RESEARCH ARTICLE

Design and Testing of an Intelligent Cut-and-Harvest Machine for Apocynum Venetum

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Abstract

Apocynum venetum **has clustered, highly branched stems with strong phloem fiber adhesion, which makes mechanical harvesting prone to entanglement, grip slippage, conveyance blockage, and uneven, high stubble. Existing cutting and bundling machines do not match this morphology well and cannot meet both low-stubble and anti-clogging requirements. To address these problems, an integrated** ***Apocynum venetum*** **cutting-bundling harvester was developed that combines a reciprocating cutting mechanism, stem-folding assembly, vertical anti-clogging conveyor at the cutting table, height-adjustable crop-plate compaction device, and cord-based bundling mechanism, which was supported by a combined navigation system integrating BeiDou satellite navigation and inertial navigation. Field trials in Xinjiang demonstrated that the prototype achieved a mean stubble height of 12.4 cm, a blockage incidence of 0.30 events per hour, a bundling success rate of 98%, a fiber damage rate of 0.8% and a harvesting efficiency of 0.0537 ha h^{-1}, meeting ISO 11279:2021 performance thresholds. The coordinated action of the cutting, folding, conveying, and bundling subsystems improved the throughput and maintained stable machine operation under clustered growth conditions. These results indicate that the developed prototype harvester is technically feasible and agronomically suitable for large-scale** ***Apocynum venetum*** **production. The intelligent** ***Apocynum*** **baling harvester can enhance the automatic driving functionality of agricultural machinery, improve the operational quality of agricultural machinery navigation, and thereby comprehensively increase harvesting efficiency.**

Keywords: apocynum venetum, cutting-bundling harvester, bundling mechanism, integrated navigation system, mechanized harvesting, anti-clogging conveyance.

1 Introduction

Apocynum venetum is a wild perennial plant exhibiting robust environmental resilience. This species is tolerant of drought, salinity, and extreme thermal fluctuations. Its primary distribution encompasses desert, saline-alkali, and riparian zones

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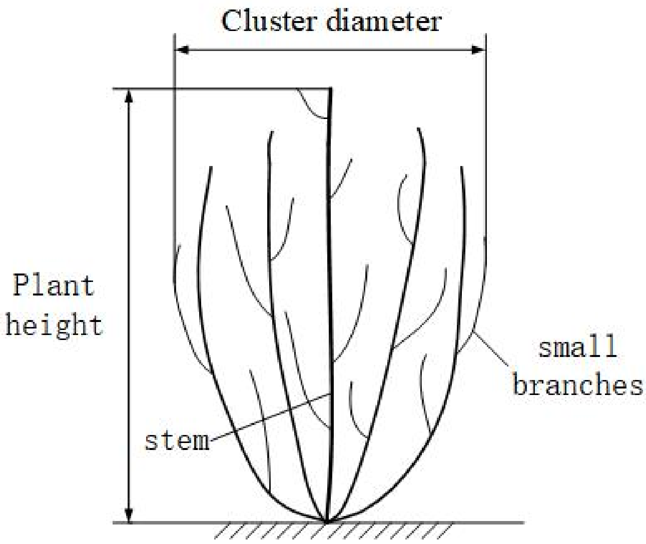
in northwestern and northern China [1, 2]. The phloem fibers are recognized as the "preeminent wild fiber source," whereas the leaves possess significant medicinal properties [1, 3]. *Apocynum* fiber, derived from stem phloem, constitutes an advanced past fiber exhibiting mercerization-like characteristics with superior air permeability and antibacterial efficacy [4, 5]. Large-scale cultivation has been implemented in Xinjiang and other comparable regions [1, 2], as illustrated in Figure 1.

(a)

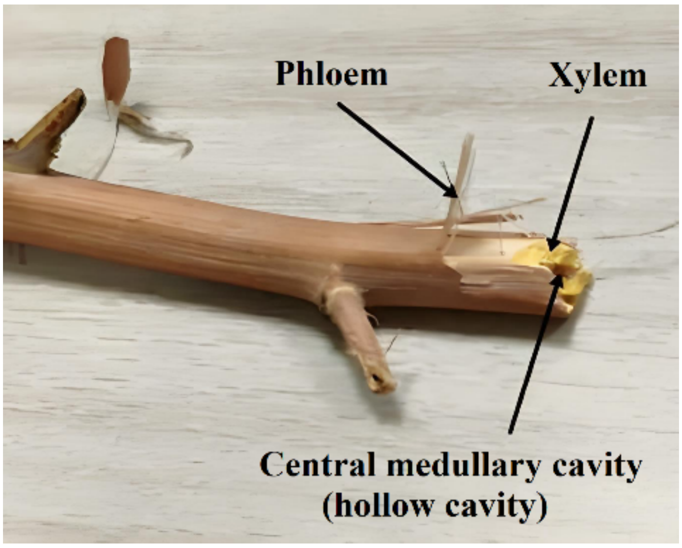
(b)

Figure 1. Large-scale cultivation of *Apocynum venetum* in Xinjiang.

Apocynum plants exhibit substantial height (1.0–1.6 m) with cluster diameters averaging 1.0 m; stems are upright, rigid, and highly branched, as depicted in Figure 2. Current harvesting and processing operations predominantly rely on manual sickle-based whole-plant cutting [6]. The stem phloem fibers demonstrate exceptional tensile strength, yet exhibit a propensity for entanglement-induced obstruction in mechanical cutting and conveyance systems during harvesting [7, 8], resulting in frequent operational downtime [9] and compromised fiber integrity [10, 11]. Concurrently, the irregular morphology, excessive branching, and susceptibility to lodging preclude consistent low-stubble mechanical cutting [12]. Furthermore, the absence of specialized equipment models leads to recurrent gripping slippage and conveyance inefficiencies in existing machinery [13, 14].



