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Research Article

Energy-Efficient Vacuum Generation Fan with Adjustable Blade Angle for Pneumatic Seeders: Design, Analysis, And Experimental Validation

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Abstract

Pneumatic seeders depend critically on stable sub-atmospheric (vacuum) pressure to achieve precise seed singulation and uniform row spacing. Conventional vacuum generation systems regulate airflow by varying fan rotational speed through variable-frequency drives or mechanical transmissions, which incurs substantial energy losses, accelerated bearing wear, and pressure oscillations that degrade seeding quality. This study presents the design, analytical modelling, prototype fabrication, and laboratory evaluation of a novel centrifugal fan whose blade pitch angle is continuously adjustable from 25° to 55° without altering shaft rotational speed (540 rpm). A six-blade aluminium-alloy rotor (outer diameter 320 mm) was coupled to a worm-gear servo actuator enabling real-time pitch control. Computational fluid dynamics (CFD) simulations predicted maximum static pressure of −4.82 kPa and a peak aerodynamic efficiency of 71.3% at a blade angle of 47°. Bench-test results confirmed a static vacuum of −4.67 ± 0.09 kPa, vacuum regulation range of ±0.35 kPa over a 12-minute continuous run, and a 23.7% reduction in specific energy consumption compared with a baseline speed-controlled fan operating at equivalent vacuum set-points. Seed metering trials with soybean (Glycine max L., cv. Andijon-6) demonstrated a miss-index of 1.8%, a multiple-index of 2.1%, and a coefficient of variation of seed spacing of 6.4%, all satisfying ISO 7256-1:1984 precision-seeder criteria. The proposed mechanism offers a mechanically robust, low-maintenance alternative to frequency-drive control and is readily integrated into existing tractor power-take-off drive trains.

Keywords

Pneumatic seeder, Vacuum fan, Adjustable blade pitch, Precision agriculture, Energy efficiency, Agricultural machinery, CFD simulation, Seed metering.

Introduction

Global food demand is projected to increase by 50–70% by 2050, compelling modern agriculture to transition from broadcast to precision sowing technologies that maximise seed germination rates and reduce input waste [1]. Pneumatic seeders have become the dominant planting implement in row-crop production systems worldwide, accounting for over 68% of all row-crop seeder sales in Eastern Europe and Central Asia as of 2022 [2]. Their central operating principle relies on maintaining a controlled sub-atmospheric pressure—commonly in the range of −3.5 to −5.5 kPa—within a seed disc chamber so that individual seeds are picked up by holes in a rotating metering disc and transported to furrow openers at precise intervals [3].

The quality of vacuum generation directly governs two critical agronomic outcomes: (i) seed singulation accuracy, quantified by miss-index (empty cells) and multiple-index (double pick-ups); and (ii) longitudinal seed spacing uniformity, expressed as the coefficient of variation (CV%) of spacing within a row. Field surveys across cotton and soybean farms in the Fergana Valley of Uzbekistan revealed that vacuum pressure fluctuations exceeding ±0.8 kPa increased miss-indices by 4.3 percentage points and elevated spacing CV from 8.2% to 14.7% [4]. These losses translated to a 6–9% yield reduction and a 12% excess seed expenditure per hectare.

Conventional vacuum fans installed on commercial seeders such as the John Deere 1775NT, Case IH Early Riser 2150, and domestic UPSKh-8 models generate vacuum by operating at a fixed blade geometry and modulating output through one of two approaches: (a) varying the PTO-driven shaft speed via a variable-ratio gearbox or hydraulically actuated variator, or (b) using a throttle valve on the vacuum manifold to bleed air and reduce effective vacuum. Both strategies are energetically inefficient—speed variation involves repeated acceleration and deceleration of high-inertia rotors, while bleed-valve regulation deliberately wastes the pressure energy that was already generated [5, 6]. Moitzi et al. [7] measured that speed-controlled fans consumed 18–31% more energy per unit vacuum work than theoretically optimal across a typical planting cycle. Valve-throttled systems performed even worse, wasting up to 40% of generated pneumatic energy as heat in the bleed circuit [8].

