection Efficiency (%)	50–60	85–90+	+30%
Labor Required (persons)	6–10	1–2	↓ 80%
Time per Hectare (hr)	8–12	1.5–2.0	↓ 75%
Environmental Impact	Burning residue	Eco-friendly	High
Soil Health Effect	Negative (burning)	Positive	Improved

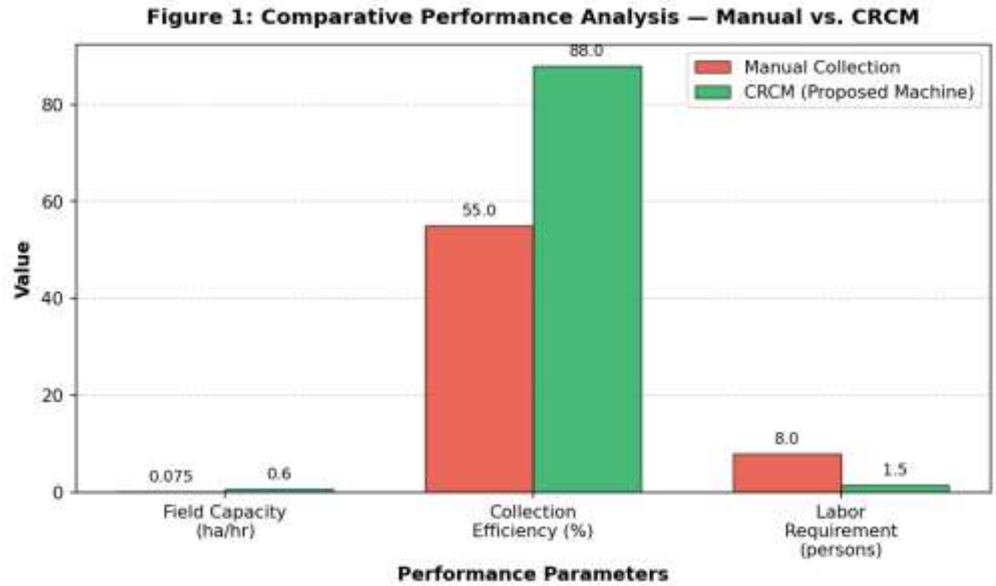

Figure 1: Comparative performance analysis — Manual collection vs. CRCM (field trials)

4.2 Economic Analysis

The total fabrication cost of the CRCM prototype is ₹25,795 (approximately USD 310 at current exchange rates), inclusive of all mechanical components, power transmission elements, finishing, and overhead charges. Figure 2 illustrates the cost distribution across component categories.

