

CFD-Guided design and experimental validation of a horizontal ribbon-blade mixer for commercial *Leucaena leucocephala*-based ruminant feed production

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Received 23 May 2026

Revised 10 July 2026

Accepted 3 August 2026

Abstract

Homogeneous mixing of compound animal feed is a prerequisite for nutritional consistency, growth performance, and economic feasibility in commercial ruminant production. Acacia (*Leucaena leucocephala*) wood chips have emerged as a low-cost, locally available protein-rich roughage in tropical Southeast Asia, but their irregular particle geometry and density mismatch with conventional concentrates pose a persistent processing challenge. This study presents a coupled computational and experimental framework for the design and validation of a 1.5 m³ horizontal ribbon-blade mixer tailored for *L. leucocephala*-based feed production. Three blade geometries—screw, paddle, and double helical ribbon—were comparatively evaluated using a transient three-dimensional CFD model (Volume-of-Fluid multiphase coupled with a moving reference frame and the $k-\epsilon$ turbulence closure) at shaft speeds of 10, 20, and 50 rpm over a 20 min mixing cycle. The ribbon geometry consistently outperformed the screw and paddle blades, reducing the predicted Coefficient of Variation (CV) from 42.1 % to 11.7 % within 6 min. A full-scale prototype with a centerline ribbon diameter of 1.14 m, pitch of 0.51 m, and a 10 kW motor was subsequently fabricated. Experimental sampling at ten radial-axial locations and one discharge point yielded a minimum CV of 7.01 % and a Lacey mixing index of 0.987 at 10 rpm after 5 min, in close agreement with the CFD prediction (CV = 7.1 %; relative error = 1.3 %). The validated prototype achieved a throughput of 4.5 t h⁻¹ at a specific energy consumption of 0.42 kWh t⁻¹ and a simple payback period of 2.63 years. The combined numerical-experimental-economic evidence demonstrates that CFD-guided geometric selection can deliver a commercially deployable, energy-efficient mixer for heterogeneous lignocellulosic-protein feed mixtures.

Keywords: Ribbon-Blade mixer, CFD, Coefficient of variation, *Leucaena leucocephala*, Agricultural machinery design, Ruminant feed

1. Introduction

Compound feed manufacturing has become the dominant pathway for supplying balanced nutrition to ruminant livestock in tropical agroecosystems. In Southeast Asia, smallholder cattle, buffalo, and goat producers increasingly rely on locally available agro-forestry biomass to lower feed costs while maintaining nutritional quality. Among such biomass resources, the leguminous tree *Leucaena leucocephala* has attracted particular attention because of its high crude protein content (23–35 % DM), favorable amino acid profile, and adaptation to marginal soils [1, 2]. Recent reviews further confirm that, when ruminants are progressively adapted, the rumen bacterium *Synergistes jonesii* detoxifies mimosine and dihydroxypyridine derivatives, eliminating the historical toxicity concern [3–6]. Collectively, this body of nutritional and toxicological evidence confirms that *L. leucocephala* is a safe, high-protein roughage for ruminant diets once properly processed, and that maintaining a target Coefficient of Variation (CV) ≤ 10 % during mixing is essential for consistent animal performance.

Although the nutritional value of *Leucaena* is well established, processing it into a homogeneous compound feed at commercial scale remains a non-trivial mechanical problem. Acacia wood chips differ markedly from conventional concentrates in shape, density, and elastic response: bulk densities range from 380 to 520 kg m⁻³, whereas roasted soybean and palm kernel cake fall between 580 and 650 kg m⁻³ [7, 8]. This density disparity, combined with the elongated and angular geometry of the chips, promotes segregation and

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<https://doi.org/10.64960/easr.2026.268104>

dead-zone formation in conventional vertical and screw mixers. Mix uniformity—quantified by the Coefficient of Variation (CV) and the Lacey mixing index—directly governs animal growth, feed conversion ratio, and economic margin: industry guidelines recommend $CV \leq 10\%$ for finished ruminant feed [9-12]. Failure to meet this threshold leads to micronutrient under- or overdosing and is a recognized cause of variability in commercial weight-gain performance.

Horizontal ribbon-blade mixers are widely promoted for heterogeneous granular blends because the counter-pitched double helix simultaneously generates axial and radial convective flow, suppressing stagnant zones [13, 14]. Reported CV values for ribbon mixers handling agricultural materials range from 4 to 13 % depending on blade geometry, fill level, and rotational speed [15-18]. Comparative studies remain dominated, however, by trial-and-error scale-up and rarely couple computational fluid dynamics (CFD) with full-scale experimental validation for biomass-rich tropical feeds.

CFD and the Discrete Element Method (DEM) have matured into reliable tools for predicting granular and multiphase mixing in industrial blenders [19-21]. Recent CFD-DEM studies confirm that the Lacey index is the most robust descriptor of steady-state mixing in ribbon-type devices at both particle and macro scales [14, 22]. Yet, three gaps remain. First, most CFD studies of ribbon mixers consider idealized spherical particles and binary mixtures, whereas commercial ruminant feed combines fibrous wood chips, oilseed meals, and pelleted premix in three or more density classes. Second, the link between CFD-predicted CV and field-scale CV measured under industry-standard sampling protocols is rarely quantified. Third, integration with techno-economic indicators—throughput, specific energy consumption, payback—is seldom reported, even though such metrics are required for technology transfer to small- and medium-scale feed plants.

This study addresses these gaps by combining (i) a transient three-dimensional VOF–MRF CFD analysis of three competing blade geometries (screw, paddle, ribbon) operated at 10, 20, and 50 rpm; (ii) full-scale fabrication and experimental validation of the selected ribbon-blade prototype using a 1 t batch of dense ruminant feed amended with 500 kg of *Leucaena* chips; and (iii) techno-economic evaluation against manual mortar-based preparation. The specific objectives are to: (1) compare blade geometries on the basis of CV and Lacey mixing index evolution; (2) validate the CFD-selected geometry under industrial sampling conditions at ten spatial locations; (3) quantify the throughput, specific energy consumption, and payback of the developed prototype; and (4) benchmark its performance against published horizontal feed mixers. The work contributes a transferable CFD-to-prototype workflow for the rational design of commercial mixers handling heterogeneous lignocellulose-protein feed in tropical livestock systems.

2. Materials and methods

2.1 Overall research workflow

The investigation followed a three-stage workflow: (i) numerical screening of three candidate blade geometries by transient three-dimensional CFD; (ii) design and fabrication of a full-scale prototype around the CFD-selected geometry; and (iii) experimental performance and energy testing against an industrial feed formulation. The variables, sampling strategy, and response metrics for each stage are summarized below.

2.2 Feed materials and target formulation

The target formulation reflected a commercial dense ruminant feed amended with chopped *Leucaena leucocephala* (*L. leucocephala*) (Table 1 and Table 2). The base mixture comprised 1 t of compound feed combined with 500 kg of acacia wood chips, giving a 2:1 concentrate-to-roughage ratio. The chemical composition of *L. leucocephala* relative to grass and corn silage is shown in Table 1; bulk densities and volume fractions of the three principal CFD constituents (acacia wood, roasted soybeans, palm kernel cake) are reported in Table 2. Moisture content of the feed mixture was $13.4 \pm 0.6\%$ wet basis, measured in triplicate using AOAC method 934.01. The acacia (*L. leucocephala*) wood chips used in both the CFD model and the physical mixing trials had a mean chip length of 15–25 mm and a mean thickness of 3–5 mm, determined by manual caliper measurement of a 100-chip sample; this size range is consistent with the particle-scale assumptions of the VOF continuum treatment discussed in Section 2.3.2.

Table 1 Chemical composition (% DM) of *L. leucocephala* compared with conventional roughage sources (adapted from Barros-Rodríguez et al. [1]).

Material	N	C	P	K	Tannins
<i>L. leucocephala</i>	4.00	39.94	0.03	0.73	3.24
Pangola grass	0.56	42.49	0.01	0.64	1.94
Corn silage	2.40	37.01	0.03	1.62	—

Table 2 Density and volume fraction of the three principal materials used in the CFD simulation.