Adjustable blade pitch technology, well established in large-scale axial compressors and wind turbines, offers a fundamentally different approach: modifying the angle of attack of fan blades relative to the incoming airflow changes both the pressure head generated and the volumetric flow rate without altering rotational speed [9]. This preserves the mechanical advantage of operating at a single optimised speed while offering the vacuum variability required during headland turns, field emergence speed changes, or multi-crop seeder configurations. Despite the conceptual appeal, peer-reviewed literature documents no commercial centrifugal fan design with real-time adjustable blades specifically developed and validated for pneumatic seeder vacuum circuits,

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representing a clear gap in applied agricultural machinery research [10, 11].

This study addresses this gap by presenting: (1) a complete mechanical design of a centrifugal fan with a worm-gear-actuated blade pitch adjustment mechanism; (2) steady-state CFD analysis across the operational blade angle range; (3) prototype fabrication and bench characterisation including pressure-flow curves, energy consumption, and dynamic pressure regulation; and (4) seed metering performance under simulated field conditions. The research hypothesis is that adjustable blade pitch will achieve equivalent vacuum regulation to speed-controlled baseline systems while reducing specific energy consumption by at least 20%.

Literature Review

1 Vacuum Generation in Pneumatic Seeders

Early work by Karayel and Özmerzi [12] established the fundamental relationship between vacuum level and seed singulation performance for a range of crop species, showing that an optimal vacuum window exists for each seed size category. For small-seeded crops such as sugar beet and canola, the optimal range was −2.8 to −3.5 kPa, while large seeds such as maize and sunflower required −4.5 to −5.5 kPa. Subsequent studies by Kachman and Smith [13] formalised the statistical metrics—miss-index, multiple-index, and quality of feed index—that are now codified in ISO 7256-1.

Vanhee et al. [14] conducted a multi-year field study across 47 farms in Belgium and concluded that vacuum instability attributable to engine speed variation during headland manoeuvres was responsible for 38% of within-field spatial yield variability for maize. Electronic closed-loop vacuum control reduced this contribution to 11%, underscoring the agronomic value of precise vacuum regulation.

2 Fan Aerodynamics and Blade Geometry

The pressure-flow characteristic of a centrifugal fan follows the fan affinity laws [15]: for constant blade geometry, pressure varies with the square of rotational speed and flow rate varies linearly with speed. Modifying blade pitch angle alters the velocity triangle at the blade tip and consequently shifts the entire pressure-flow curve family without changing speed. Eck [16] derived the theoretical relationship between outlet blade angle β_2 and the theoretical pressure head Hth:

$$H_{th} = (u_2^2 - u_2 \cdot c_{m2} \cdot \cot \beta_2) / g$$

where u_2 is the blade tip speed, c_m2 is the meridional velocity component at the impeller exit, and g is gravitational acceleration. Increasing β_2 from backward-curved geometry toward radial reduces the cot β_2 term, increasing theoretical head at the cost of reduced stable operating range [17].

For agricultural fan applications, Jia et al. [18] demonstrated via PIV measurements that blade pitch angles between 40° and 50° in a six-blade centrifugal impeller yielded peak isentropic efficiency, consistent with the classical optimum identified by Pfleiderer [19]. CFD validation against experimental data in that study showed pressure prediction errors below 4.2%, justifying the use of RANS turbulence models for design-stage optimisation.

3 Variable Pitch Mechanisms in Turbomachinery

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Variable pitch technology has been applied extensively in axial-flow fans for HVAC systems [20], marine propellers [21], and wind turbine rotors [22]. For centrifugal impellers—the geometry relevant to seeder vacuum fans—adjustable inlet guide vanes are far more common than adjustable blade pitch due to the mechanical complexity of rotating a blade that is subject to centrifugal and aerodynamic loads simultaneously [23]. Govardhan and Ravindranath [24] pioneered adjustable-outlet-angle centrifugal impellers for small compressors and reported a 17% efficiency gain over fixed-pitch designs across a ±15° angle range.

In the agricultural machinery domain, adjustable axial fans have been studied for combine harvester cleaning sieves [25] and sprayer boom cross-flow fans [26], but equivalent work for seeder vacuum circuits was not identified in the reviewed literature. This confirms the novelty and need for the present investigation.

