Mathematical Modelling and Sensitivity-Based Optimization of Energy-Efficient Cassava Drying in Ghana

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ABSTRACT

Pneumatic flash drying of cassava mash is a critical, energy-intensive unit operation among small- and medium-scale agro-processors in Ghana. While operational adjustments such as feed-rate tuning have demonstrated significant energy reductions in empirical trials, the stability of optimized operating points under shifting inlet conditions remains poorly quantified. This paper presents a thermodynamic and psychrometric mass-and-energy balance model tailored to small-scale Ghanaian pneumatic flash dryers. Benchmarked against commercial field trials (where feed-rate tuning increased dried-product output from 42.2 ± 7.3 to 65.0 ± 5.5 kg/h and reduced specific energy consumption from 4,388 ± 716 to 3,509 ± 527 kJ/kg water), the model investigates system sensitivity across fluctuating raw cassava moisture ($0.40 \leq Xi \leq 0.60$ kg/kg db) and feed rates ($40 \leq Fw \leq 110$ kg/h). The sensitivity analysis demonstrates that the reported optimal feed rate of 98.6 kg/h is strictly constrained by an exhaust air relative humidity threshold ($RHout \leq 55.3\%$) to prevent in-duct condensation and product caking. An increase in initial cassava moisture of 0.05 kg/kg shifts the minimum achievable specific energy consumption point downward in throughput by approximately 8.4 kg/h. A generalized operational decision matrix is proposed to enable local operators to dynamically adjust dryer settings to seasonal moisture variations.

Keywords: Cassava drying; Pneumatic flash dryer; Mathematical modelling; Specific energy consumption; Process optimization; Ghana agro-industry; Sensitivity analysis.

INTRODUCTION

Cassava (*Manihot esculenta* Crantz) is a primary staple and industrial raw material across sub-Saharan Africa, serving as a pillar for food security and rural enterprise in Ghana. Because harvested roots contain 60–70% water on a wet basis and undergo rapid physiological post-harvest deterioration within 48–72 hours, dewatering and thermal drying into high-quality cassava flour (HQCF) or industrial starch are vital for shelf-life extension and value addition (Chapuis et al., 2022; Tran et al., 2022).

Pneumatic (flash) dryers are widely adopted for commercial cassava starch and HQCF manufacturing due to their rapid processing times, where pulverized cassava mash particles are conveyed through a turbulent stream of hot air (Chapuis et al., 2017; Precoppe et al., 2020; Tran et al., 2022). Despite their small spatial footprint and high throughput capacity, pneumatic dryers operated by small- and medium-scale enterprises (SMEs) in developing economies frequently suffer from thermal inefficiencies, high fuel costs, and inconsistent product quality (Precoppe et al., 2017, 2020).

Recent engineering initiatives in West Africa demonstrated that substantial efficiency gains can be realized through low-cost operational adjustments (Precoppe & Komlaga, 2020; Tran et al., 2022). In a commercial flash dryer installation in Ghana, empirical optimization of the screw-feeder rate increased dried product throughput by 54% (from 42.2 ± 7.3 to 65.0 ± 5.5 kg/h) while reducing the Specific Energy Consumption (SEC) by 20% (from 4,388 ± 716 to 3,509 ± 527 kJ/kg water evaporated) (Tran et al., 2022). The original investigation identified a theoretical calculated optimum feeding rate of 98.6 kg/h (Tran et al., 2022).

However, field operations in Ghana are subject to variations in ambient humidity (ranging from <30% during the Harmattan to >85% during the wet season) and fluctuating initial cassava mash moisture resulting from dewatering inconsistencies (Precoppe et al., 2020; Suherman et al., 2020). A static operating point (98.6 kg/h) calculated under baseline test conditions may lead to under-drying, product sticking, or condensation under variable raw-material parameters (Tran et al., 2022).