Material	Density (kg m ⁻³)	Volume fraction (%)
Acacia wood chip	450	40
Roasted soybean	640	25
Palm kernel cake	584	35

2.3 Computational fluid dynamics (CFD) model

2.3.1 Geometry and blade configurations

Three blade geometries representative of commercial horizontal feed mixers were modeled at identical envelope dimensions (Figure 1): (a) a single-flight screw with 1.14 m diameter and 0.51 m pitch; (b) a paddle blade with 0.10 m wide flat paddles set at 45°; and (c) a double helical ribbon with counter-pitched outer and inner ribbons, 1.14 m outer diameter and 0.51 m pitch. The cylindrical mixing chamber had an internal volume of 1.5 m³.

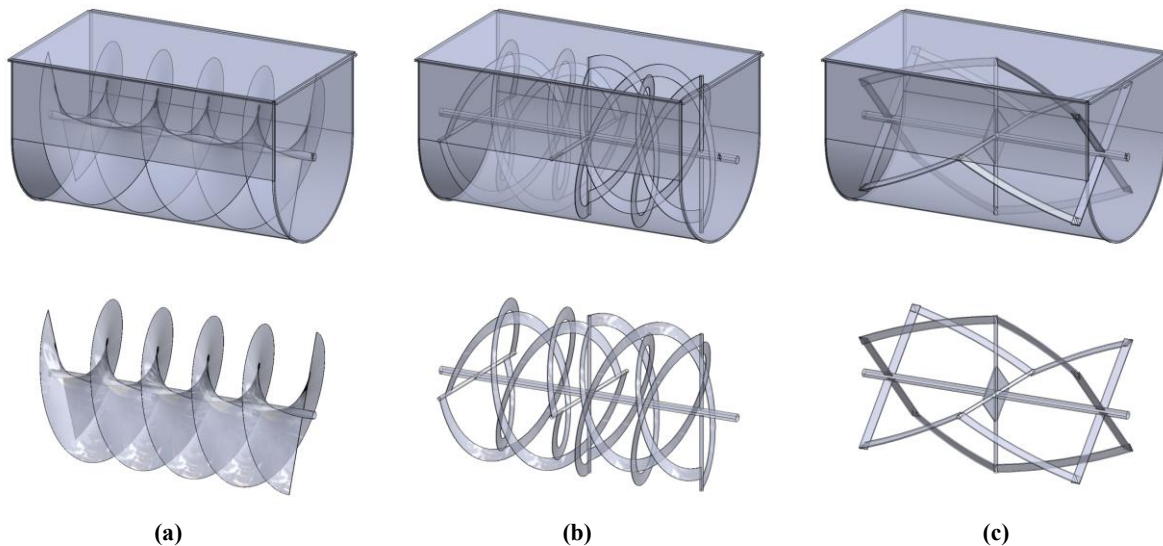


Figure 1 Three CFD blade geometries: (a) screw, (b) paddle, (c) double helical ribbon.

2.3.2 Governing equations and numerical scheme

Mixing was treated as an incompressible Newtonian multiphase flow. The Volume-of-Fluid (VOF) method was used to track the interfaces of the three constituent materials. The continuity and momentum equations solved for each phase were:

$$\partial(\alpha_k \rho_k) / \partial t + \nabla \cdot (\alpha_k \rho_k \mathbf{u}) = 0 \quad (1)$$

$$\partial(\rho \mathbf{u}) / \partial t + \nabla \cdot (\rho \mathbf{u} \otimes \mathbf{u}) = -\nabla p + \nabla \cdot [\mu (\nabla \mathbf{u} + \nabla \mathbf{u}^T)] + \rho \mathbf{g} + \mathbf{F}_{ST} \quad (2)$$

where α_k , ρ_k , $\mathbf{u}$, p , μ , $\mathbf{g}$ and $\mathbf{F}_{ST}$ denote the volume fraction, density, velocity vector, pressure, viscosity, gravitational acceleration, and surface-tension source, respectively. Turbulence closure was provided by the standard k - ϵ model, with k and ϵ transport equations integrated up to the wall using standard wall functions. The Moving Reference Frame (MRF) approach was used to represent blade rotation, providing stable numerical convergence under quasi-steady conditions while preserving computational tractability for a 20 min mixing cycle.

The selection of a VOF-MRF formulation rather than a particle-resolved Discrete Element Method (DEM) or a coupled CFD-DEM scheme deserves explicit justification. DEM and CFD-DEM remain the reference techniques for resolving individual particle-particle and particle-wall collisions, segregation patterns, and contact-force statistics in ribbon mixers [13, 14, 19, 22]. However, the computational cost of a fully particle-resolved simulation of a 1.5 m³ chamber loaded with $O(10^8-10^9)$ acacia-soybean-palm-kernel-cake particles over a 20 min physical mixing cycle is prohibitive on the 32-core workstation available for this study; published industrial-scale DEM studies are typically limited to lab-scale geometries (< 0.05 m³) or to physical times of only a few seconds [13, 22]. The target endpoint of the present study is not particle-scale segregation but the macroscopic CV evaluated from 100 g samples withdrawn at ten radial-axial locations—a sampling resolution that is two to three orders of magnitude larger than the characteristic particle size and that therefore averages over the very sub-grid fluctuations that DEM would resolve. Within this macroscopic framing, the three principal feed constituents behave as quasi-immiscible bulk phases over the convective time scale: their bulk densities differ by 30–40 % (Table 2) and the corresponding gravitational and inertial forces dominate over the sub-particle cohesive forces that would necessitate a DEM description. The VOF formulation is therefore well suited to capture the bulk-phase interface evolution and the convective-diffusive transport that ultimately governs the CV at industrial sampling resolution, while the MRF closure provides a stable representation of the quasi-steady blade-induced flow field. The validity of this engineering-level reduction is treated empirically: the predicted CV is benchmarked against full-scale experimental sampling in Section 3.2, where a relative error of 1.3 % at the operational reference point provides the ultimate validation of the modelling choice.

The pressure-velocity coupling was solved by the SIMPLE algorithm with second-order upwind discretization for momentum, volume fraction, and turbulence quantities. All residuals were converged to 10^{-5} . The time step was fixed at 1×10^{-4} s; cases were run for the equivalent of 20 min of physical mixing time on a 32-core Intel Xeon workstation. Identical operating conditions—initial layered loading, no-slip walls, zero-velocity inlets/outlets—were imposed across the three blade geometries to allow unbiased comparison.

2.3.3 Mesh and grid independence

Three unstructured tetrahedral meshes were generated for the ribbon-blade case: coarse ($\approx 0.5 \times 10^6$ cells), medium ($\approx 1.2 \times 10^6$ cells), and fine ($\approx 2.1 \times 10^6$ cells). Refinement was concentrated at the blade-tip clearance and the chamber wall. The grid-independence criterion was a < 5 % change in the volume-averaged velocity magnitude between successive levels. The medium and fine meshes differed by 3.2 %, while the predicted streamline topology was visually identical (Figure 2). The medium mesh was therefore retained for all production runs. The three panels of Figure 2 correspond to: (a) coarse mesh ($\approx 0.5 \times 10^6$ cells), (b) medium mesh ($\approx 1.2 \times 10^6$ cells), and (c) fine mesh ($\approx 2.1 \times 10^6$ cells). For each mesh, the upper row shows the total pressure contour (Pa) and the lower row shows the velocity magnitude contour (m s⁻¹) on the same longitudinal cross-section; both rows carry an explicit numeric colour-scale legend (minimum/maximum value) as generated directly by the CFD post-processor.

