DESIGN AND EXPERIMENTATION OF A SELF-PROPELLED RECTANGULAR-BALE PICKUP AND STACKING MACHINE
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自走式方捆包捡拾码垛机的设计与试验

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ABSTRACT

During straw removal, bale collection, transportation, and stacking are key factors affecting efficiency and labor intensity. Conventional traction-type machines involve fragmented operations and low automation, requiring extensive manual work. To address this, a self-propelled rectangular-bale pickup and stacking machine integrating pickup, conveying, stacking, and unloading was developed. Its structure and working principles were analyzed, emphasizing the innovative pickup, tilting, and hydraulic systems. Field tests showed an operating speed of 15 km/h, pickup efficiency of 410 bales/h, and bale integrity above 98%. The machine significantly improves efficiency, adaptability, and automation, offering a novel solution for intelligent straw removal.

摘要

秸秆离田过程中，方捆的收集、运输与堆垛是决定作业效率与劳动强度的核心环节。长期以来，国内外农机装备多依赖牵引式捡拾机具，作业环节分散，自动化水平低，且需大量人工参与，不仅劳动强度大，还造成作业效率低和秸秆利用率不高。为解决这一问题，本文研制了一种自走式方捆捡拾码垛机，该机创新性地将捡拾、输送、码垛和卸载等环节集成于自走式平台，实现了一体化、自动化、高效化作业。本文系统介绍了整机结构与工作原理，重点分析了捡拾机构、翻转码垛机构和液压控制系统的创新设计，并通过田间试验验证了其性能。试验结果表明，该机的作业速度可达 15km/h，捡拾效率可达 410 捆/h，运输速度可达 30km/h，方捆完整率超过 98%，破损率低于 2%。与传统牵引式机具相比，该设备在作业效率、适应性和自动化水平方面均表现出显著优势。本研究为秸秆高效离田与农机装备智能化发展提供了一种新型解决方案，具有广泛推广应用价值。

INTRODUCTION

Straw, the stems and leaves remaining after crop harvest, represents a valuable biomass resource *(Huo et al., 2022; Islam et al., 2022)*. Returning straw to the field enhances soil organic matter, improves soil structure, promotes nutrient cycling, and regulates microbial communities *(Wang et al., 2023; Zhang et al., 2021)*. When removed, straw serves as a renewable resource for energy, feed, and industrial applications *(Perea-Moreno et al., 2019; Liu et al., 2025; Li et al., 2022)*. Despite an annual yield of 850 million tons in China, straw utilization remains low, causing environmental pollution and resource waste *(Chen et al., 2024)*. Although the adoption of pick-up and baling machines has improved the quality of square bales, collection and stacking remain labor-intensive and time-consuming, limiting removal efficiency *(Zhang et al., 2020; Duan et al., 2022)*. Existing square bale pickers are mostly tractor-towed and operate in segmented steps, often requiring manual assistance, especially during unloading. Research on integrated pick-up, stacking, and unloading machines in China remains nascent *(Min et al., 2018)*. Side-mounted pick-up devices on trucks require manual stacking and face issues such as shifted center of gravity and low operational safety.

Rear-mounted units on balers enable automatic collection but suffer from large turning radii and still necessitate manual stacking, limiting field applicability *(Zhao et al., 2024; Zhang et al., 2019; Zhang et al., 2019; Liang, 2017; Wang, 2023; Gao et al., 2017)*.

This study presents an integrated machine for square bale pick-up, stacking, and unloading, achieving high-efficiency collection with automated stacking and unloading. Compared with conventional segmented operations, the machine offers higher efficiency and a reduced turning radius. Key components, including the pick-up, stacking, and unloading mechanisms, were systematically designed and analyzed. The design integrates the stacking mechanism's hydraulic and control systems at the rear and positions the unloading mechanism at the front, while optimizing the power, traction, and control systems to balance the center of gravity, enhancing stability and mobility *(Wang et al., 2024)*. An adjustable pick-up arm was designed based on measured bale dimensions, and the inclination angles of the conveyor board and chain were optimized. Critical parameters of the pick-up mechanism, such as dimensions, angles, and tine lengths, were tuned to accommodate bales of varying sizes. The hydraulic stacking mechanism ensures precise and stable bale arrangement, while the unloading mechanism employs a hydraulically driven tilting platform for rapid bale release, reducing labor intensity *(Roquet et al., 2022; Wang et al., 2018)*. This integrated design, combining efficient pick-up, precise stacking, and rapid unloading, significantly improves the operational efficiency and automation of straw removal.