(a)



(b)

Figure 2. Morphological characteristics of a single *Apocynum venetum* plant: (left) plant cluster schematic illustrating growth habit; (right) stem cross-section identifying key fibrous (phloem) and structural (xylem) components.

Addressing critical challenges, including entanglement-induced obstruction, gripping slippage, conveyance inefficiencies, and inconsistent low-stubble cutting in mechanical harvesting is essential for improving overall harvesting performance [15, 16]. *Apocynum venetum*, traditionally harvested during its overwintering dormancy period, is confronted with significant challenges, including harsh working conditions, low operational efficiency, and intensive manual labor. Recent advancements in intelligent agricultural technologies have demonstrated substantial potential in mitigating these challenges. For instance, Man et al. [17] comprehensively reviewed the evolution of intelligent navigation systems for agricultural machinery, highlighting the integration of Beidou satellite navigation with inertial navigation systems to improve positioning accuracy. Similarly, Tian et al. [18] effectively demonstrated the practical application of Beidou navigation in precision agriculture, particularly in cotton cultivation in Xinjiang, underscoring its potential for sand-based crops such as *Apocynum venetum*. Furthermore, Chen et al. [19] performed extensive field trials on rice transplanters equipped with Beidou navigation, illustrating enhanced operational adaptability in challenging terrains. Collectively, these studies emphasize the feasibility and advantages of integrating advanced navigation technologies into harvesting equipment designed for sand-based crops. This study proposes an integrated *Apocynum venetum* cutting and bundling harvester design, incorporating a cutting mechanism, stem-folding assembly, bundling unit, vertical obstruction-resistant conveyance system at the cutting table, a height-adjustable crop-plate compaction device, and chassis-mounted obstruction-resistant conveyance system [20, 21]. Through sequential operational phases comprising branch guidance, cutting, folding, primary bundling, secondary bundling, baling, and conveyance, efficient and uninterrupted mechanized harvesting of *Apocynum venetum* was achieved, significantly enhancing operational adaptability and system reliability [22].

2 Overall Structure of the Smart *Apocynum venetum* Cutting-Bundling Harvester

2.1 Mechanical Overall Structure Design

The *Apocynum venetum* bundling harvester comprises a cutting mechanism, gatherer assembly, bundling unit, vertical obstruction-resistant conveyance system at the cutting table, height-adjustable crop-plate compaction assembly, and chassis-mounted obstruction-resistant conveyance system, among other subsystems. Power for operational execution is derived from a diesel engine and electrical system. The system configuration is shown in Figure 3.

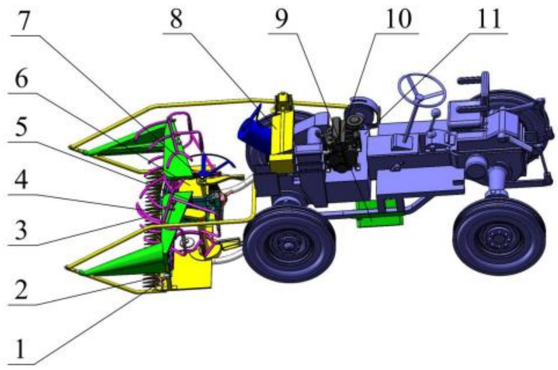


Figure 3. Overall structure of the *Apocynum venetum* cutting–bundling harvester, showing the main functional subsystems integrated on the self-propelled chassis. Numbered components: 1 pre-cut detection device; 2 separation device; 3 folding device; 4 cutting device; 5 bundling mechanism; 6 cutting-table vertical anti-blocking conveying device; 7 transmission mechanism; 8 height-adjustable stacking crop platen device; 9 walking-device anti-clogging conveying device; 10 walking device; and 11 control device.

As shown in Figure 3, the major functional subsystems of the *Apocynum venetum* cutting–bundling harvester are as follows: (1) The cutting mechanism integrates a stalk-separation assembly and reciprocating cutter assembly. The separation assembly guides stalks while an electric motor actuates a lever to drive reciprocating motion between moving and stationary blades, enabling efficient and precise *Apocynum venetum* severance. (2) The stem-folding assembly employs multiple electric motors and servo actuators to drive a two-stage gear-shifting mechanism, executing accurate raking and retention actions for efficient folding of cut stems to the bundling knot. (3) The bundling unit achieves continuous rope-based bundling of severed stems in four sequential phases: cord feeding, loop formation, knot tying, and cord severing. (4) The vertical obstruction-resistant conveyance system at the cutting table utilizes a symmetrical configuration, in which an electric motor drives drums via synchronous belts with tensioner pulleys, maintaining optimal belt tension to ensure vertical, stable, and obstruction-free stalk conveyance. (5) The height-adjustable crop-plate compaction assembly adjusts plate elevation through pin-position selection in precision-drilled holes, with motor-driven rotation enabling baling of variable-thickness crop stacks to facilitate bale egress beneath the chassis. (6) The chassis-mounted obstruction-resistant conveyance system rotates conveyor pulleys via motor-driven meshing gear sets, ensuring stable belt operation under a dual-pulley drive for efficient bale transportation and obstruction prevention. The main technical parameters of the prototype are presented in Table 1.

Table 1. Main structural and operating parameters of the *Apocynum venetum* cutting–bundling harvester prototype.