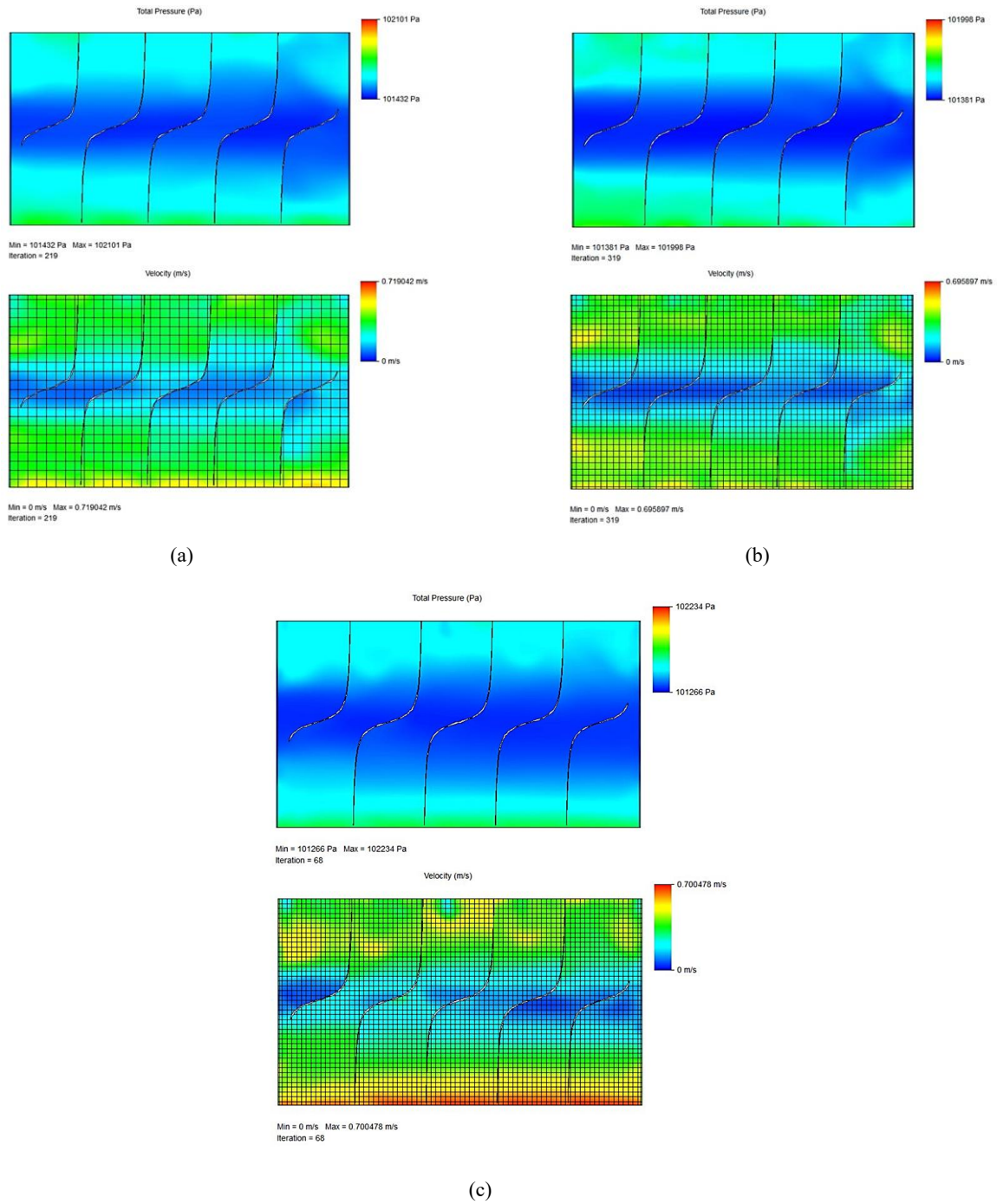


Figure 2 Velocity contours for grid-independence verification across coarse, medium, and fine meshes. (a) coarse, (b) medium, (c) fine mesh; upper row = total pressure (Pa), lower row = velocity magnitude (m s^{-1}), each with its own colour-scale legend as shown.

2.4 Mixing-quality descriptors

Two descriptors were computed from time-resolved volume-fraction or sample-composition data: the CV and Lacey's mixing index (M) [23].

$$\bar{x} = (1/n) \sum x_i \quad (3)$$

$$s = \sqrt{[\sum (x_i - \bar{x})^2 / (n - 1)]} \quad (4)$$

$$CV = (s / \bar{x}) \times 100 \% \quad (5)$$

$$M = (\sigma_0^2 - \sigma^2) / (\sigma_0^2 - \sigma_r^2) \quad (6)$$

where σ_0^2 is the variance of the fully segregated initial state, σ_r^2 is the theoretical variance of a perfectly randomized mixture, and σ^2 is the variance at time t . M ranges from 0 (complete segregation) to 1 (fully randomized). Industry-standard quality bands corresponding to M values are summarized in Table 3.

Table 3 Interpretation of Lacey's mixing index [13, 23].

M	Mixing level	Description
0	Complete segregation	Components remain distinctly separate.
0.01–0.20	Slight mixing	Limited interpenetration of components.
0.21–0.40	Moderate mixing	Distribution improves but remains incomplete.
0.41–0.60	Good mixing	Approaching uniform distribution.
0.61–0.80	Very good mixing	Distribution close to randomized.
0.81–1.00	Complete mixing	Practically random distribution; suitable for commercial feed.

2.5 Prototype design and fabrication

Guided by the CFD screening (Section 3.1), a full-scale prototype was designed around the double helical ribbon geometry. Power is supplied by a 10 kW (≈ 13.4 hp) three-phase electric motor driving a 50:1 reduction gearbox; speed is regulated by a variable-frequency inverter coupled to a programmable logic controller (PLC). Key sub-systems are summarized in Table 4 and illustrated in Figure 3.

Table 4 Specifications of the principal sub-systems of the horizontal ribbon-blade feed mixer.

Sub-system	Specification
Mixing tank	Volume 1.5 m ³ ; counter-pitched horizontal ribbon blade; centerline diameter 1.14 m; pitch 0.51 m; driven by a 10 kW motor at 1450 rpm through a 50:1 gearbox; speed regulated by a variable-frequency inverter and PLC.
Storage / holding tank	Volume 3.0 m ³ with auxiliary ribbon blade, 1.14 m centerline diameter, driven by a 7.5 kW motor through an 80:1 gearbox.
Bagging unit	Pneumatically actuated load-cell-controlled bag filler with adjustable 10–50 kg fill range.
Conveyor system	V-shaped chain-roller bucket conveyor (0.75 kW, 10:1 gearbox, inverter-controlled).

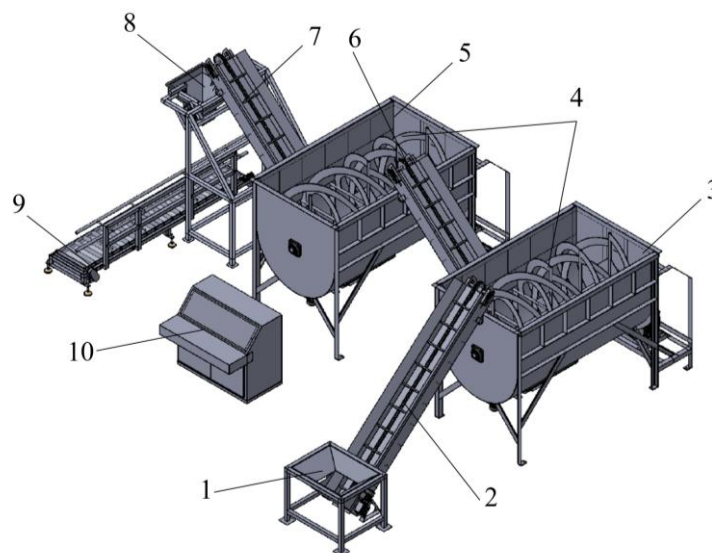


Figure 3 Integrated mixing-storage-bagging system. 1) Material intake point; 2) Conveyor to the mixing tank; 3) Mixing tank; 4) Horizontal mixed blade; 5) Storage tank; 6) Conveyor from the mixing tank to the storage tank; 7) Conveyor from the storage tank to packaging; 8) Packaging point; 9) Conveyor belt for outgoing products; 10) Control cabinet.