MATERIAL AND METHODS

Overall Structure of the Machine

The machine is mainly composed of a pick-up mechanism, first-, second-, and third-level bale collection platforms, a transmission system, a propulsion system, and a hydraulic unloading mechanism, as shown in Fig. 1.

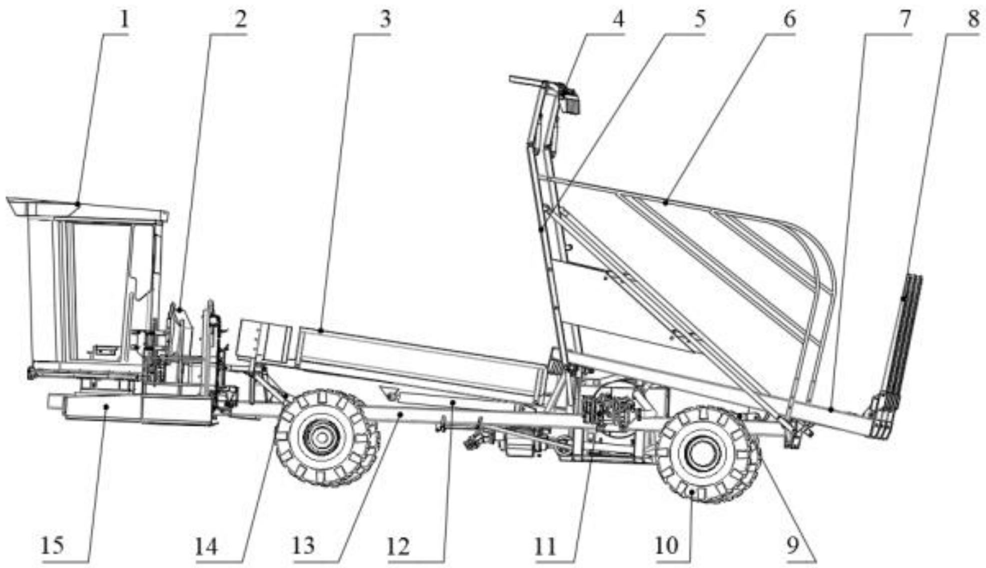

Fig. 1 - Schematic diagram of the self-propelled square bale pickup and stacking machine structure

1 - Cab; 2 - Primary bale collection platform; 3 - Secondary bale collection platform; 4 - Hay compression fork; 5 - Vertical retaining rod; 6 - Left and right guardrails; 7 - Tertiary bale collection platform; 8 - Hay retaining fork; 9 - Tertiary tilting cylinder; 10 - Travel system; 11 - Hydraulic system; 12 - Secondary tilting cylinder; 13 - Frame; 14 - Primary tilting cylinder; 15 - Pickup mechanism

Working Principle and Technical Parameters

The self-propelled square bale pick-up and stacking machine performs bale collection, stacking, transport, and unloading in a single pass. During operation, the pick-up mechanism lowers to a preset height, and adjustable arms combined with inclined conveyor chains lift bales onto the first-level collection platform. Upon reaching a preset capacity, an actuator transfers bales to the second-level platform, which accumulates bales until a full-load signal triggers tilting onto the third-level platform. Pressing forks, side guards, and retaining forks ensure uniform stacking. When the third-level platform is full, the system alerts the operator, who raises the pick-up mechanism and drives to the unloading site.

Activation of the hydraulic push rod tilts the third-level platform, while the pusher ejects the neatly stacked bales. After unloading, the platform resets for the next cycle. Main technical specifications are listed in Table 1.