Parameter	Numerical value / method
Weight of whole machine/kg	680
Drive mode of whole machine	Diesel engine + motor
Diesel engine rated power /kW	11.5
Motor rated power /kW	8
Dimensions (length × width × height)/(mm×mm×mm)	3750×1850×2130
Forward speed/ ($m{\cdot}s^{-1}$)	0.2-2.1
Stubble height/cm	12

2.2 Intelligent Navigation System Design

The final schematic diagram of the integrated navigation system is presented in Figure 4. The system comprises two main modules: a wheeled steering control module and a pose detection module. The pose detection module incorporates a bundled forming detection system, a data fusion processor, an Inertial Measurement Unit (IMU) module, and a Global Navigation Satellite System (GNSS) antenna. The wheeled steering control module consists of components such as steering gear, an angle sensor, a fault alarm system, a vehicle controller, and a throttle controller, among others.

The integrated navigation system employs the Huace NX100 agricultural machinery navigation and automatic driving system. For field global path planning, the system utilizes an improved A* algorithm developed by the company. The lateral control method is based on the pure pursuit control algorithm, while the longitudinal speed control adopts a fixed gear control approach.

The finalized schematic diagram of the integrated navigation system is presented in Figure 5. The operational principle of the system involves the integration of the BeiDou Navigation Satellite System (BDS) with an inertial sensor, which significantly enhances the stability and continuity of path tracking

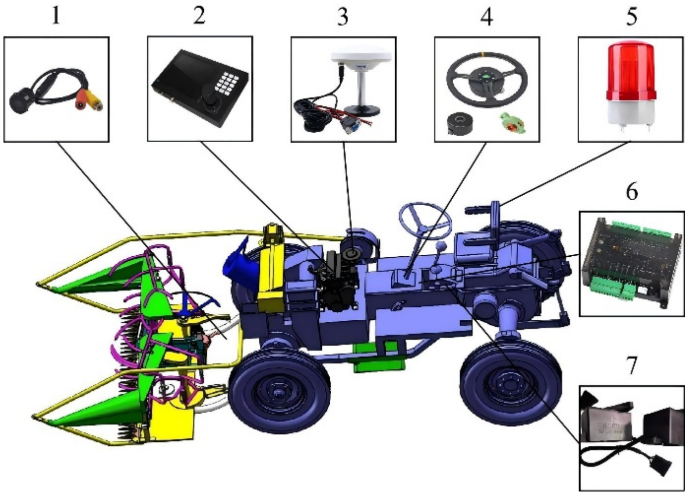


Figure 4. Intelligent *Apocynum* cutting baler automatic driving installation diagram, featuring: (1) bundling forming detection system, (2) IMU module, (3) Antenna, (4) steering gear, angle sensor, steering wheel, (5) Fault alarm, (6) Vehicle controller, and (7) Throttle controller.

for *Apocynum* balers operating in desert-oasis ecotones. This integration leverages Inertial Measurement Unit (IMU) technology, combining gyroscopes and accelerometers with Real-Time Kinematic Global Navigation Satellite Systems (RTK-GNSS), specifically utilizing the BDS system, to achieve precise real-time positioning. Furthermore, it enables the continuous calculation of motion parameters such as velocity and attitude. Continuous corrections facilitated by the BeiDou system markedly improve the positioning continuity and accuracy of the hoist, particularly in areas characterized by weak signals, obstructions, and environmental interference. By employing a combined positioning algorithm, the system can accurately plan paths within the complex environments of oasis ecotones, effectively avoiding obstacles and ensuring both the rationality and coverage of harvesting routes.

3 Principles of Operation

The working process of the *Apocynum* cutting bale harvester is shown in Figure 6.

During operation, the track system propels the harvester forward with uniform motion. The pre-harvest monitoring assembly, positioned anteriorly, dynamically measures crop cluster velocity and width, relaying data to the central control unit for real-time adjustment of cutter speed and radial time orientation. The frontal crop-separation assembly features a conical apex structure designed to segregate crop rows and guide stalks into the harvesting zone. Subsequently, a hydraulic actuator