2.6 Experimental procedure

The prototype was charged with 1 t of dense compound feed, 500 kg of acacia chips, and 10 kg of color-coded tracer pellets (5 mm diameter) representing a non-segregating quality marker. Three shaft speeds (10, 20, 50 rpm) were tested. These three speeds were selected, rather than a denser sweep including 30 or 40 rpm, in order to observe the broader trend in mixing performance across a wider span of the practical operating range: sampling at widely separated low, intermediate, and high rotational speeds (10, 20, and 50 rpm) reveals how CV, the Lacey mixing index, and specific energy consumption evolve with increasing shaft speed more clearly than a narrower band of closely spaced values would, while keeping the experimental programme manageable (3 speeds $\times$ 3 replicate batches = 9 physical trials). At each speed, ten 100 g samples were withdrawn every minute for 8 min: nine from a 3×3 radial-axial grid inside the mixing chamber and one from the discharge chute (Figure 4). Tracer counts were converted to component fractions, from which CV and M were computed using Eqs. (3)–(6). Three independent batches were performed at each speed ($n = 3$); reported values are means $\pm$ standard deviation.

Energy consumption was logged with a three-phase digital power meter (accuracy $\pm 1.0\%$) for the duration of each batch. Specific energy consumption was calculated as the integrated electrical energy divided by the mass of finished feed. Direct labor and electricity costs were evaluated against the manual baseline using a constant electricity tariff of 4.50 THB kWh⁻¹ and a minimum wage of 300 THB day⁻¹.



Figure 4 Sampling positions: nine intra-tank locations plus one discharge sample.

3. Results

3.1 CFD analysis of blade geometry

Velocity contours on the longitudinal mid-plane of the mixing chamber are presented in Figure 5 for the three blade geometries operated at 10 rpm. The double helical ribbon produced the most uniform velocity field, with a pronounced counter-rotating recirculation that displaced material across both the axial and radial directions. The paddle generated localized high-velocity pockets adjacent to the blade tips but left low-velocity wake regions in the trailing zone, whereas the screw geometry produced essentially axial pumping with limited radial exchange, leading to early formation of a stagnant zone near the inner shaft. In Figure 5, the three rows correspond, from top to bottom, to the screw, paddle, and ribbon geometries; within each row, the left-hand panel shows the velocity contour on the transverse cross-sectional plane at the tank mid-length, and the right-hand panel shows the corresponding longitudinal mid-plane section. Colour represents velocity magnitude (m s^{-1}) using a common scale across all panels.

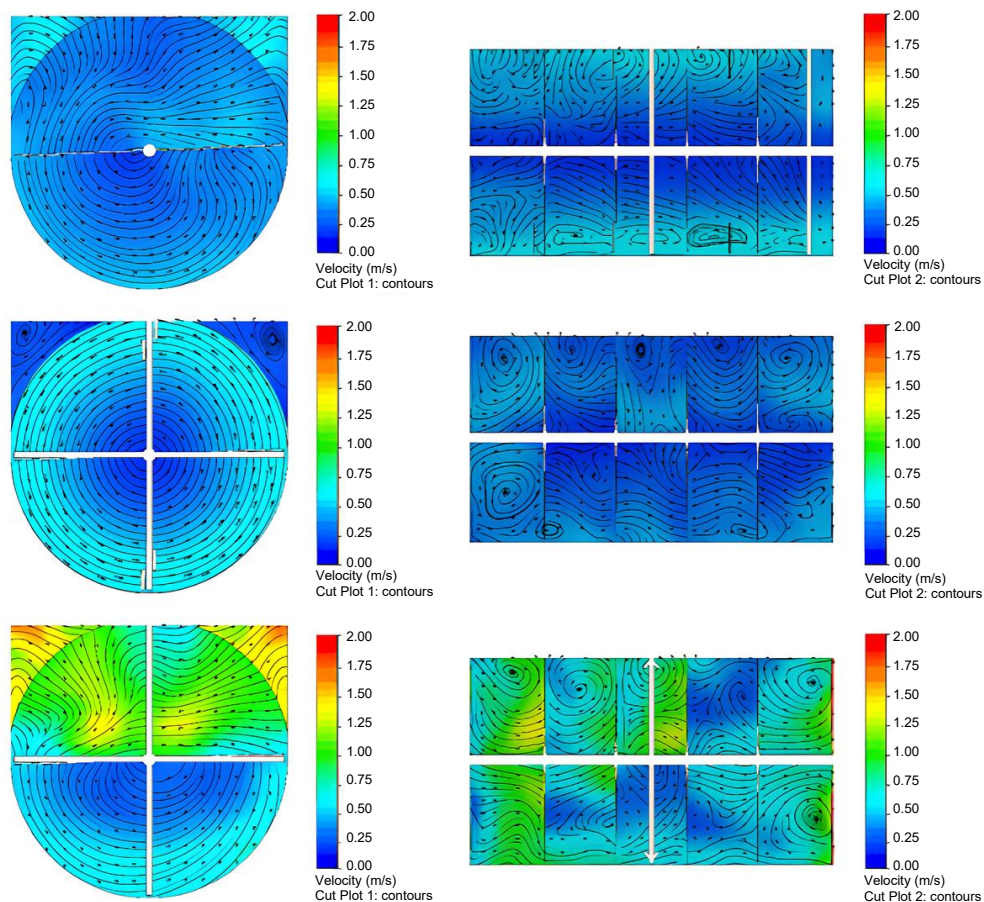
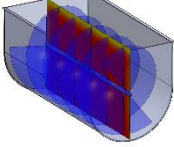
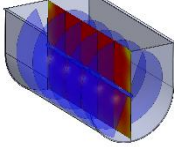
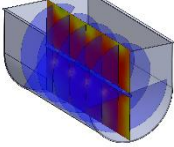
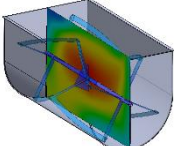
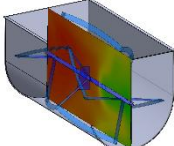
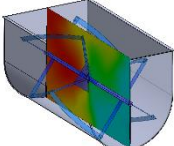
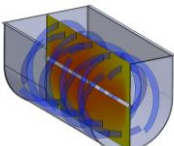
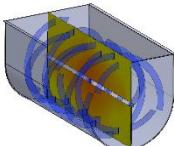
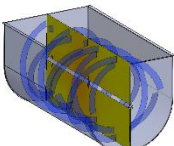


Figure 5 Velocity contours for the screw, paddle, and ribbon blades at 10 rpm (longitudinal mid-plane). Rows (top–bottom): screw, paddle, ribbon. Left column: transverse cross-section; right column: longitudinal mid-plane.

Time-resolved volume-fraction snapshots (Table 5) further illustrate that the ribbon blade achieved visible compositional homogeneity within 3 min, whereas the screw and paddle blades still showed coherent material layers at $t = 3$ min. The combination of axial transport from the outer ribbon and counter-axial recirculation from the inner ribbon explains the rapid dispersion: the two flow streams continuously fold and stretch the interface between the heavy concentrate and the lower-density acacia chips, accelerating diffusive-like mixing at the macroscale.

Table 5 Qualitative volume-fraction snapshots inside the mixing chamber for each blade at 10 rpm (visualization frames at $t = 1, 2, 3$ min).

Blade	t = 1 min	t = 2 min	t = 3 min
Screw			
Paddle			
Ribbon			

Quantitatively, the CFD-predicted CV decreased from an initial value of 42.1 % to 11.7 % after 6 min for the ribbon blade, compared with 13.7 % after 10 min for the paddle and 14.8 % after 20 min for the screw. At all three rotational speeds (10, 20, 50 rpm), the ribbon geometry was the fastest of the three geometries to cross the commercial threshold of $CV \leq 10\%$, confirming its superiority for heterogeneous biomass-rich feeds and corroborating the DEM findings of Gao et al. [14] and Jin et al. [22]. Increasing speed from 10 to 50 rpm shortened the time-to-target but plateaued in terms of asymptotic CV, suggesting diminishing returns above 20 rpm and a likely energy-efficiency optimum at the lower end of the range. The complete time evolution of the CV and the Lacey mixing index for the three candidate blade geometries at 10, 20, and 50 rpm is presented in Figure 6.