Table 1

Major technical parameters

Item	Technical parameters
Complete machine size/(mm×mm×mm)	8900×4300×5800
Complete machine weight/kg	4000
Pickup width/mm	560×460×360; 800×600×600
Matched power/kW	40

Design of the Pickup Mechanism

As shown in Fig. 2, the pick-up mechanism of the self-propelled square bale pick-up and stacking machine comprises a pick-up arm, front baffle, conveying baffle, conveyor chain, conveying switch, guide rod, hydraulic motor, guard rail, mounting frame, and locking mechanism. By adjusting the pick-up arm geometry, the mechanism accommodates bales of varying sizes, ensuring stable and efficient operation. The mechanism is inclined relative to the chassis to optimize bale entry onto the first-level collection platform and reduce mechanical resistance.

During operation, the pick-up arm reorients bales through its retracting motion, guiding them smoothly into the mechanism. Upon contact with the conveying switch, the hydraulic motor drives the conveyor chain to lift the bale. The spring-mounted front baffle adapts its position during lifting, while the coordinated action of the guard rail and conveying baffle ensures smooth transfer onto the first-level platform. The trigger-based conveying switch activates the chain only when a bale is detected, automatically stopping otherwise, conserving energy and reducing operational risk. Controlled by the onboard system, the pick-up mechanism lowers during operation and raises during transport, where it is secured by the locking mechanism to prevent interference. This design enhances operational flexibility, as well as safety and stability during transport.

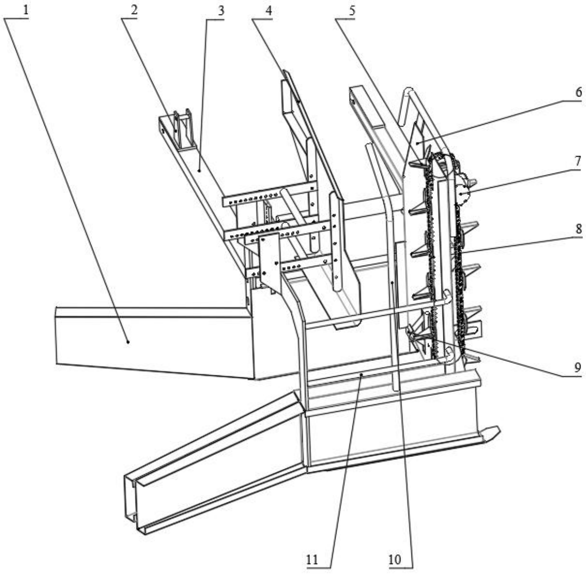

Fig. 2 - Schematic Diagram of the Pickup Mechanism Structure

1 - Pickup arm; 2 - Locking mechanism; 3 - Mounting bracket; 4 - Front side panel; 5 - Tine; 6 - Conveyor plate; 7 - Hydraulic motor; 8 - Conveyor chain; 9 - Conveyor switch; 10 - Guide rod; 11 - Guardrail

Design of the Tilting and Stacking Mechanism

The tilting and stacking mechanism of the self-propelled square bale pick-up machine, comprising three bale collection platforms, support arms, blocking rods, limit switches, and hydraulic cylinders, serves as the core functional subsystem for aggregation, stacking, and transport. Controlled by an integrated electro-hydraulic system, the tilting assembly enables rapid, efficient bale handling, improving operational efficiency over conventional methods.

The first-level platform integrates guiding plates (Fig. 3), intelligent triggering, hydraulic actuation, and auxiliary conveying to ensure smooth transition from pick-up to aggregation. The guiding mechanism, with adjustable baffles and retractable plates (15°-25°), centers bales and reduces accumulation.

Dual-proximity switches with hydraulic buffering prevent false triggers (<1%), while a dual-row chain power unit with pre-tensioning ensures >96% transmission efficiency. The hydraulic tilting actuator with closed-loop displacement control achieves ±1° angle accuracy, and rubber-coated guiding rollers reduce friction and lateral deviation. Modular design allows rapid adjustment for bales 2700–3200 mm, achieving >30% higher conveying efficiency and >98% transfer success.