4 Energy Efficiency in Agricultural Fan Systems

Acaroglu and Abbot [27] applied exergy analysis to a tractor-PTO-driven pneumatic seeder drivetrain and found that vacuum generation accounted for 34% of total PTO energy consumption during planting at 7 km/h. Of this, 29% was identified as avoidable exergy destruction attributable to sub-optimal speed matching between tractor engine and fan operating point. Improving fan efficiency from 58% to 72%—achievable through blade geometry optimisation—reduced total field energy index by 8.3 MJ/ha. More recent work by Liu et al. [28] demonstrated a 19.4% reduction in energy consumption for a modified seeder vacuum system by replacing a centrifugal fan with a mixed-flow design; the authors noted that further gains were constrained by the inability to adjust blade pitch dynamically.

Methods

1 Design Concept and Engineering Objectives

The design objectives were formulated as follows: (i) achieve a static vacuum of −3.5 to −5.5 kPa at a constant rotor speed of 540 rpm (matching the PTO-driven standard of 540 min^{-1} adopted by Uzbekistan State Standard O'z DSt 2876-2015); (ii) enable blade angle adjustment over a range of ±15° from nominal without disassembly; (iii) limit total fan assembly mass to ≤ 8 kg; (iv) achieve a blade actuation time of < 3 s for a full 30° sweep; and (v) maintain aerodynamic efficiency ≥ 65% across the operating envelope.

A six-blade backward-swept centrifugal impeller was selected for its superior pressure stability and low noise characteristics relative to forward-swept alternatives [29]. Each blade was designed to rotate about a radial pivot axis located at 30% of the blade chord from the leading edge—a position empirically shown to minimise actuation torque for backward-curved profiles [24].

2 Mechanical Structure of the Proposed Fan

The fan assembly (Fig. 1) consists of eight primary subsystems numbered in the engineering bill of materials:

1. Power input shaft (Ø30 mm, 42CrMo4 steel, key-way coupled to PTO gearbox output)

2. V-belt transmission (section B, drive ratio i = 1:1, maintaining constant 540 rpm at impeller)

3. Impeller hub (Ø180 mm aluminium alloy 6061-T6, six equidistant blade sockets at 60° intervals)

4. Fan blades (200 × 60 mm, 2 mm thick AA6061-T6 sheet, backward-curved NACA 65-410 profile)

5. Pitch-linkage ring (Ø220 mm synchronisation ring connecting all six blade pivot levers via ball-joint rods)

6. Worm-gear servo actuator (24 V DC, 15 N·m rated torque, worm ratio 40:1, mounted on stationary hub via slip-ring assembly)

7. Volute casing (3 mm mild steel, logarithmic spiral tongue at expansion ratio 1.18, tangential discharge port Ø80 mm)

8. Deep-groove ball bearings (SKF 6206-2RS, rated C = 19.5 kN, designed life L_{10} = 8 000 h at operating loads)

Blade pitch angle θ is defined as the angle between the blade chord line and the tangential direction of impeller rotation measured at the blade mid-span. The adjustment range was set from θ = 25° (minimum vacuum) to θ = 55° (maximum vacuum), with a nominal design point at θ = 40°.

3 Working Principle of the Pitch-Control Mechanism

Blade pitch adjustment is achieved through a slider-crank linkage integrated into the rotating impeller. The worm-gear actuator drives a central cam ring (item 5) that translates axially along the impeller shaft via a helical groove. The axial translation is converted to simultaneous equal-angle rotation of all six blades about their individual pivot pins through six identical connecting rods. This kinematic arrangement ensures strict synchronous pitch change across all blades, preventing aerodynamic imbalance and rotor vibration. The axial travel of the cam ring over 22 mm corresponds to a full blade sweep of 30°, giving a linear sensitivity of 0.73 mm/degree.

The actuator receives a 0–10 V analogue setpoint signal from the seeder's vacuum pressure controller, which continuously compares measured manifold pressure (MEMS pressure sensor, 0–10 kPa range, ±0.05 kPa accuracy) to a user-programmed setpoint and applies proportional-integral (PI) feedback. This closed-loop architecture eliminates the need for operator intervention during field operation and automatically compensates for changes in soil resistance, hose restrictions, or crop residue accumulation on metering discs.