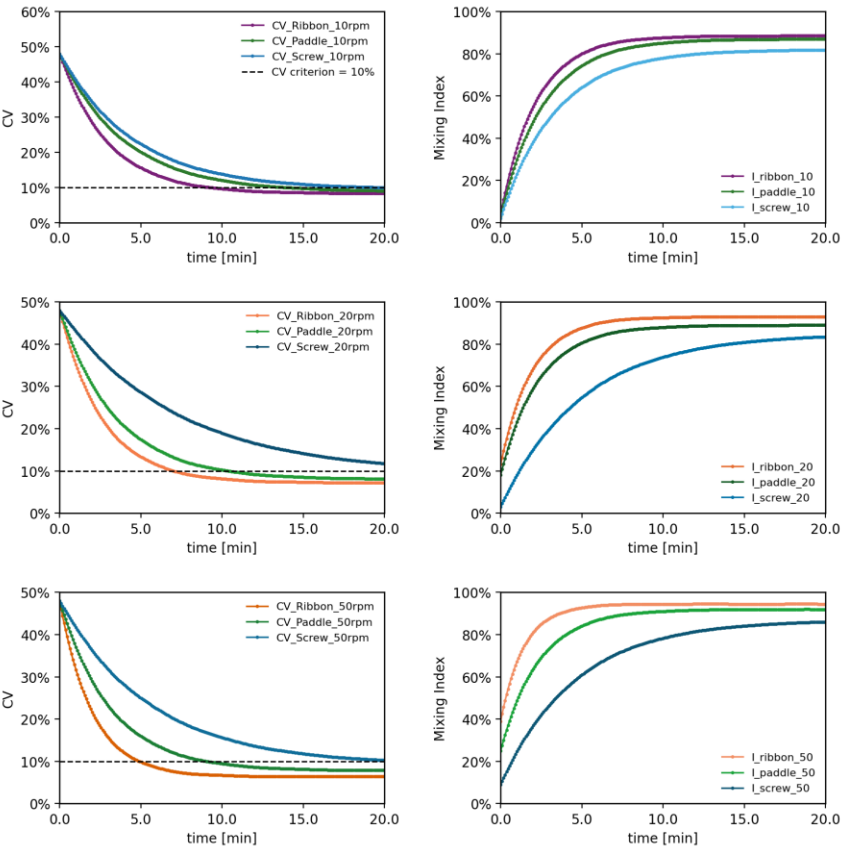


Figure 6 Time evolution of the Coefficient of Variation and Lacey mixing index for the three blades at 10, 20, and 50 rpm (CFD predictions).

Figure 6 confirms that the double helical ribbon is indeed the fastest of the three geometries to cross the $CV \leq 10\%$ threshold at every speed tested (≈ 9.2 min at 10 rpm, ≈ 7.0 min at 20 rpm, and ≈ 4.9 min at 50 rpm), whereas the paddle blade crosses later (≈ 13.8 , 10.4, and 9.1 min, respectively) and the screw blade only approaches the threshold by the end of the 20-min window at 10 rpm and does not cross it at all within 20 min at 20 or 50 rpm. Separately, the CFD value of $CV = 7.1\%$ quoted in Section 3.2 for the operational reference point (10 rpm, 5 min) comes from a dedicated validation run configured to exactly reproduce the fabricated prototype's geometry and loading, which is distinct from the geometry-screening curves of Figure 6 (at 10 rpm, the screening curve for the ribbon blade reads $\approx 16\%$ at $t = 5$ min); this explains why the two CFD values differ even though both originate from the same overall VOF-MRF framework. Finally, the apparently divergent trends of CV and the Lacey mixing index M for the ribbon blade at 10 rpm (CV falling below the 10 % threshold, reaching $\approx 8\%$ by 20 min, while M asymptotes to only $\approx 88\%$, not 100 %) are mathematically expected rather than contradictory: as defined in Eqs. (3)–(6), M is normalised between the fully segregated (σ^2) and fully randomised (σ^2) variance limits and therefore measures relative progress toward an idealised random-mixture reference, whereas CV is an absolute measure of sample-to-sample variability computed directly from the sample compositions; there is no requirement that both metrics reach their respective limiting values ($CV \rightarrow 0$, $M \rightarrow 1$) simultaneously.

3.2 Validation of the CFD model

Experimental sampling of the fabricated ribbon-blade prototype was used to test the predictive accuracy of the CFD model. At the operational reference point (10 rpm, 5 min), the CFD model predicted $CV = 7.1\%$, whereas the mean experimental CV across three batches was $7.01 \pm 0.55\%$, yielding a relative error of 1.3 %. This level of agreement is comparable to or better than recent multiphase mixing simulations of agricultural granular systems [19, 20] and is considered acceptable given the irregular geometry of the acacia chips, the polydispersity of the feed components, and the simplifying VOF assumption of a continuum mixture. The agreement supports the use of the present CFD framework as a design tool for upstream geometry screening of industrial mixers handling heterogeneous biomass-protein feeds.

3.3 Prototype performance

Photographic documentation of the prototype, control panel, and fabricated double-ribbon blade is provided in Figure 7–9. The complete experimental dataset for the prototype is summarized in Table 6. CV decreased monotonically with mixing time at all three speeds; the most favorable balance between mixing quality and energy use was obtained at 10 rpm and 5 min ($CV = 7.01\%$, $M = 0.987$). At 20 rpm, the system reached a comparable CV of 6.46 % at the same elapsed time, while at 50 rpm the CV minimum dropped to 5.32 % but only after 5 min of operation that consumed substantially higher electrical energy and induced visible attrition of the soybean fraction (an undesirable secondary outcome for downstream pelletization).

Table 6 CV (%) as a function of mixing time at three rotational speeds (mean of three batches; standard deviations $< 0.5\%$).

Speed (rpm)	1	2	3	4	5	6	7	8
10	69.09 $\pm$ 7.98	38.08 $\pm$ 2.28	28.38 $\pm$ 5.82	15.27 $\pm$ 1.23	7.01$\pm$0.55	8.05 $\pm$ 2.84	4.09 $\pm$ 0.29	2.88 $\pm$ 0.21
20	31.57 $\pm$ 2.22	26.27 $\pm$ 2.12	15.10 $\pm$ 1.37	9.24 $\pm$ 2.79	6.46 $\pm$ 1.05	4.05 $\pm$ 0.49	3.19 $\pm$ 0.42	3.27 $\pm$ 0.69
50	26.43 $\pm$ 0.95	21.15 $\pm$ 2.99	16.06 $\pm$ 2.28	9.51 $\pm$ 2.67	5.32 $\pm$ 1.44	3.92 $\pm$ 0.58	2.06 $\pm$ 0.25	2.48 $\pm$ 0.56



Figure 7 Fabricated horizontal ribbon-blade feed mixer.



Figure 8 PLC-based electrical control cabinet.



Figure 9 Double helical ribbon blade (1.14 m diameter, 0.51 m pitch).

The detailed reference feed formulation used for the prototype validation experiments, including the mass of each ingredient that constitutes the 1.5 t batch, is summarized in Table 7. The principal feed components and the sampling positions used during prototype testing are illustrated in Figure 10.

Table 7 Reference feed formulation used in the prototype experiments (total batch = 1.5 t).

Ingredient	Mass (kg)
Acacia (<i>L. leucocephala</i>) wood chip	500
Dried compound feed	450
Rice bran	420
Roasted soybean	60
Coconut shell pulp	60
Mineral / salt premix	10

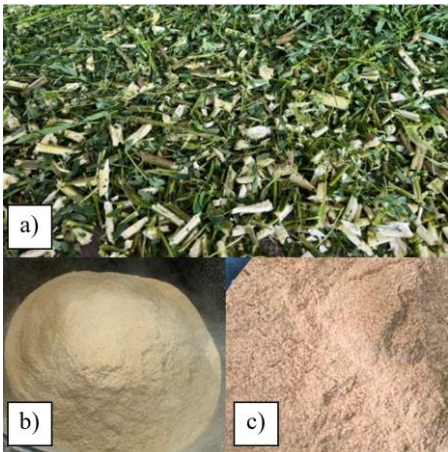


Figure 10 Sampling positions used during prototype testing. a) Acacia wood chips; b) Premix with powdered salt; c) Dense animal feed (dry).