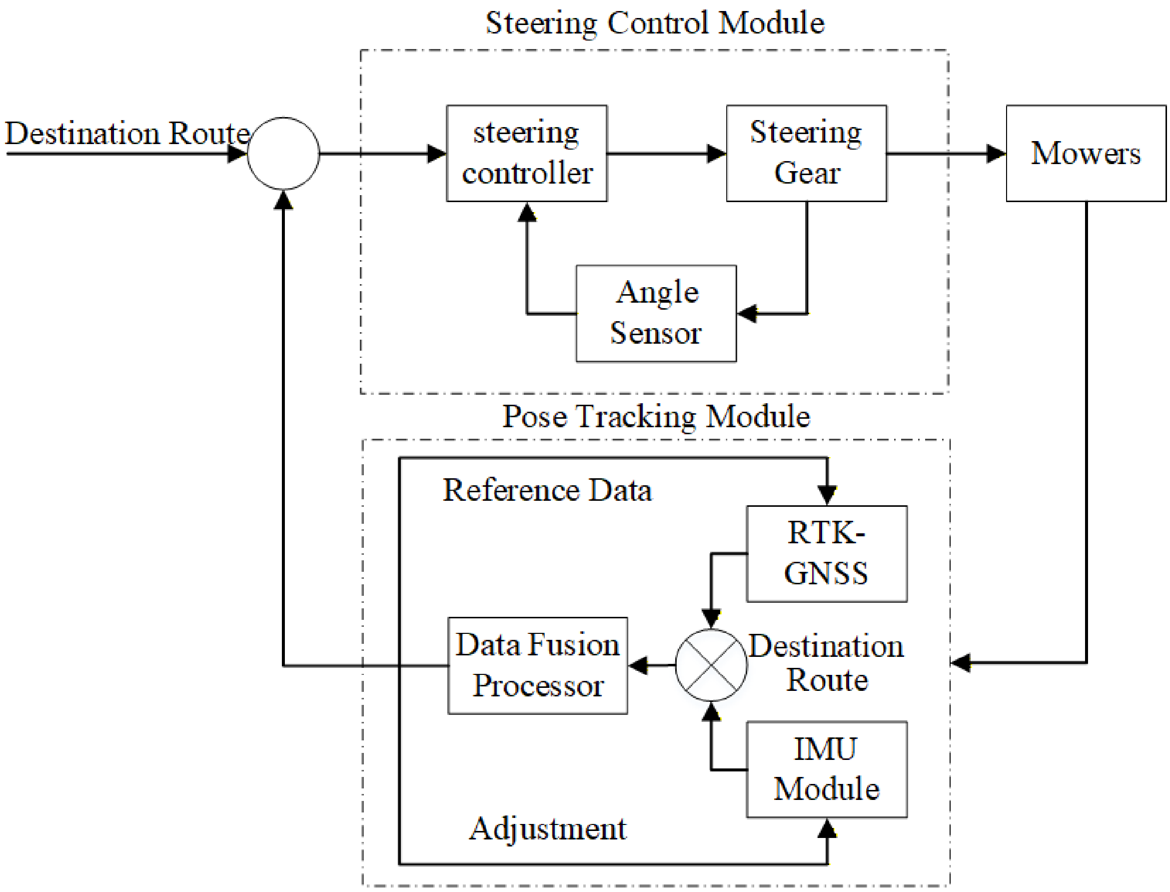


Figure 5. Architecture diagram of integrated navigation system.

within the cutting mechanism drives the reciprocating blade via lever linkage to precisely sever basal *Apocynum venetum* stalks against the stationary blade. The folded-stem handling assembly received the cut stalk. A terrain-following linkage supports a reel assembly incorporating compliant tines on a rotating disc structure, executing gentle crop retention before conveying folded stems to the bundling unit via a vertical obstruction-resistant conveyance system at the cutting table [23]. This conveyance system maintains stalk verticality through motor-driven drums and synchronous belts, thereby ensuring unobstructed upward transport. The bundling unit then initiates operation: the cord reservoir supplies binding material, while the cord pathing subsystem directs it to the knotter via guide pulleys and tensioners. The knotter, which is driven by a positive-drive cam mechanism, executes loop formation, knot tying, and cord severing to produce uniform bundles for discharge. As the harvester advances, *Apocynum venetum* bales accumulate between the track system and cutting table. The height-adjustable crop-plate compaction assembly auto-adjusts to crop conditions, compressing material to facilitate bale clearance beneath the chassis. Finally, the chassis-mounted obstruction-resistant conveyance system transports bales traversing the chassis clearance zone, preventing accumulation and eliminating operational downtime.

4 Design of Key Mechanisms

4.1 Design of the Cutting Mechanism

In mechanized harvesting of fiber-yielding *Apocynum venetum*, the cutting methodology directly governs cut morphological integrity and subsequent fiber processing quality. This study systematically compared the operational mechanisms and performance characteristics of single-harvest, reciprocating-cut, and rotary-cut systems for *Apocynum venetum* fiber harvesting, with morphological configurations of all three harvesting mechanisms presented in Figure 7.

The single-plant harvesting mechanism employs a manually operated handheld power unit that drives a cutting head, designed for individual *Apocynum venetum* plants or small clusters. This configuration offers a compact structural integration and operational flexibility, making it suitable for selective harvesting. The reciprocating cutter

Figure 6. Harvesting workflow of the *Apocynum venetum* cutting–bundling harvester, from pre-harvest monitoring and crop separation through basal reciprocating cutting, stem folding, vertical obstruction-resistant conveyance, cord-based bundling, crop-plate compaction, and chassis-mounted conveyance of formed bales.

assembly comprises an exposed moving blade and a stationary blade, forming a linear shear mechanism that operates through continuous closed-shear action. A power transmission system drives the high-speed reciprocating motion of the moving blade relative to that of the fixed blade, enabling instantaneous stalk severance via scissor-action cutting. Conversely, rotary cutting utilizes a free-cut impact mechanism, wherein high-speed rotation imparts kinetic energy to the cutterhead and fracturing stalks through impact-induced rupture. Performance analysis reveals that single-plant harvesting ensures precise crop selection and individual plant quality, but exhibits insufficient operational efficiency for large-scale production. Although rotary cutting achieves higher throughput, its impact-based severance frequently induces irregular fracture surfaces and fiber rupture, compromising structural integrity and failing to meet high-quality fiber agronomic specifications. Reciprocating cutting replicates the continuous shearing action of scissors to achieve instantaneous transverse stalk severance,

(a)

(b)

(c)

Figure 7. Comparison of three cutting methods for *Apocynum venetum* fiber harvesting: (a) single-plant harvesting mechanism driven by a handheld power unit; (b) reciprocating cutting mechanism using a moving and stationary blades to provide linear shear; and (c) rotary cutting mechanism relying on impact-based stalk fracture.

producing low, uniform stubble while preserving fiber morphology and tensile strength, and providing optimal raw material characteristics for subsequent retting and decortication processes. Consequently, this study adopts the reciprocating cutting methodology as the core harvesting mechanism to optimize the trade-off between operational efficiency and fiber quality.

The mechanism primarily comprises a hydraulic linear actuator, push rod linkage, lever transmission assembly, moving blade, stationary blade, and crop divider. The morphological configuration is presented in Figure 8. The conical crop divider, positioned at the machine's anterior terminus, guides and segregates *Apocynum venetum* stalks. The cutting mechanism resides beneath the reel assembly, with its core components consisting of the hydraulic linear actuator, lever transmission system, and reciprocating cutter assembly formed by the moving and stationary blades. During operation, the actuator drives the push rod linkage to execute linear reciprocation, transmitting power through the lever transmission to the moving blade, enabling precise basal severance relative to the stationary blade mounted on the cutterbar, achieving low-precision cutting at the plant base, as illustrated in Figure 9.