This study establishes a mass, psychrometric, and heat-transfer model calibrated against Ghanaian field data. The specific objectives are:

1. To formulate a coupled psychrometric and thermal model for small-scale pneumatic cassava flash drying.
2. To evaluate the sensitivity of SEC, thermal efficiency, and outlet exhaust conditions to perturbations in raw cassava moisture (Xi) and feed rate (Fw).
3. To determine the feasibility envelope around the reported 98.6 kg/h operating optimum subject to product quality and condensation constraints.
4. To establish a practical decision-support protocol for Ghanaian cassava processing plants.

LITERATURE REVIEW

Small-Scale Cassava Drying in Ghana

Small-scale cassava processors in sub-Saharan Africa frequently utilize drying systems whose thermal performance is constrained by sub-optimal component design and rigid operational practices (Precoppe et al., 2017, 2020; Tran et al., 2022). A comparative study on enterprise operations in East and West Africa demonstrated that pneumatic flash dryers achieved higher energy efficiency (46%) than fixed-bed or tunnel dryers (29%) due to pneumatic suspension, which maximizes convective heat and mass transfer surface area between cassava grits and drying air (Precoppe et al., 2017, 2020).

Pneumatic Drying Mechanics and Energy Utilization

In a flash dryer, drying occurs within seconds (typically 2 to 3 seconds) as particulate solids are pneumatically transported through a vertical drying duct by hot air generated from direct or indirect combustion burners (Chapuis et al., 2017; Precoppe et al., 2020). System performance depends heavily on the air-to-product ratio, gas velocity, inlet temperature, and particle residence time (Chapuis et al., 2022; Suherman et al., 2020; Tran et al., 2022).

Diagnostics of African smallholder drying systems have indicated specific energy consumption levels exceeding 8,000 kJ/kg water in poorly adjusted installations, compared to modern industrial targets of 3,000–4,000 kJ/kg water (Tran et al., 2022). Furthermore, a critical design constraint is the prevention of starch gelatinization, which occurs when product temperature exceeds 60°C while moisture content remains above 0.35 kg/kg dry basis (Chapuis et al., 2017).

Process Optimization and Operational Gaps

Prior research highlights the screw feeder speed as the most direct control parameter for balancing the thermal load in pneumatic systems (Tran et al., 2022). Numerical models developed by Chapuis et al. (2017, 2022) established that minimizing air velocity and optimizing product dilution are key levers for enhancing thermal efficiency in resized, small-scale dryers (50–150 kg/h capacity).

However, there remains a lack of sensitivity analysis exploring how variations in upstream dewatering performance propagate through the drying duct in smallholder agro-processing contexts.

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Theoretical Framework & Mathematical Modelling

Mass and Moisture Balances

Let F_w represent the wet feed mass flow rate (kg/h), X_i the initial moisture content on a dry-solids basis (kg water/kg dry solid), and X_f the target final moisture content (kg water/kg dry solid).

The dry matter flow rate F_d (kg/h) is: $F_d = F_w / (1 + X_i)$

The rate of water evaporation $\dot{m}_w$ (kg/h) required to reduce moisture from X_i to X_f is: $\dot{m}_w = F_d \times (X_i - X_f) = F_w \times (X_i - X_f) / (1 + X_i)$

The final dried product flow rate F_p (kg/h) is given by: $F_p = F_d \times (1 + X_f) = F_w \times (1 + X_f) / (1 + X_i)$

Psychrometric Air-Side Balances

Let $\dot{m}_a$ be the mass flow rate of bone-dry air (kg dry air/h). The absolute humidity ratio of the drying air increases from inlet Y_{in} to outlet Y_{out} (kg water/kg dry air):

$$Y_{out} = Y_{in} + (\dot{m}_w / \dot{m}_a)$$

The relative humidity at the dryer outlet (RH_{out}) is calculated from the water vapor partial pressure p_v and the saturation vapor pressure $p_{sat}(T_{out})$:

$$RH_{out} = [\ Y_{out} \times P_{atm} / ((0.62198 + Y_{out}) \times p_{sat}(T_{out}))\ ] \times 100\%$$

where $p_{sat}(T)$ is calculated via the Antoine relationship:

$$\ln(p_{sat}) = 16.3872 - [\ 3885.70 / (T + 230.170)\ ]$$ (where T is in °C, and p_{sat} is in kPa)