The corresponding time evolution of the CV for the fabricated prototype at the three rotational speeds is plotted in Figure 11. The visual appearance of the resulting feed mixture obtained at 10 rpm after 5 min of mixing is shown in Figure 12, confirming the homogeneous dispersion of the acacia chips throughout the dense compound feed matrix.

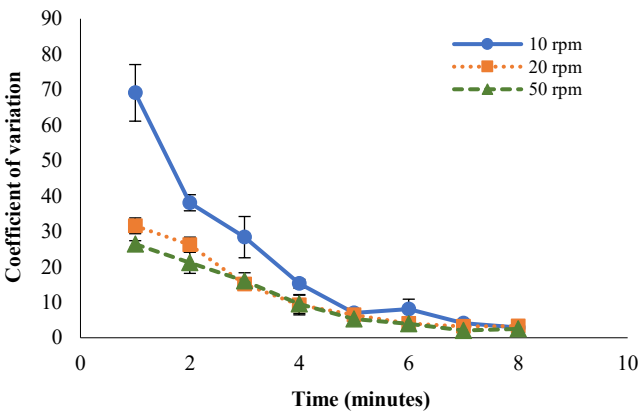


Figure 11 Coefficient of variation versus mixing time for the fabricated prototype (10, 20 and 50 rpm).



Figure 12 Visual appearance of the feed mixture at 10 rpm after 5 min.

At 10 and 20 rpm, the CV decreased below the commercial 10 % threshold by 5 min, corresponding to Lacey indices of 0.987 and 0.983, respectively. At 50 rpm, the CV continued to decrease but did so at the cost of higher electrical demand and observable material attrition. The progression of CV with time followed the canonical three-stage profile reported for ribbon mixers (convective stage → diffusive stage → asymptotic plateau), with the convective stage clearly dominant during the first 3 min of operation.

3.4 Energy and economic performance

The active power, energy consumed per cycle, specific energy consumption, and corresponding electricity cost measured for each of the three rotational speeds are summarized in Table 8.

Table 8 Energy consumption per batch at three rotational speeds (electricity tariff: 4.50 THB kWh⁻¹).

Speed (rpm)	Active power (kW)	Energy / cycle (kWh)	Specific energy (kWh t ⁻¹)	Cost / cycle (THB)
10 (5 min)	7.42±0.20	0.62±0.02	0.42±0.01	2.78±0.07
20 (5 min)	9.73±0.20	0.81±0.02	0.54±0.01	3.65±0.08
50 (4 min)	15.21±0.11	1.01±0.01	0.67±0.01	4.56±0.03

Operating at 10 rpm delivered the lowest specific energy consumption (0.42 kWh t⁻¹) while still satisfying the CV ≤ 10 % criterion in 5 min. Accounting for upstream conveyance and downstream discharge to the storage tank, the integrated mixing cycle was 20 min per 1.5 t batch, corresponding to an effective throughput of 4.5 t h⁻¹ and a daily capacity of 36 t for an 8 h shift. Daily electricity cost at 10 rpm was 273.6 THB.

3.5 Benchmarking against published mixers

A performance benchmark of the developed mixer against representative horizontal ribbon mixers reported in the literature is summarized in Table 9.

Table 9 Performance benchmark of the developed mixer against representative horizontal mixers reported in the literature.

Reference	Blade	Size	Speed (rpm)	Time (min)	M (%)	CV (%)
This study (2025)	Horizontal double ribbon	1.14 m (1.5 m ³)	10	5	98.65	7.01
Tongtib & Wichitkul [24]	Horizontal ribbon (rice)	350 mm	21.75	5	—	22.70
Clark et al. [25]	Double ribbon (broiler feed)	Industrial batch	—	5	—	9.47
Yeow et al. [26]	Horizontal convective batch ribbon (powder)	400 mm	80	10	—	≤10
Halidan et al. [13]	Two- / four-bladed ribbon (DEM)	200 mm	50–200	—	85–95	—

Table 9 benchmarks the developed mixer against representative horizontal ribbon mixers reported in the literature, with mixing performance expressed primarily as the CV. At 10 rpm and 5 min, the present 1.5 m³ prototype achieved CV = 7.01 % and a degree of mixing M = 98.65 %, comfortably below the industry-accepted ceiling of 10 % CV for compound feeds [27]. This performance is competitive with the 9.47 % CV obtained by Clark et al. [25] for a commercial double-ribbon mixer using dl-methionine as a marker after 5 min, and with the homogeneity limit (≤ 10 % CV equivalent) reported by Yeow et al. [26] for a 400 mm convective batch ribbon mixer at 80 rpm and 10 min on a lactose-ascorbic-acid-zinc-oxide blend. By contrast, the rice-feed horizontal ribbon mixer of Tongtib and Wichitkul [24] attained CV = 22.70 % at 21.75 rpm and 5 min, indicating that geometry and ingredient compatibility are decisive when the rotational speed alone is similar. DEM simulations of two- and four-bladed ribbon mixers by Halidan et al. [13] further corroborate that increasing impeller speed improves the Lacey mixing index up to a threshold (≈ M = 0.85–0.95) beyond which de-mixing of cohesive particles is observed — a regime that the present prototype deliberately avoids by operating at the low end of the practical rpm range. Taken together, the benchmark confirms that the CFD-guided ribbon geometry delivers feed-grade homogeneity at a substantially lower rotational speed (10 vs. 21.75–200 rpm) and a shorter or equivalent mixing time (5 vs. 5–10 min) than the published comparators, translating into lower specific energy consumption and reduced mechanical wear while preserving practical scalability for commercial *Leucaena*-based ruminant feed production.

3.6 Techno-economic comparison with manual preparation

The techno-economic comparison between the manual mortar-based preparation and the developed mixer, evaluated for an annual production target of 150 t, is presented in Table 10.

Table 10 Techno-economic comparison between manual mortar preparation and the developed mixer for an annual output of 150 t.

Indicator	Manual labor	Mixer (this study)
Workload (kg day ⁻¹)	500	36,000
Annual production (t)	150	150
Required operating days	300	4.17
Annual operating cost (THB)	270,000	3,750
Annual savings (THB)	—	266,250
Simple payback period (years)	—	2.63

At the prevailing Thai minimum wage of 300 THB day⁻¹ and an electricity tariff of 4.50 THB kWh⁻¹, the developed mixer reduces the annual operating cost of producing 150 t of compounded *Leucaena*-based feed from 270,000 to 3,750 THB, yielding savings of 266,250 THB year⁻¹ and a simple payback of 2.63 years against the capital investment of the prototype. The economic case is reinforced

by intangible benefits—reduced manual drudgery, improved hygiene, and consistent product quality—that are not captured in the simple payback analysis but are routinely cited by small- and medium-scale feed processors as decisive factors for technology adoption [2, 21].

Break-even point (BEP) analysis with fixed costs. The simple payback of 2.63 years implies a total capital investment of approximately 700,000 THB ($= 2.63 \text{ years} \times 266,250 \text{ THB year}^{-1}$ in operating savings). Using this back-calculated capital cost and standard techno-economic assumptions consistent with established agricultural-machinery and process-plant costing practice [28]: a 10-year equipment life with 10 % salvage value (straight-line depreciation $\approx 63,000 \text{ THB year}^{-1}$), an interest charge of 8 % year^{-1} on capital as the opportunity cost of ownership ($\approx 56,000 \text{ THB year}^{-1}$), a combined housing-and-insurance allocation of 2 % of capital ($\approx 14,000 \text{ THB year}^{-1}$), and a property tax allowance of 1 % of capital ($\approx 7,000 \text{ THB year}^{-1}$), the total annual fixed cost of the mixer system is approximately 140,000 THB year^{-1} . Combined with the variable (operating) cost of 3,750 THB year^{-1} at 150 t year^{-1} (25 THB t^{-1}) versus the manual baseline's variable cost of 270,000 THB year^{-1} at 150 t year^{-1} (1,800 THB t^{-1} , with negligible fixed cost), the break-even annual production is approximately 79 t year^{-1} [$140,000 \div (1,800 - 25) \approx 79 \text{ t}$]. Because the target annual output of 150 t is nearly double this break-even volume, the mixer remains the economically preferred option even after fixed costs (depreciation, interest, taxes, insurance, and housing) are explicitly accounted for, reinforcing the conclusion of the simple payback analysis above.