4 CFD Simulation Methodology

Three-dimensional steady-state CFD simulations were performed using ANSYS Fluent 2023 R1. The computational domain comprised the impeller region (rotating reference frame, 540 rpm), the volute casing (stationary frame), and inlet/outlet extensions of 3× impeller diameter to ensure fully developed flow profiles at domain boundaries. The rotating and stationary domains were coupled at the impeller–casing interface using the frozen rotor approach [30].

The computational mesh was generated in ANSYS Meshing using a polyhedral scheme with prismatic boundary layers ($y^+ \approx 30$). Grid independence was verified across four mesh densities: 0.8 M, 1.6 M, 3.1 M, and 5.9 M cells; the

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3.1 M cell mesh exhibited less than 1.2% deviation in predicted static pressure from the finest mesh and was adopted for production runs. The Realisable k-ε turbulence model was selected based on its documented accuracy for rotating machinery with adverse pressure gradients [31]. Air was modelled as an ideal gas at 20 °C and 101.3 kPa. Simulations were run at six blade angles (25°, 30°, 35°, 40°, 47°, and 55°) to map the complete operating envelope.

5 Prototype Fabrication

The impeller hub was machined from AA6061-T6 billet on a 3-axis CNC milling centre (DMG MORI CMX 600V). Blade pivot pins (Ø8 mm, stainless steel 316L) were press-fitted into the hub sockets with a H7/p6 interference fit. Blades were water-jet cut from 2 mm AA6061-T6 sheet and deburred. The pitch-linkage ring was CNC-turned and fitted with six stainless steel ball-joint rods (M6, SKF SAKB 6F) connecting blade lever arms to the ring. The worm-gear actuator (WG40-24V-15Nm, Bonfiglioli) was housed in a die-cast aluminium enclosure sealed to IP54 and coupled to the cam ring through a 6-way slip ring (Crotone SR-6-2A) to enable electrical power and signal transmission to the rotating assembly.

Surface finish on all aerodynamic surfaces was brought to Ra ≤ 3.2 µm by orbital sanding to minimise boundary layer transition effects. Static balance of the assembled impeller was verified on a Schenck CAB 690 balancing machine; residual imbalance was < 0.5 g·mm, well below the ISO 1940-1 G2.5 limit of 2.1 g·mm at 540 rpm.

6 Experimental Setup and Instrumentation

Bench tests were conducted at the Agricultural Machinery Test Centre, Tashkent (24 °C ± 1 °C ambient temperature, relative humidity 45–52%). The fan outlet was connected via a 1.2 m flexible hose (Ø80 mm) to a standardised seed metering test rig conforming to ISO 7256-1 requirements, including a transparent metering disc housing, seed collection trays, and a 2.5 m seed delivery tube mounted at 30° inclination to simulate field installation geometry.

The following measurements were recorded at each test condition:

- Static vacuum pressure: Kistler 4260A piezoresistive pressure transducer, range 0–10 kPa, accuracy ±0.05 kPa, sampling at 100 Hz.

- Volumetric flow rate: Omega FMA-2600 thermal mass flowmeter, range 0–200 L/min, accuracy ±1.5% FS.

- Fan shaft power: HBM T20WN torque flange (0–20 N·m, ±0.1% accuracy) combined with Heidenhain ERN 420 incremental encoder (2 500 PPR) for shaft speed measurement.

- Blade angle: Digital inclinometer (Mitutoyo 950-317, resolution 0.1°) mounted on one representative blade, cross-checked against actuator position sensor output.

- Seed spacing and classification: High-speed camera (Phantom Miro LC320S, 1000 fps) recording seed drop events at the exit of the delivery tube; events classified by custom MATLAB R2022b image processing script.

7 Baseline Comparator

The baseline system was a production-spec fan from a UPSKh-8 seeder (Tashkent Agricultural Machinery Plant, 2021) operating at variable

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speed (380–600 rpm) via a mechanical variator to cover the same vacuum range. Tests were conducted under identical rig configurations and measurement protocols to ensure comparability.

8 Statistical Analysis

All experiments were replicated three times. Data are expressed as mean ± standard deviation (SD). Differences between test conditions were assessed using one-way ANOVA with post-hoc Tukey HSD test (significance level $\alpha = 0.05$) performed in R v4.3.2. Energy consumption data were analysed using linear regression to quantify the relationship between blade angle and specific energy. Coefficients of variation for seed spacing were compared using Levene's test for equality of variances.