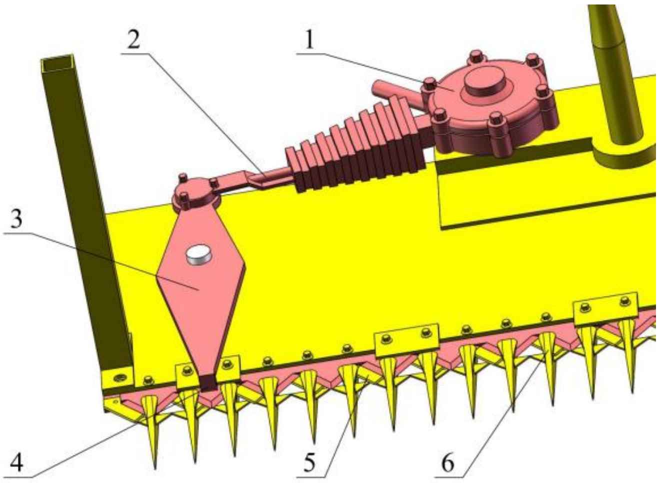


Figure 8. Design of the reciprocating cutting mechanism, including: (1) thrust motor; (2) push rod; (3) lever assembly; (4) moving blade; (5) stationary blade (guard); and (6) crop separator.

Controlled laboratory testing demonstrated that *Apocynum venetum* stem shear force increases proportionally with stem diameter, with maximum recorded shear force reaching 220 N for high-fiber-content specimens (fiber mass fraction >45%), indicating elevated shear resistance; consequently, per GB/T 1209.3-2009 Agricultural

Figure 9. Post-harvest field measurement of stubble height, demonstrating the low-cutting capability of the reciprocating device.

Machinery – Cutting Apparatus – Part 3: Safety Requirements for Reciprocating Blades, a toothed reciprocating blade assembly was selected, with operational parameters detailed in Table 2.

Table 2. Key design parameters of the type II reciprocating cutting device used for basal stalk severance in *Apocynum venetum* harvesting.

Parameter	Value / Type
Cutter	type II
Moving blade	type II
Knife rod	type I
Shear bar	type II
Cutting stroke S/mm	76.2
Cutting clearance angle of moving blade /°	60
Edge thickness of moving blade h/mm	1.4
Edge angle λ/°	30
Tooth pitch t/mm	2

4.2 Design of the Stem-Folding Assembly

The stem-folding assembly primarily integrates a bevel gear mechanism, horizontally configured hydraulic actuator, four-bar linkage assembly, vertically configured hydraulic actuator, left servo actuator, rocker assembly, frame linkage, and right servo actuator, as illustrated in Figure 10.

The stem-folding assembly utilizes crank rotation within a planar four-bar linkage to drive translational motion of the connecting rod. This bilaterally symmetric mechanism comprises identical left and

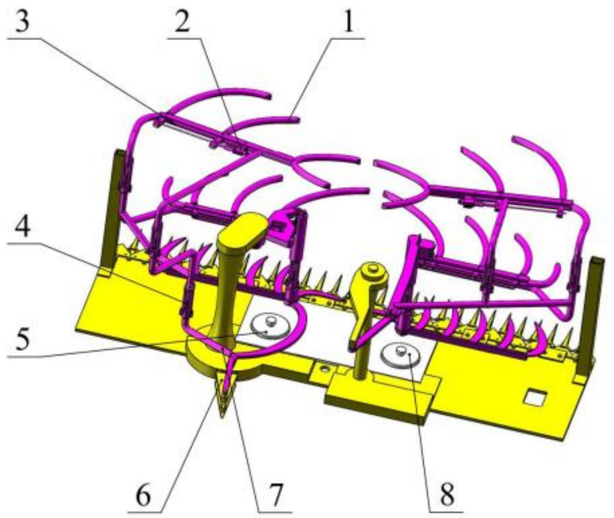
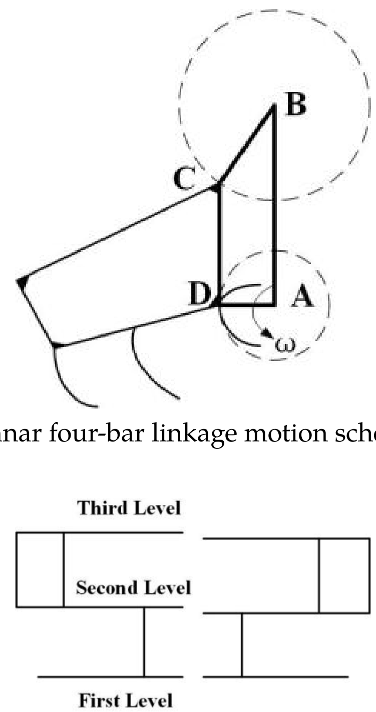


Figure 10. Schematic of the stem-folding assembly, featuring: (1) folding tines, (2, 4) horizontal and vertical actuators, (3) linkage lever, (5, 8) left and right servo actuators, (6) rocker, and (7) support frame.



(a) Planar four-bar linkage motion schematic.

(b) Layered configuration of the tine assembly.