An intelligent control system coordinates detection, tilting, and transmission, with real-time diagnostics and self-recovery to correct positional deviations, enhancing reliability, reducing failures, and enabling efficient, automated operation.

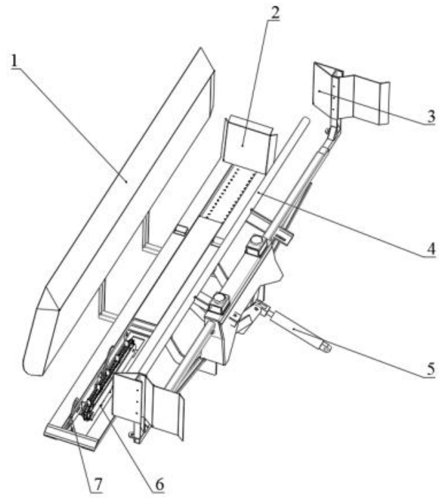

Fig. 3 - Schematic Diagram of the Structure of the Primary Bundling Platform
1 - Baffle; 2 - Limit extension plate; 3 - Bundle guard plate; 4 - Auxiliary roller;
5 - Primary platform tilting cylinder; 6 - Drive chain; 7 - Trigger Mechanism

The secondary tilting platform of the self-propelled square bale stacking machine (Fig. 4) serves as a transitional module between the primary pick-up and tertiary stacking systems, critically affecting transfer smoothness and stacking precision. Its inclined design, optimized for angle and center-of-gravity distribution, enables automatic bale transfer under combined gravity and conveyor thrust, enhancing efficiency and reliability.

The platform, mounted on a welded box-beam high-strength steel frame, offers high load-bearing capacity and torsional rigidity, with FEA indicating maximum deformation <1.2 mm under rated load. The tilting plate, reinforced with V-shaped corners and anti-slip bars, improves impact resistance and prevents bale slippage. Side-curved plates and a balance beam maintain lateral equilibrium and distribute loads evenly. An adjustable working table (2700–3200 mm) accommodates variable bale sizes, enhancing versatility.

A three-point proximity sensing system enables real-time monitoring of tilting angle, position, and bale presence. Signals processed by a microcontroller control the hydraulic unit, providing closed-loop proportional control with smooth motion, rapid response, and positioning accuracy ≤ ±1.5 mm, repeatability 98.7%. Anti-misoperation logic and alarms prevent mechanical interference and ensure safe, reliable operation under field conditions.

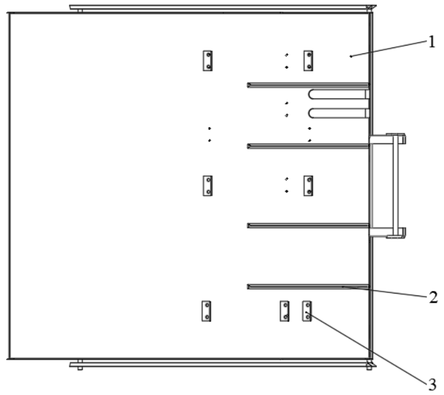

Fig. 4 - Schematic Diagram of the Structure of the Secondary Bundling Platform
1 - Secondary bundling platform; 2 - Reinforcing angle; 3 - Anti-Slip Block

The tertiary bale collection platform of the self-propelled square bale stacking machine functions as the core unit for automated bale stacking and unloading, directly influencing operational efficiency and stacking precision. A modular intelligent control design integrates the pressing fork, sliding and fixed retaining forks, slide-rail mechanism, protective guardrail, and upright rods into a reconfigurable, self-adaptive system.

The Q345B high-strength steel frame with internal stiffeners ensures rigidity and load-bearing capacity while minimizing mass for stability. A servo-driven slide-rail system (stroke 2800 mm, accuracy ±1 mm) with ball-screw transmission enables precise linear control of the sliding retaining fork. The hydraulic pressing mechanism, equipped with a 0–500 kg pressure sensor, adaptively regulates force to prevent bale deformation and maintain stacking stability. Servo-controlled pressing and retaining forks move at 0.2 m/s with segmented velocity and smooth acceleration, forming a three-dimensional clamping interface that achieves ±2 cm stacking alignment, outperforming conventional ±5 cm designs.