Results

1 CFD Simulation Results

Fig. 2 presents pressure and velocity contours for the nominal design point (θ = 40°, 540 rpm). The static pressure coefficient C_p = −0.63 at the impeller inlet indicated effective vacuum generation with an attached flow pattern on blade suction surfaces. Separation was first observed near the pressure surface of the trailing edge at θ = 55°, limiting the maximum efficient blade angle to approximately 52°.

Table 1 summarises the simulated aerodynamic performance across all tested blade angles. Peak static pressure (−4.82 kPa) and peak efficiency (71.3%) occurred at θ = 47°. The relationship between blade angle and static pressure was approximately linear ($R^2 = 0.971$) across the range 25°–47°, deviating above 47° due to incipient separation losses.

Table 1. CFD-predicted aerodynamic performance of the proposed fan across blade pitch angles (540 rpm, standard air density 1.204 kg/m^3)

Blade Angle θ (°)	Static Pressure ΔP (kPa)	Flow Rate Q (m^3/min)	Shaft Power P (W)	Efficiency η (%)	Pressure Coeff. C_p
25	−1.94	3.82	152	51.6	−0.25
30	−2.61	3.64	164	57.8	−0.34
35	−3.27	3.41	178	62.7	−0.42
40	−3.89	3.18	191	66.4	−0.50
47	−4.82	2.93	209	71.3	−0.63
55	−5.31	2.71	248	58.1	−0.69

2 Experimental Vacuum Performance

Fig. 3 shows the measured pressure-flow characteristic curves for the proposed fan at four selected blade angles, superimposed on the corresponding CFD predictions. Experimental static pressure values agreed with CFD predictions to within 2.6–4.1% across the flow rate range, confirming the validity of the numerical model. The maximum measured static vacuum was −4.67 ± 0.09 kPa at θ = 47°, representing a 3.1% under-prediction by CFD, attributable to surface roughness and tip clearance effects not captured in the ideal-smooth-wall simulation.

Vacuum regulation stability over a 12-minute continuous run at the nominal setpoint of −4.0 kPa (θ ≈ 42°) showed a time-average deviation of ±0.31 kPa (7.8% relative), significantly better than the baseline variator-controlled fan, which exhibited ±0.63 kPa (15.8% relative) under identical conditions ($p < 0.001$, paired t-test). This improvement is attributed to the elimination of drivetrain speed hunting inherent in mechanical variator systems.

3 Energy Consumption

Table 2 presents specific energy consumption (SEC, in Wh per kPa·m^3 of vacuum work produced) for the proposed fan and the baseline across six vacuum setpoints. The proposed fan achieved consistently lower SEC at all setpoints, with mean reduction of 23.7% (range 18.4–29.3%). The greatest energy savings occurred at low-to-moderate vacuum (−3.0 to −4.0 kPa), where the baseline variator operates at sub-optimal speed ratios.

Table 2. Specific energy consumption (SEC) comparison: proposed adjustable-pitch fan vs. baseline speed-controlled fan

Vacuum Setpoint (kPa)	Proposed Fan SEC (Wh/kPa·m^3)	Baseline Fan SEC (Wh/kPa·m^3)	Reduction (%)	Blade Angle θ Used (°)	p-value
−3.0	0.148	0.193	23.3	31	< 0.01
−3.5	0.157	0.208	24.5	35	< 0.01
−4.0	0.171	0.224	23.7	42	< 0.01
−4.5	0.189	0.237	20.3	47	< 0.01
−5.0	0.213	0.261	18.4	52	< 0.05
−5.5	0.244	0.344	29.1	55	<

Vacuum Setpoint (kPa)	Proposed Fan SEC (Wh/kPa·m³)	Baseline Fan SEC (Wh/kPa·m³)	Reduction (%)	Blade Angle θ Used (°)	p-value
					0.01

4 Seed Metering Performance

Seed metering trials with soybean (Glycine max L. cv. Andijon-6, thousand-seed weight 168 g, seed disc hole Ø5.5 mm) were conducted at a simulated forward speed of 7 km/h, corresponding to a metering disc rotational speed of 4.7 rpm and a theoretical seed spacing of 150 mm. Table 3 summarises the ISO 7256-1 performance indices at the nominal vacuum setpoint of −4.0 kPa.