Figure 11. Kinematic and structural details of the folding tines.

right subassemblies, mirror-imaged in the horizontal plane with equal rotational velocity but opposite angular direction, as depicted in the four-bar linkage schematic (Figure 11). To accommodate *Apocynum venetum* cluster morphology, a tandem-mounted terrain-following reel assembly featuring compliant tines was implemented for stalk collection. The left tine assembly maintained a 15° elevation relative to the right counterpart to prevent inter-tine interference during operation (Figure 11). Operators adjust horizontally and vertically configured hydraulic actuators to modulate tine aperture via linkage (width adaptation for variable crop clusters) and vertical strokes (height matching for diverse plant stands), enabling precise morphological alignment. Finally, left and right servo actuators drive rocker assemblies to execute oscillatory retention motions, conveying *Apocynum venetum* stems to the bundling unit.

4.3 Design of the Bundling Mechanism

As illustrated in Figure 12, the bundling unit integrates a cord reservoir, cord pathing subsystem, left servo actuator, right servo actuator, knotter assembly, drive motor, and cord-severing mechanism. The operation begins with the pathing subsystem extracting the cord from the reservoir, where the left servo actuator drives the needle-piercing mechanism to form a programmed loop count around the crop bundle. Upon loop completion, the drive motor and right servo actuator coordinate to position and secure the cord end for knot formation, after which the knotter assembly executes loop consolidation, and the cord-severing mechanism simultaneously severs excess cord during knot tightening to produce a consolidated bundle.

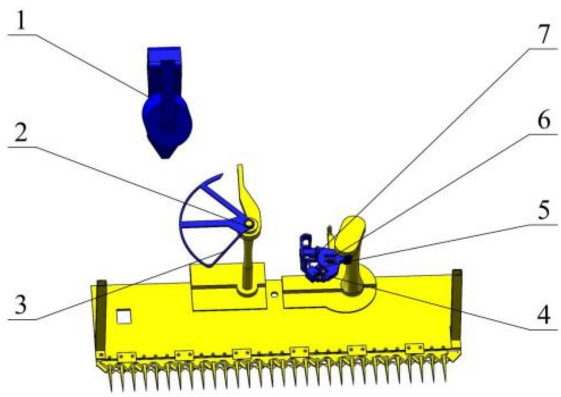


Figure 12. Diagram of the bundling and knotting unit, showing: (1) cord reservoir, (2) cord feeding mechanism, (3, 4) servo actuators, (5) knotter assembly, (6) drive motor, and (7) cord-severing mechanism.

4.4 Design of the Cutting-Table Vertical Anti-Clogging Conveyor

The vertical obstruction-resistant conveyance system at the cutting table features a left-right symmetrical configuration, primarily integrating a motor mounting bracket, cutting-table drive motor, timing pulley, timing belt, tapered drive drum, conveyor belt assembly, belt guard enclosure, tensioner pulley bracket, idler pulley assembly, and driven drum, as depicted in Figure 13.

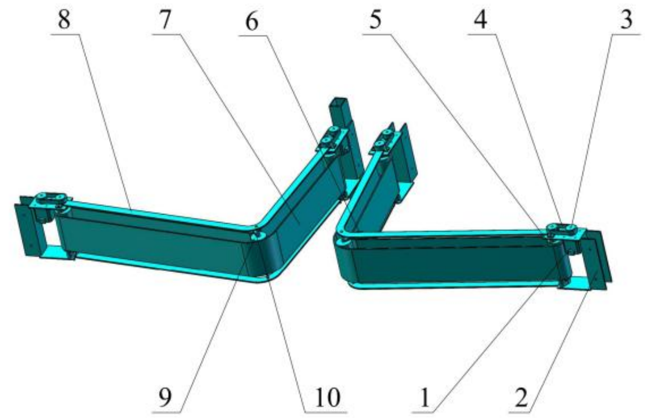


Figure 13. Vertical obstruction-resistant conveying device at the cutting table, showing the drive and support components that maintain stable vertical stem transport and prevent blockage at the header. Numbered components: (1) cutter drive motor; (2) motor bracket; (3) synchronous pulley; (4) synchronous belt; (5) variable-diameter conveyor drum; (6) tensioning pulley; (7) conveyor belt; (8) conveyor belt guard; (9) tensioning pulley bracket; and (10) guide roller.

The dual-motor mounting brackets reside within a common horizontal plane, with the drive motor and tapered drive drums installed thereupon. The timing pulleys are mounted on the motor output shaft and drum shafts, enabling power transmission via timing belts. The conveyor belt assembly forms a continuous-loop conveyance path at the external periphery of the tapered drive drums. Belt guard enclosures are positioned at both termini, whereas the motor brackets are rigidly interconnected with a driven drum mounted centrally. The idler pulley assembly is connected to the driven drum through a tensioner bracket to maintain optimal belt tension. During operation, the drive motor rotates the tapered drive drums to induce frictional engagement with the conveyor belt, ensuring stable and continuous material conveyance through maintained tension.

4.5 Design of the Height-Adjustable Crop-Plate Compaction Assembly

The height-adjustable crop-plate compaction assembly integrates a structural housing, motor mounting bracket, drive motor, support platen, flexible coupling, crop-plate assembly, lateral support frame, and fastening bolts, as depicted in Figure 14.

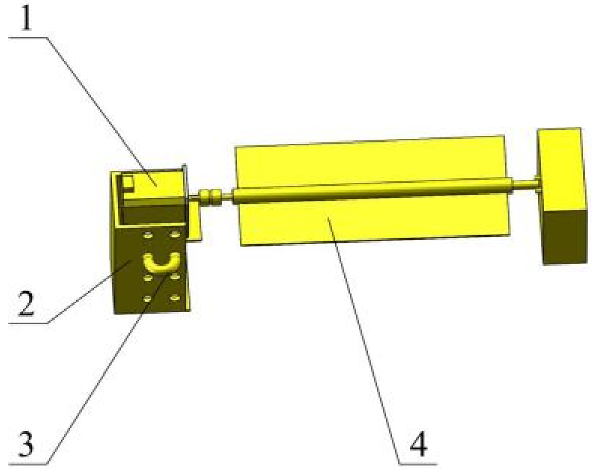


Figure 14. Height-adjustable stacking crop platen device, used to compact and support bundles at different heights according to crop load and stack thickness. Numbered components: (1) pressboard drive motor; (2) housing; (3) adjustable pin; and (4) pressure plate.