A dual-layer PLC–microcontroller system provides coordinated logic, real-time feedback, self-diagnostics, and fault alarms to ensure safe, reliable operation. Field tests indicate a throughput of 360 bales/h with >35% efficiency improvement and ~20% reduced maintenance costs. The design offers high structural robustness, control precision, and cost-effectiveness, establishing a benchmark for automated bale stacking systems (Fig. 5).

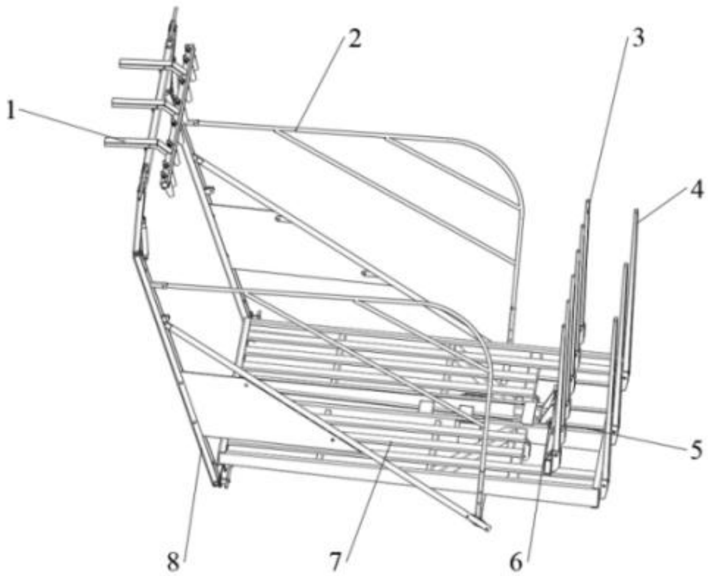

Fig. 5 - Schematic Diagram of the Three-stage Bale Collection Platform Structure

1 - Bale compression fork; 2 - Safety guardrail; 3 - Slidable bale retainer fork; 4 - Fixed bale retainer fork; 5 - Slide rai; 6 - Sliding mechanism; 7 - Bale collection platform; 8 - Vertical retaining rod

Design of Hydraulic Control Systems

The electro-hydraulic system of the self-propelled rectangular-bale stacking machine adopts an intelligent integrated design, forming a mechatronic-hydraulic control architecture that enables real-time monitoring, precise control, and efficient coordination of all operations *(Yang et al., 2023; Kang Zhiyong, 2025)* (Fig. 6). A high-performance microcontroller serves as the core control unit, and modular programming with hierarchical control ensures intelligent management from data acquisition to motion execution *(Yao Wei et al., 2025)*.

The control system comprises three modules:

(1) Information acquisition: High-precision limit switches and pressure sensors on the pickup and bale platforms form a data network monitoring bale quantity and platform status in real time. The processed signals generate dynamic commands for the tilting and conveying mechanisms, achieving closed-loop feedback control.

(2) Execution: Solenoid valves, hydraulic motors, actuating cylinders, and alarms convert electrical signals into mechanical actions. Optimized timing allows pickup, tilting, stacking, and unloading operations to respond within milliseconds, ensuring smooth coordination.

(3) Safety protection: Equipped with error interception, overflow protection, and non-working state locking, this module prevents misoperation and overload. It also provides emergency shutdown and alarm functions to enhance reliability.

A 16 MPa constant-pressure hydraulic system supplies stable power to multiple actuators simultaneously. Controlled via pulse-width modulation (PWM), the multi-way solenoid valves regulate oil flow and direction based on feedback signals, driving *(Lui et al., 2024; Zhang & Gui, 2024)*:

(1) the pickup conveyor motor for continuous bale transfer;

(2) the tilting cylinders with ±1.5 mm precision; and

(3) the tertiary platform for automatic stacking and unloading

Compared with traditional mechanical linkage systems, the new design achieves a 0.5 s response time, pressure fluctuation within ±0.3 MPa, and 99.2% motion completion accuracy. It also features adaptive pressure compensation and fault diagnosis with 95% alarm accuracy, reducing maintenance and downtime while improving system stability and control precision.