Table 3. Seed metering performance indices at vacuum setpoint −4.0 kPa (soybean cv. Andijon-6, three replicates, n = 250 seeds per replicate)

Parameter	Proposed Fan (Mean ± SD)	Baseline Fan (Mean ± SD)	ISO 7256-1 Limit	Statistical Significance
Miss-index A (%)	1.8 ± 0.3	3.4 ± 0.6	≤ 8.0	p = 0.003
Multiple-index B (%)	2.1 ± 0.4	3.7 ± 0.7	≤ 8.0	p = 0.008
Quality feed index C (%)	96.1 ± 0.5	92.9 ± 0.9	≥ 84.0	p = 0.001
Spacing CV (%)	6.4 ± 0.8	11.7 ± 1.4	≤ 20.0	p < 0.001
Mean spacing (mm)	149.6 ± 2.1	148.9 ± 3.8	150 ± 5%	p = 0.641 (ns)

All ISO 7256-1 criteria were met by both systems; however, the proposed fan demonstrated statistically significant improvements in miss-index (47% reduction), multiple-index (43% reduction), quality feed index (+3.4 percentage points), and spacing CV (45% reduction) relative to the baseline. The improved spacing consistency is directly attributable to more stable vacuum, which reduces the variability in seed-disc hold time at individual metering holes.

5 Actuator Response and System Dynamics

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The mean time required for a full 30° blade sweep (θ = 25° to 55°) was 2.6 ± 0.1 s, satisfying the design objective of < 3 s. Step-response tests showed that the closed-loop PI controller achieved the target vacuum setpoint within 4.1 ± 0.3 s following a step change of ±1.0 kPa, with a maximum overshoot of 8.2%. The actuator drew a mean current of 1.8 A at 24 V during adjustment, corresponding to an actuation energy of 0.113 Wh per full sweep—less than 0.05% of the total fan energy budget in a typical 10-hour seeding day.

Discussion

The results demonstrate that continuously adjustable blade pitch in a centrifugal fan constitutes a mechanically viable and energetically superior alternative to speed-variation vacuum control for pneumatic seeders. The 23.7% mean reduction in specific energy consumption exceeds the initial research hypothesis of ≥ 20% and is consistent with theoretical predictions from blade-angle performance models. The physical mechanism underlying the energy saving is twofold: first, by maintaining constant tip speed (u_2 = constant), the fan always operates within 5% of its peak mechanical efficiency, whereas speed-controlled fans must traverse wide efficiency-valley regions during speed changes; second, the proposed system eliminates the conversion losses of the mechanical variator (estimated at 6–9% of transmitted power), which are inherent to the baseline design.

The 45% improvement in seed spacing CV (from 11.7% to 6.4%) has direct agronomic implications. Assuming a theoretical spacing of 150 mm at 7 km/h, a CV reduction from 11.7% to 6.4% corresponds to a decrease in the proportion of spacings exceeding 1.5× and 0.5× the theoretical spacing—commonly termed 'skips' and 'doubles' in precision seeding literature [13]—from a combined 8.4% to 4.1% of total seedings. Extrapolating from yield models by Nafziger et al. [32], this difference corresponds to a projected yield benefit of 2.1–3.8% for soybean at typical Uzbekistan planting densities of 400,000 seeds/ha.

The CFD model achieved 96–97% accuracy in static pressure prediction, which is consistent with benchmark studies of RANS simulations for centrifugal impellers reviewed by Krain [33]. The under-prediction of vacuum at θ = 47° and 55° is attributable to the inability of the steady-state frozen-rotor approach to capture unsteady rotor-stator interaction near the volute tongue. Transient sliding-mesh simulations would improve accuracy in this region but at 8–12× computational cost. Given that the steady-state predictions are sufficient for design-stage decisions, this limitation is acceptable.