4. Discussion

4.1 Agreement between CFD predictions and experimental measurements

The transient VOF–MRF CFD framework reproduced the experimental CV at the operational reference point (10 rpm, 5 min) with a relative error of 1.3 % (predicted 7.1 % vs. measured $7.01 \pm 0.55 \%$). This level of agreement is comparable to, or better than, recent CFD–DEM studies of ribbon and planetary mixers that report 5–12 % deviation against industrial-style sampling [19, 20, 22]. The agreement is non-trivial because the VOF formulation treats each ingredient as a continuum phase and therefore averages over the discrete, irregular geometry of the acacia wood chips. The fact that the macroscopic mixing descriptor remains within experimental scatter suggests that, for the mixing-quality endpoint targeted by industrial sampling protocols, the continuum assumption is acceptable when the mixer operates at intermediate Reynolds numbers and the blade clearance is large relative to the characteristic particle dimension of the acacia chips and other feed constituents.

It is important to delimit the range of validity of this engineering-level reduction. The VOF–MRF model is appropriate when three conditions are simultaneously satisfied. First, the deliverable mixing descriptor must be evaluated at a sampling scale that is large relative to the characteristic particle dimension; in the present prototype, the 100 g samples encompass $O(10^4\text{--}10^5)$ particles per sample, so the sample-averaged composition is statistically dominated by bulk-phase transport rather than by individual particle trajectories. Second, the inter-phase density disparity must be sufficient (here 30–40 %, Table 2) for the constituent materials to behave as quasi-immiscible bulk phases over the convective time scale—a regime in which gravitational and inertial forces dominate over the inter-particle cohesion and rolling-friction terms that would normally necessitate a DEM description. Third, the blade-tip clearance must be large relative to the characteristic particle dimension so that the local flow is not controlled by jamming or arching; the 1.14 m centerline ribbon diameter and the 0.10 m blade-tip clearance in the present prototype satisfy this criterion by more than an order of magnitude. Within these bounds, the VOF–MRF approach is best regarded as a macroscopic transport model that predicts the convective–diffusive evolution of bulk composition—the quantity sampled by industrial QC protocols—rather than as a particle-physics model. The 1.3 % relative error against full-scale experimental sampling therefore provides empirical confirmation that, for the design-for-CV objective pursued here, the modelling choice is fit for purpose. Outside these bounds—notably at substantially smaller geometries, at extreme density ratios, or for cohesive powders dominated by inter-particle van der Waals or capillary forces. In those regimes, a fully resolved DEM or coupled CFD–DEM approach would be required to reliably capture particle-scale segregation, contact forces, and local packing effects.

4.2 Mechanistic insight into the superiority of the double helical ribbon

The CFD velocity contours of Figure 5 expose the physical mechanism that underlies the consistently superior performance of the double helical ribbon. The counter-pitched outer and inner ribbons generate two interpenetrating axial flow streams of opposite sign, simultaneously transporting material along the shaft and recirculating it across the radial direction. This dual convective pattern continuously folds and stretches the interface between the dense concentrate fraction and the lower-density acacia chips, an effect analogous to the chaotic-advection mechanism long recognized in laminar industrial blenders [13, 19]. By contrast, the single-flight screw geometry produces essentially unidirectional axial pumping with limited radial exchange, leading to early formation of a stagnant core near the inner shaft and a slow asymptotic approach to homogeneity ($\text{CV} = 14.8 \%$ only after 20 min). The paddle blade, while generating intense local shear at the blade tips, leaves persistent low-velocity wake regions in the trailing zone that act as transient dead zones for the lower-density chips. These observations are consistent with the DEM results of Halidan et al. [13] and Gao et al. [14], who reported that the Lacey mixing index increases monotonically with the degree of axial–radial flow coupling. The present results extend those findings from idealized binary particle mixtures to a realistic three-density commercial feed blend and confirm that geometric coupling—rather than rotational speed alone—is the dominant control variable for the mixing-quality endpoint at the operating point relevant to commercial Leucaena-based feed production.

4.3 Energy efficiency and techno-economic implications

A practically important finding is that the lowest rotational speed (10 rpm) simultaneously delivered the most favorable mixing quality ($\text{CV} = 7.01 \%$) and the lowest specific energy consumption (0.42 kWh t^{-1}). Increasing the shaft speed to 50 rpm shortened the time-to-target but produced no further improvement in the asymptotic CV and incurred a 1.6-fold increase in specific energy together with visible attrition of the soybean fraction—an undesirable secondary outcome for downstream pelletization and pellet durability. This non-monotonic energy–quality response is consistent with the de-mixing threshold reported by Halidan et al. [13] for cohesive particle blends in DEM simulations and reinforces the recommendation, also made by Jin et al. [22], to operate industrial ribbon mixers at the lower end of the practical rpm range when ingredient density disparities are large. From a techno-economic perspective, the integrated mixing–storage–bagging system reduced the annual operating cost of producing 150 t of Leucaena-amended compound feed

from 270,000 to 3,750 THB, yielding savings of 266,250 THB year⁻¹ and a simple payback of 2.63 years. Even allowing for $\pm 30\%$ uncertainty in electricity tariffs and minimum-wage indexing typical of medium-term economic projections in tropical Southeast Asia, the payback remains comfortably within the 5-year horizon commonly cited as the adoption threshold for small- and medium-scale feed processors [2, 21]. The intangible benefits—reduced manual drudgery, improved hygiene, and consistent product quality—further strengthen the case for technology transfer.

4.4 Limitations and future research directions

Three limitations should be acknowledged. First, the VOF–MRF formulation cannot resolve discrete chip–chip and chip–wall collisions and therefore cannot predict particle attrition or segregation hot-spots at the sub-grid scale; a CFD–DEM coupling, although computationally expensive, would refine the prediction of local quality fluctuations and inform blade-wear modelling. Second, the experiments were conducted at a single moisture content ($13.4 \pm 0.6\%$ wet basis); the convective–diffusive mixing balance is known to shift with moisture because of capillary cohesion between fibrous particles, and a dedicated parametric study would clarify the operating window for tropical wet-season conditions. Third, the techno-economic comparison assumed a constant electricity tariff and minimum wage; a Monte–Carlo sensitivity analysis would quantify the robustness of the 2.63-year payback against macroeconomic volatility. Beyond these immediate engineering scopes, the validated CFD-to-prototype workflow also opens the way to a broader rational design of mixers handling other low-cost tropical forages (e.g., *Gliricidia sepium*, *Moringa oleifera*), thereby contributing to the diversification of low-input ruminant feed systems in tropical Southeast Asia. In particular, because the feed blend combines three constituents of markedly different particle size and shape (irregular acacia wood chips, rounded roasted soybeans, and granular palm kernel cake), a particle-resolved DEM (or coupled CFD–DEM) treatment would be needed to explicitly capture particle-particle and particle-wall interactions, including size- and density-driven segregation, percolation of fines, and localized particle-particle friction/contact effects that the continuum VOF-MRF formulation cannot resolve. The present VOF-MRF approach is therefore best suited to, and was validated against, the macroscopic sample-averaged CV endpoint (Section 3.2), and should not be interpreted as predictive of particle-scale segregation phenomena; DEM studies such as those of Basinskas and Sakai and Cleary and Sinnott provide the appropriate framework for resolving these finer-scale interactions in future work.