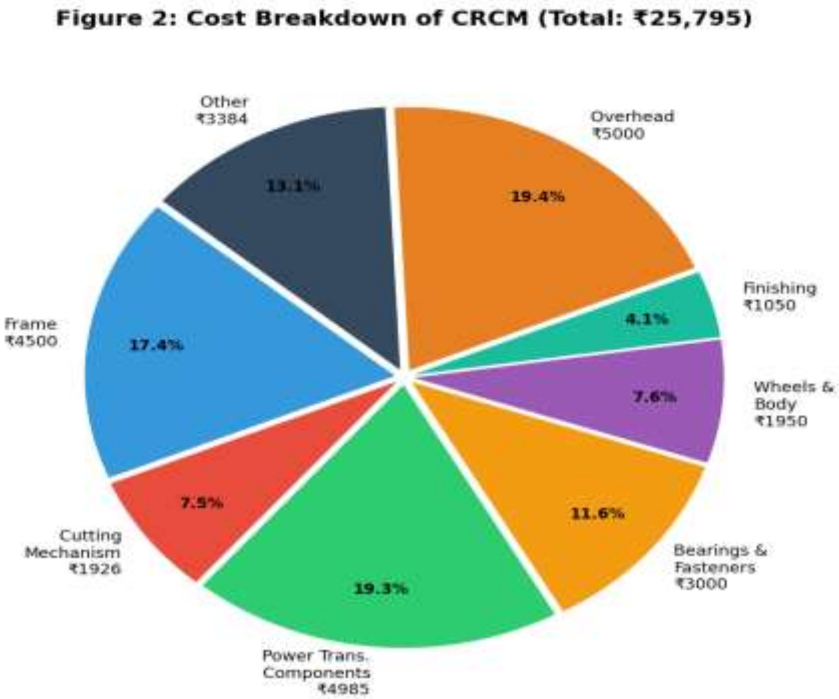

Figure 2: Cost breakdown of CRCM by component category (Total: ₹25,795)

The largest cost centers are overhead charges (19.4%), the structural frame (17.4%), and power transmission components (chains, sprockets, pulleys, belts, bevel gears) which collectively account for approximately 19.3% of total cost. This cost profile is significantly lower than commercially available balers (typically ₹1.5–2.5 lakh) or rotary mulchers (₹1–1.8 lakh), making the CRCM an economically viable alternative for smallholder and cooperative farm settings.

Long-term economic benefits include: (a) reduction in hired labor costs by 80%, (b) revenue generation from sold biomass for fodder, compost, or bioenergy feedstock, (c) avoidance of fines imposed on stubble burning in regulated states, and (d) faster field turnaround enabling an additional cropping cycle per year in multi-crop systems.

4.3 Environmental and Soil Health Outcomes

By eliminating the need for open-field burning, the CRCM directly reduces emissions of CO_2, CO, $PM_{2.5}$, and NOx associated with residue combustion. Each tonne of straw burned releases approximately 3 kg of particulate matter, 60 kg of CO, 1,460 kg of CO_2, and 199 kg of ash [16]. At a national scale, mechanizing residue collection for even 10% of the burned biomass (14 million tonnes) could prevent the release of millions of tonnes of greenhouse gases annually.

Furthermore, collected residue can be composted and returned to the field, improving soil organic matter and long-term fertility, consistent with the findings of Bin Fu et al. (2022) [13] and Marjanovic (2020) [15]. The machine thus supports the dual goals of climate-smart agriculture and circular economy principles by converting an environmental liability into a valuable agricultural resource.

4.4 Challenges and Limitations

Performance was observed to be optimal in dry, firm, and relatively level fields. In wet or muddy conditions, wheel traction and cutter clearance presented operational challenges. Minor misalignment in the bevel gear assembly was corrected during trial runs through shimming. The storage bin capacity, while adequate for the prototype, would require scaling for commercial operation. These limitations outline the primary areas for future design iterations.

5. Conclusion

This study presented the design, fabrication, and evaluation of a PTO-driven Crop Residue Collection Machine (CRCM) as a sustainable and economically viable alternative to open-field burning. The following conclusions are drawn:

- The CRCM achieved a field capacity of >0.5 ha/hr and collection efficiency >85%, representing an 8-fold and 30-point improvement, respectively, over manual collection.
- The prototype was fabricated at a total cost of ₹25,795 using locally available materials, establishing a strong case for affordable mechanization in developing-country agriculture.
- The integrated sickle-bar cutter, rod-type chain conveyor, bevel gear transmission, and V-belt pulley system operated in a synchronized and reliable manner under field conditions.
- The machine reduces labor requirement by approximately 80% and eliminates the primary driver of residue burning, thereby reducing greenhouse gas emissions and preserving soil health.
- A Government of India design patent (Design No. 439135-001) was granted, and the project received recognition at zonal and national-level competitions (Aavishkar 2025, LOGMIEER Techfest 2K26, PROJIT National Techfest 2K26).

Future work will focus on scaling the storage capacity, developing a hydraulic tipping mechanism for discharge, integrating GPS-based field coverage mapping, and conducting multi-season, multi-crop field trials to validate performance across diverse agro-climatic conditions.

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