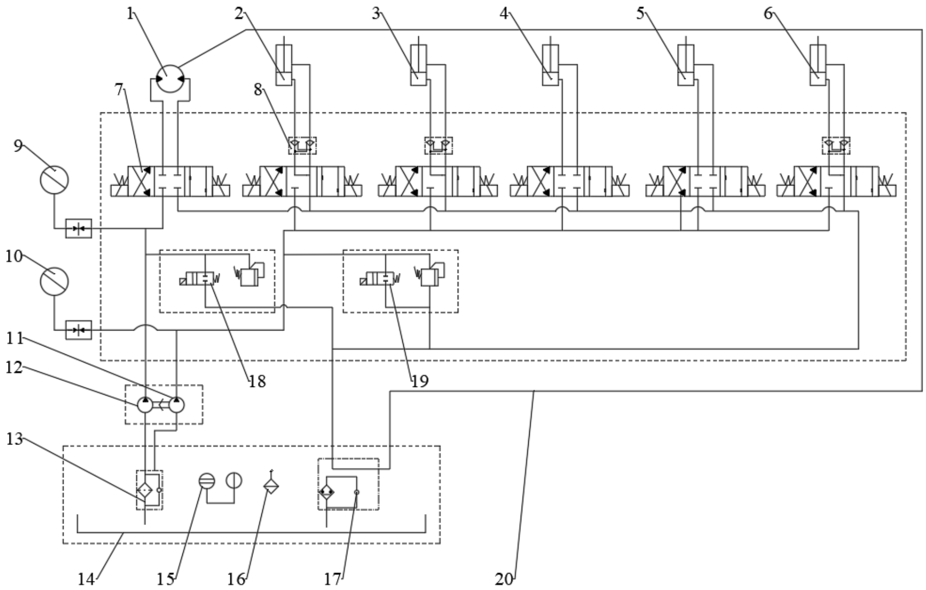

Fig. 6 - Schematic Diagram of the Mechatronic-Hydraulic Integrated Control System

1 - Bale Conveying Motor; 2 - Pickup Mechanism Tilting Cylinder; 3 - Stage-1 Bale Platform Cylinder; 4 - Stage-2 Bale Platform Cylinder; 5 - Stage-3 Bale Platform Cylinder; 6 - Pusher Rod Cylinder; 7 - Electro-hydraulic Directional Valve; 8 - Hydraulic Lock; 9 - Pressure Gauge 1; 10 - Pressure Gauge 2; 11 - Medium-pressure Pump; 12 - High-pressure Pump; 13 - Suction Filter; 14 - Hydraulic Tank; 15 - Level/Temperature Indicator; 16 - Breather Filter; 17 - Return Line Filter; 18 - Pilot-operated Solenoid Relief Valve 1; 19 - Pilot-operated Solenoid Relief Valve 2; 20 - Piping

RESULTS

Performance Analysis of Each Operation

To systematically evaluate the engineering performance of the self-propelled rectangular bale pickup and stacking machine under non-field conditions, a comprehensive analysis was conducted focusing on the pickup and conveying system, the tilting and stacking mechanism, and the mechatronic-hydraulic integrated control system from the perspective of the overall operational workflow. By progressively examining the performance of each key subsystem under continuous operating conditions, their coordinated roles in automated bale pickup, accumulation, and stacking, as well as their contributions to overall operational stability and efficiency, were clearly identified.

The performance of the pickup and conveying system directly determines the stability and continuity of bale transfer into the bundling platforms. Results show that the adjustable pickup arms combined with guiding structures significantly improve bale posture alignment during the initial pickup stage, effectively reducing lateral deviation at the conveyor entrance. The inclined conveyor chain, controlled by a trigger-based logic, operates only upon bale detection, thereby reducing idle energy consumption and mechanical impact. Under continuous operation, the conveying system operated smoothly with a transmission efficiency exceeding 96%, and the successful transfer rate of bales to the primary bundling platform was above 98%, with no evident clogging.