5. Conclusions

A coupled CFD–experimental workflow was applied to the design of a 1.5 m³ horizontal ribbon-blade mixer for commercial *L. leucocephala*-based ruminant feed. Four principal conclusions are drawn:

(1) Among the three candidate blade geometries, the double helical ribbon delivered the fastest reduction in CV under all tested rotational speeds, reaching $CV \leq 12\%$ within 6 min of CFD-simulated mixing time and outperforming the paddle and screw geometries by 4–8 min.

(2) The CFD model—based on a transient VOF formulation, the standard k – ϵ turbulence closure, and a moving reference frame for blade rotation—predicted a CV of 7.1 % at the operational reference point (10 rpm, 5 min), in good agreement with the experimental value of 7.01 % (relative error 1.3 %). The framework therefore offers a robust, transferable upstream tool for blade-geometry screening in heterogeneous biomass-protein feed systems.

(3) The fabricated full-scale prototype achieved a minimum CV of 7.01 % and a Lacey mixing index of 0.987 at 10 rpm and 5 min, a throughput of 4.5 t h⁻¹, and a specific energy consumption of 0.42 kWh t⁻¹—values that compare favorably with horizontal mixers reported in the literature, particularly considering the lower operating speed.

(4) Replacing manual mortar-based preparation with the developed mixer saves 266,250 THB year⁻¹ at 150 t annual output, yielding a simple payback of 2.63 years and a positive technology-transfer outlook for small- and medium-scale ruminant feed processors in tropical Southeast Asia.

Future work will (i) extend the CFD framework with a CFD–DEM coupling to resolve discrete chip motion at the particle scale, (ii) explore the effect of moisture content and fibre pre-treatment on the convective–diffusive mixing balance, and (iii) integrate online near-infrared spectroscopy for real-time CV monitoring during industrial operation.

6. Acknowledgements

This work was supported by the Technology and Innovation Networks Programme, Khon Kaen University; the National Science and Technology Development Agency of Thailand; and PPP Woodchip Co., Ltd. The authors thank the FOOD ENERGY WATER Security Research Institute (FEWs), Khon Kaen University, for the provision of laboratory and prototyping facilities.

7. References

- [1] Barros-Rodríguez M, Sandoval-Castro CA, Solorio-Sánchez J, Sarmiento-Franco LA, Rojas Herrera R, Klieve AV. *Leucaena leucocephala* in ruminant nutrition. Trop Subtrop Agroecosystems. 2014;17:173-83.
- [2] Halmemies-Beauchet-Filleau A, Rinne M, Lamminen M, Mapato C, Ampapon T, Wanapat M, et al. Review: Alternative and novel feeds for ruminants: nutritive value, product quality and environmental aspects. Animal. 2018;12:s295-309.
- [3] Irawan F, Halliday MJ, Hegarty RS, Cowley FC. The effects and toxicological mechanisms of leucaena toxicity on ruminant reproduction: a review. Toxicon 2025;260:108367.
- [4] McSweeney CS, Halliday M, Mackie RI. Rumen Synergistota: new insights into their role in mimosine and fluoroacetate toxicity of ruminant livestock. Appl Environ Microbiol. 2025;91:e00380-25.
- [5] Phesatcha K, Wanapat M. Improvement of nutritive value and in vitro ruminal fermentation of *Leucaena* silage by molasses and urea supplementation. Asian-Australas J Anim Sci. 2015;29(8):1136-44.
- [6] Giang NTT, Wanapat M, Phesatcha K, Kang S. Level of *Leucaena leucocephala* silage feeding on intake, rumen fermentation, and nutrient digestibility in dairy steers. Trop Anim Health Prod. 2016;48:1057-64.
- [7] Soltan YA, Morsy AS, Sallam SMA, Louvandini H, Abdalla AL. Comparative in vitro evaluation of forage legumes (prosopis, acacia, atriplex, and leucaena) on ruminal fermentation and methanogenesis. J Anim Feed Sci. 2012;21(4):759-72.

- [8] Halliday MJ, Padmanabha J, McSweeney CS, Kerven G, Shelton HM. Leucaena toxicity: a new perspective on the most widely used forage tree legume. *Trop Grassl-Forrajes Trop*. 2013;1:1-11.
- [9] Mohamed M. Mixing: guidelines for quality feed production ensuring better animal performance [Internet]. 2020 [cited 2026 May 1]. Available from: https://en.engormix.com/feed-machinery/feed-pelletizing/mixing-guidelines-quality-feed_a45826/.
- [10] Basinskas G, Sakai M. Numerical study of the mixing efficiency of a ribbon mixer using the discrete element method. *Powder Technol*. 2016;287:380-94.
- [11] Cleary PW, Sinnott MD. Assessing mixing characteristics of particle-mixing and granulation devices. *Particuology*. 2008;6(6):419-44.
- [12] Chandratilleke GR, Zhou YC, Yu AB, Bridgwater J. Effect of blade speed on granular flow and mixing in a cylindrical mixer. *Ind Eng Chem Res*. 2010;49(11):5467-78.
- [13] Halidan M, Chandratilleke GR, Dong KJ, Yu AB. Mixing performance of ribbon mixers: effects of operational parameters. *Powder Technol*. 2018;325:92-106.
- [14] Gao W, Liu L, Liao Z, Chen S, Zang M, Tan Y. Discrete element analysis of the particle mixing performance in a ribbon mixer with a double U-shaped vessel. *Granular Matter*. 2019;21:12.
- [15] Cajindos JR. Design and fabrication of horizontal screw type mixer for livestock feed meal. *JPAIR Multidisciplinary Research*. 2014;15:82-100.
- [16] Bekele G, Gebiso T. Development of livestock feed mixer. Oromia Agricultural research institute workshop proceeding on Adaptation and Generation of Agricultural Technologies, vol. 3; 2019 Jun 26-29; Addis Ababa, Ethiopia. Addis Ababa: Oromia Agricultural Research Institute (IQOO); 2019. p. 316-26.
- [17] Bridgwater J. Mixing of powders and granular materials by mechanical means—a perspective. *Particuology*. 2012;10(4):397-427.
- [18] Groesbeck CN, Goodband RD, Tokach MD, Dritz SS, Nelssen JL, DeRouchey JM. Diet mixing time affects nursery pig performance. *J Anim Sci*. 2007;85(7):1793-8.
- [19] Jin X, Chandratilleke GR, Wang S, Shen Y. DEM investigation of mixing indices in a ribbon mixer. *Particuology*. 2022;60:37-47.
- [20] Xu W, Zhu J, Du X, Ma Y, Long J, Li X. CFD analysis of mixing homogeneity and mass transfer synergy in a three-blade planetary mixer. *AIChE J*. 2025;71(11):e70043.
- [21] Fan C, Shi Y, Sun J, He R, Xu G, Li Y. DEM-CFD simulation of organic–inorganic fertiliser mixing-spreading: optimizing inorganic fertiliser placement for uniformity. *Agriculture*. 2025;15(21):2256.
- [22] Jin X, Wang S, Shen Y. Effects of operating conditions and particle properties on mixing performance in an industrial-scale U-shape ribbon mixer. *Powder Technol*. 2022;411:117933.
- [23] Berk Z. Food process engineering and technology. 3rd ed. New York: Academic press; 2018.
- [24] Tongtib A, Wichitkul P. Design and test of horizontal rice mixer with ribbon stirring blade. *Academic Journal Uttaradit Rajabhat University Science and Technology*. 2022;17(2):37-54. (In Thai)
- [25] Clark PM, Behnke KC, Poole DR. Effects of marker selection and mix time on the coefficient of variation (mix uniformity) of broiler feed. *J Appl Poult Res*. 2007;16(3):464-70.
- [26] Yeow ST, Shahar A, Abdul Aziz N, Anuar MS, Yusof YA, Taip FS. The influence of operational parameters and feed preparation in a convective batch ribbon powder mixer. *Drug Des Devel Ther*. 2011;5:465-9.
- [27] Herrman T, Behnke K. Testing mixer performance Manhattan: Kansas State University; 1994.
- [28] ASABE. ASAE EP496.3: Agricultural machinery management. St. Joseph: American Society of Agricultural and Biological Engineers; 2006.