The structural housing mounts rigidly to the frame, featuring four pairs of precision-drilled holes that are symmetrically distributed across its surface. The crop-plate drive motor was installed above the support platen via the motor mounting bracket, with height adjustment achieved through pin engagement in the precision-drilled holes of the housing. One terminus of the crop-plate assembly connects to the drive motor output shaft via flexible coupling, whereas the opposing terminus engages the linear guide channel within the lateral support frame. Three pairs of alignment holes flank both sides of the lateral support frame, enabling axial displacement fixation via pin insertion. During operation, the drive motor rotates the crop-plate assembly, with working height modulated by repositioning the pin across discrete hole sets to accommodate variable crop-stack thicknesses. This configuration enables uniform compaction across diverse biomass densities.

4.6 Design of the Chassis-Mounted Anti-Clogging Conveyor

The chassis-mounted obstruction-resistant conveyance system features a symmetrical configuration, primarily integrating a structural frame assembly, chassis-mounted drive motor, conveyor drive shaft, primary gear set, secondary gear set, and conveyor belt assembly, as depicted in Figure 15.

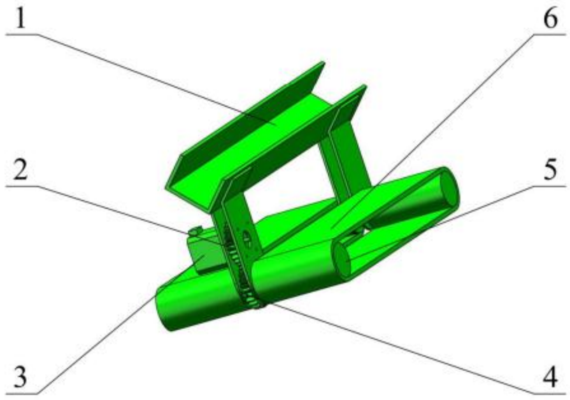


Figure 15. Chassis anti-clogging conveying device, transferring formed bundles through the chassis clearance zone while preventing material accumulation. Numbered components: (1) frame; (2) drive gear; (3) lower drive motor; (4) driven gear; (5) conveyor pulley; and (6) conveyor belt.

The structural frame assembly mounts rigidly to the chassis at its upper terminus, with conveyor drive and idler pulleys mounted at the lower terminus; the driven-side pulley incorporates the chassis-mounted drive motor. The motor output shaft engages the primary gear set, while the secondary gear set is mounted coaxially on the conveyor drive shaft and meshes with the primary set. The conveyor belt assembly engages circumferentially with both pulleys. Upon motor activation, the gear mesh transmits rotational motion to the drive pulley, thereby inducing stable belt tracking. This configuration ensures reliable material conveyance while maintaining obstruction-free operation.

5 Field Experiments

5.1 Test Materials and Methods

Field validation of the *Apocynum venetum* bundling harvester was conducted at a Xinjiang cultivation site, as illustrated in Figure 16. The technical parameters and daily throughput requirements for *Apocynum venetum* production are listed in Table 3. The crop configuration featured 20 cm intra-row spacing, 20 cm inter-row spacing in paired rows, drip irrigation tape deployment at 150 cm intervals (one tape per two rows), with typical cluster characteristics of 20–25 stems, 1.1–1.6 m height, 1.0 m diameter, and 3–7 mm stem diameter. The test harvester employed a diesel-electric hybrid powertrain with 1,400 mm cutting width [24].

Figure 16. Field prototype of the *Apocynum venetum* bundling harvester during validation trials in Xinjiang, demonstrating integrated operation under commercial planting conditions with drip-irrigated paired rows and clustered stem stands.

Table 3. Agronomic layout and target daily workload requirements for *Apocynum venetum* cultivation in the experimental test field.

Project	Numerical value
Distance between hills P/cm	20
Row spacing (within two rows)/cm	20
The number of rows per drip tape service N	2
Drip irrigation belt spacing S_d/cm	150
Number of stems per cluster N_c/root	20-25
Plant height /m	1.1-1.6
Cluster diameter D/m	1
Stem diameter d/mm	3-7
Work efficiency requirements $\eta/\text{hm}^2 \cdot \text{h}^{-1}$	0.5
Power: diesel + motor	11.5kW+8kW
Cutting width /mm	1400

Field validation of the *Apocynum venetum* bundling harvester was performed using crop-specific technical parameters and daily throughput requirements. Pre-test procedures included no-load operation initiation and functional status verification of all subsystems. Under normal idling conditions, the operator advanced the machine via clutch engagement, with iterative gear ratio optimization yielding an operationally optimal forward speed of 1.05 m/s. A 150 m test section was randomly selected within the field, and manual weed removal was conducted to ensure unobstructed operation. Ten consecutive test repetitions were performed, and the final performance metrics were derived from the arithmetic mean of all trials.

5.2 Analysis of Test Results

The experimental validation quantified seven performance metrics: stubble height, stubble unevenness, harvesting efficiency, blockage incidence, bundling success rate, fiber damage rate, and specific fuel consumption, as summarized in Table 4. The bundling harvester achieved a mean stubble height of 12.4 cm, stubble unevenness of 9.4 cm, harvesting efficiency of 0.537 ha h^{-1}, and blockage incidence of 0.3 events h^{-1}. Cylindrical bundles formed at 0.4 m above cut points exhibited mean diameter of 243 mm ($n = 40$), with bundling success rate of 98%, fiber damage rate of 0.8%, and specific fuel consumption of 12.31 L ha^{-1}. All metrics comply with ISO 11279:2021 performance thresholds, demonstrating optimal operational efficacy. The physical appearance of the produced bales, as shown in Figure 17, further confirms the uniformity and suitability for transport and processing.