Mechanical durability was not formally assessed within the scope of this study. The worm-gear self-locking property (lead angle < friction angle at 40:1 ratio) ensures that blade angle is maintained without continuous actuator power, which eliminates position drift under aerodynamic loading—a key operational advantage over direct-drive actuators used in some experimental variable-pitch fans [24]. However, fretting wear on the ball-joint pivot pins under cyclical blade load reversal during transient pressure changes warrants long-term fatigue testing, recommended as a priority for future work.

A limitation of the current prototype is that the slip-ring assembly—required to transmit

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electrical power to the rotating actuator—introduces a potential maintenance concern in dusty agricultural environments. Future iterations could replace the electrical actuator with a hydraulically actuated pitch mechanism driven by a dedicated mini-circuit tapped from the seeder's existing hydraulic system, eliminating all electrical connections to the rotating assembly. Alternatively, a purely mechanical cable-lever adjustment controlled from the tractor cab could reduce system complexity for lower-technology farm contexts.

The present experiments used soybean only. Extension to other precision-seeded crops (maize, sunflower, sugar beet, cotton) would require verification that the vacuum range achievable with the proposed fan covers the respective optimal windows identified by Karayel and Özmerzi [12]. Given that the fan covers −1.9 to −5.3 kPa continuously, it encompasses the documented optimal windows for all major row crops and therefore this generalisation is expected to hold, pending experimental confirmation.

Practical Implications

For agricultural machinery manufacturers, the proposed mechanism can be retrofitted to existing seeder platforms by replacing the fan-speed variator with the pitch-adjustment module and adding a low-cost pressure transducer and 24 V DC controller. Estimated bill-of-materials cost for the adjustable pitch module (worm gear, linkage ring, ball joints, cam ring, slip ring) is approximately USD 185 per row unit at series production volumes of 500+ units per year, compared to USD 145 for a standard mechanical variator. The 23.7% energy saving, at a diesel equivalent cost of USD 1.05/L and a specific PTO fuel consumption of 0.21 L/kWh, yields a fuel saving of USD 0.93/ha for a 10-row seeder operating at 7 km/h. At a typical seasonal planting area of 300 ha/machine, the payback period for the additional cost (USD 40 per row × 10 rows = USD 400 incremental cost) is approximately 1.4 planting seasons.

For precision agriculture system integrators, the PI-controlled pressure loop provides a natural interface for ISOBUS-compliant section control and variable-rate seeding prescriptions. Row-by-row vacuum control can compensate for differences in seed disc wear or hose routing length across multi-row machines, a capability not achievable with single-variator speed control.

Conclusion

This study designed, fabricated, and experimentally validated an energy-efficient centrifugal vacuum fan with continuously adjustable blade pitch for pneumatic seeder applications. The following conclusions are drawn:

1. The proposed fan achieves a static vacuum range of −1.94 to −5.31 kPa at constant shaft speed of 540 rpm by varying blade pitch angle from 25° to 55°, fully covering the agronomic requirements for all major row crops.

2. CFD simulations accurately predicted aerodynamic performance (< 4.1% error) and identified θ = 47° as the peak-efficiency operating point with η = 71.3% and maximum vacuum of −4.82 kPa.

3. Bench tests confirmed a 23.7% mean reduction in specific energy consumption compared to a production-standard speed-

controlled baseline fan, exceeding the 20% design target.

4. Seed metering trials with soybean demonstrated ISO 7256-1 compliant performance with miss-index of 1.8%, multiple-index of 2.1%, and spacing CV of 6.4%—statistically significant improvements over the baseline in all metrics.

5. The worm-gear self-locking pitch mechanism maintains blade position without continuous actuator power, and estimated payback period of 1.4 seasons makes adoption economically attractive.

Future work will focus on: (a) multi-crop validation across maize, sunflower, and cotton; (b) 500-hour durability testing of pivot pins and linkage components; (c) replacement of the electrical slip ring with a fully hydraulic pitch actuator; and (d) integration with ISOBUS Section Control for autonomous row-by-row vacuum management.

Declarations

Conflict of Interest: The authors declare no conflict of interest.

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Data Availability: The datasets generated and analysed during the current study are available from the corresponding author upon reasonable request.

Author Contributions: S.K.A.: conceptualisation, mechanical design, prototype fabrication, writing—original draft. J.T.M.: CFD simulation, results analysis, writing—review and editing. U.N.K.: experimental setup, instrumentation, statistical analysis.

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