The tilting and stacking mechanism, composed of three coordinated bundling platforms, serves as the core unit for continuous bale accumulation and orderly stacking. Results indicate that the tilting angle control accuracy of the primary bundling platform is maintained within ±1.0°. The secondary bundling platform enables smooth bale transition through its inclined structure and optimized center-of-gravity distribution, with a maximum structural deformation of less than 1.2 mm under rated load. The tertiary bundling platform, operating under coordinated servo-driven slide rails and hydraulic compression forks, achieves high-precision bale positioning and stable stacking, with stacking deviation limited to less than ±2 cm. Stable performance was observed at a working capacity of 360 bales/h, demonstrating excellent reliability and engineering applicability.

The mechatronic-hydraulic integrated control system exhibits favorable response characteristics and operational stability under multi-actuator coordinated operation. The overall system response time is less than 0.5 s, while hydraulic pressure fluctuations are confined within ±0.3 MPa under a constant supply pressure of 16 MPa. The stroke control accuracy of the tilting cylinders is better than ±1.5 mm, and no significant hydraulic shock was observed during operation. Overall, the machine demonstrates stable structure, reliable control, and smooth workflow under continuous high-load conditions, fulfilling the design objectives for efficient automated rectangular bale pickup and stacking and providing a solid engineering basis for subsequent field validation.

Filed Trial

The field experiment was conducted on July 29-30, 2025, in an alfalfa field at Rufueng Agricultural Machinery Co., Ltd., Wudi County, Binzhou City, Shandong Province. Alfalfa was compressed and baled into rectangular bales measuring 500 X 500 X 800 mm (length X width X height) using a CLAAS rectangular baler, as shown in Figure 7a. The prototype used for testing is shown in Figure 7b. Measuring instruments, including a tape measure, electronic scale, and stopwatch, were employed to carry out the bale pickup experiments.

(a) Straw Baling *(b) Bale Pick-Up*

Fig. 7 - Field Experiments

The distance between bales was measured at 2 m, with each bale weighing approximately 27 kg. The pickup conveyor chain was operated at a speed of 150 r/min, while the operator drove the machine at 5 different forward speeds: 6, 8, 10, 12, and 15 km/h, to perform bale pick-up operations. For each speed, five experimental runs were conducted, with nine bales per run. The average pick-up time was measured to calculate the bale pick-up efficiency, while the pre- and post-pick-up uniformity of the bales was assessed to determine the bale damage rate. The detailed results are presented in Table 2.

Table 2

Field Experiment Results

No.	Machine Travel Speed	Pick-Up Efficiency	Bale Damage Rate
1	6km/h	205bales/h	1.3%
2	8km/h	273bales/h	2.1%
3	10km/h	360bales/h	3%
4	12km/h	410bales/h	3.9%
5	15km/h	405bales/h	5.5%

CONCLUSIONS

(1) The self-propelled square bale pick-up and stacking machine is powered independently, enabling the operator to complete bale pick-up, stacking, transport, and unloading in a single operation without leaving the cab. This design effectively reduces straw burning and addresses challenges associated with off-field straw transport and high labor intensity.

(2) By overcoming the limitation of single-size bale handling, the machine employs an adjustable pick-up arm, allowing it to efficiently handle both large and small square bales. This significantly enhances machine versatility and utilization, while reducing operational costs.

(3) The overall control and hydraulic systems are meticulously engineered, integrating microcontroller-based control technology to ensure stable operation and precise command execution. Additionally, the machine's weight distribution is optimized to guarantee stability during unloading operations.

(4) Field trials indicate that the machine's performance meets operational requirements. It achieves a pick-up speed of up to 15 km/h and a transport speed of up to 30 km/h, demonstrating strong adaptability to various bale sizes, with a bale integrity rate of 98%, fully satisfying practical agricultural operation demands.

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