Table 4. Field performance indicators of the *Apocynum venetum* cutting–bundling harvester.

Performance parameters	Test result
Stubble height/cm	12.4
Stubble unevenness/cm	9.4
Efficiency of crop /hm^2 h^{-1}	0.537
Blockage frequency / times $\cdot$ h^{-1}	0.3
Bundling rate/%	98
Fiber damage rate/%	0.8
Fuel consumption /L $\cdot$ hm^{-2}	12.31

Figure 17. *Apocynum venetum* bales produced by the cutting–bundling harvester, showing uniform bundle diameter, consistent compression, and tight cord binding suitable for transport, storage, and downstream fiber processing.

Under the guidance of an integrated navigation system that combined the BeiDou Navigation Satellite System (BDS) and inertial sensors, the intelligent *Apocynum* bundling machine achieved precise control over route tracking, steady-speed operation, turning maneuvers, and alarm-triggered braking in the event of signal loss during harvesting operations. This highlighted the practical applicability of the integrated navigation system for the intelligent *Apocynum* bundling machine. The system employed the NX100 controller from Huaco, which performed global path planning with the support of the Huace information management platform. The NX100 controller is utilized to regulate the course of the *Apocynum* baling machine, while speed adjustments are manually controlled through gear shifting.

To assess the path tracking performance of the integrated navigation system combined with the *Apocynum* baling machine, the path tracking accuracy and operational coverage within a specific area were analyzed. Figure 18 illustrates the driving trajectory and operational coverage of the integrated navigation system during the operation of the intelligent *Apocynum* cutting baler. The results demonstrated that the driving trajectory was smooth, with no significant yawing observed. Additionally, the operational coverage rate of the *Apocynum* cutting baler during harvesting reached 93.65%, confirming its capability to effectively meet the demands of real-world harvesting tasks.

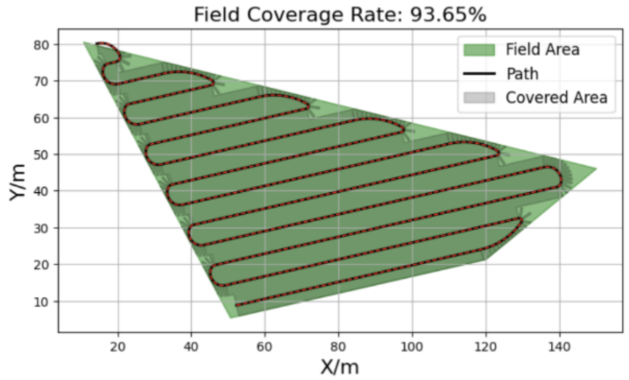


Figure 18. Operation trajectory and coverage of the *Apocynum* cutting baler.

6 Conclusion

This study proposes an intelligent *Apocynum venetum* cutting-bundling harvester specifically engineered to address the unique morphological characteristics of clustered stem growth and overcome critical harvesting challenges, including entanglement-induced obstruction, gripping slippage, conveyance inefficiencies, and inconsistent low-stubble severance. The system integrates six core functional modules: branch guidance, precision low-stubble cutting, stem folding, vertical obstruction-resistant conveyance, high-throughput bundling, and chassis-mounted obstruction-resistant transportation. Through the synchronized operation of these subsystems, continuous and high-efficiency harvesting from stalk severance to bundle formation is achieved. Furthermore, by integrating Beidou and inertial navigation positioning technologies, the driving path was automatically adjusted, and a global path-planning and autonomous-driving experiment was conducted in a predefined *Apocynum venetum* harvesting plot. Experimental results demonstrate that the integrated navigation and matching equipment enabled the harvesting coverage rate to exceed 93%, significantly enhancing the practical performance of autonomous driving technology for intelligent *Apocynum venetum* harvesters.

Leveraging the morphological characteristics of *Apocynum venetum* stalks, the stem-folding assembly and vertical obstruction-resistant conveyance system were specifically designed to resolve entanglement-induced obstructions during fiber handling. Functional subsystems, including reciprocating cutting, stem folding, vertical conveyance, and high-throughput bundling, were seamlessly integrated into a sequentially coordinated operational sequence, resulting in a 22.7% increase in system throughput. The coordinated performance of the cutting mechanism, stem-folding assembly, bundling mechanism, and dual anti-clogging conveyors ensures stable operation under clustered growth conditions while maintaining consistent cutting and bundling quality. Additionally, the implementation of pre-harvest monitoring and a height-adjustable crop-plate compaction assembly enables adaptive responses to variable crop cluster configurations and accumulation states, thereby improving operational reliability and agronomic adaptability.

In conclusion, the design of the intelligent *Apocynum venetum* cutting-bundling harvester provides an innovative engineering solution to address critical challenges such as entanglement-induced obstruction and inconsistent low-stubble severance, while enabling reliable autonomous driving in mechanized harvesting, in accordance with ISO 11279:2021 standards. Future work will focus on extending field validation under ASABE S572 protocols, followed by the optimization of key subsystems based on expanded operational datasets to support reliable large-scale deployment. This iterative refinement process aims to accelerate commercial deployment, thereby promoting modernization and mechanization within the *Apocynum venetum* cultivation industry.

Data Availability Statement

Data will be made available on request.

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Conflicts of Interest

The authors declare no conflicts of interest.

Ethical Approval and Consent to Participate

Not applicable.

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