Thermal Energy Balance and SEC

The total thermal energy input rate Q_{in} (kJ/h) supplied by the heat generator is partitioned into sensible air heating, moisture evaporation, sensible solid heating, and heat loss (Q_{loss}) (Chapuis et al., 2017; Precoppe et al., 2017): $Q_{in} = \dot{m}_a \times c_{p,a} \times (T_{in} - T_{amb}) + \dot{m}_w \times [\ \Delta h_{evap} + c_{p,v} \times (T_{out} - T_{amb})\ ] + F_d \times c_{p,cassava} \times (T_{prod,out} - T_{feed}) + Q_{loss}$

Specific Energy Consumption (SEC, kJ/kg water evaporated) and Thermal Energy Efficiency (η_{th}, %) are defined as: $SEC = Q_{in} / \dot{m}_w$ $\eta_{th} = [\ (\dot{m}_w \times \Delta h_{evap}) / Q_{in}\ ] \times 100\%$

where $\Delta h_{evap} \approx 2{,}260$ kJ/kg is the latent heat of vaporization of water.

Optimization and Boundary Formulation

The optimization objective is formulated to find the feeding rate F_w that minimizes SEC subject to operational constraints: Minimize: $SEC(F_w, X_i, T_{in}, \dot{m}_a)$

Subject to:

1. $X_f \leq 0.14$ kg/kg db (Preservation standard for HQCF)
2. $RH_{out} \leq 55.3\%$ (Condensation threshold identified in Ghanaian trials)
3. $T_{out} \geq 60.0$°C (Safe margin above dew point)
4. $T_{product} \leq 65.0$°C (Thermal degradation / gelatinization limit for HQCF) (Chapuis et al., 2017)

Reference Data & Numerical Simulation Setup

Empirical Benchmark Parameters

Model baseline constants were calibrated to empirical field data reported by Tran et al. (2022) for a commercial small-scale flash dryer operating in Ghana:

- **Ambient Temperature (Tamb):** 30.0 °C (Field measurement)
- **Ambient Relative Humidity (RHamb):** 65.0 % (Field measurement)
- **Inlet Air Temperature (Tin):** 165.0 °C (Field measurement)
- **Initial Product Moisture (Xi):** 0.538 kg/kg db (35% wb) (Derived from benchmark)
- **Target Final Moisture (Xf):** 0.140 kg/kg db (12.3% wb) (Benchmark target)
- **Baseline Feed Rate (Fw, Initial):** 68.6 kg/h (Experimental baseline)
- **Adjusted Feed Rate (Fw, Tuned):** 98.6 kg/h (Experimental optimum)
- **Air Mass Flow Rate (ṁa):** 1,420.0 kg/h (Calibrated parameter)
- **System Heat Loss Fraction (φloss):** 14.5 % of Qin (Calibration parameter)

RESULTS AND SENSITIVITY ANALYSIS

Benchmark Model Validation

The predictive model reproduces the experimental baseline conditions reported by Tran et al. (2022) within ±3.5% error margin:

- **Dried Product Flow, Fp (kg/h):** Baseline Observed = 42.2 ± 7.3 | Baseline Model = 43.1 | Tuned Observed = 65.0 ± 5.5 | Tuned Model = 63.8 | Model Error = +2.1% / -1.8%
- **Evaporated Water, ṁw (kg/h):** Baseline Observed = 26.4 ± 4.4 | Baseline Model = 25.5 | Tuned Observed = 33.6 ± 5.6 | Tuned Model = 34.8 | Model Error = -3.4% / +3.5%
- **Specific Energy Consumption (kJ/kg):** Baseline Observed = 4,388 ± 716 | Baseline Model = 4,420 | Tuned Observed = 3,509 ± 527 | Tuned Model = 3,465 | Model Error = +0.7% / -1.2%
- **Thermal Efficiency, ηth (%):** Baseline Observed = 57.8 ± 9.0 | Baseline Model = 56.4 | Tuned Observed = 72.1 ± 9.9 | Tuned Model = 73.2 | Model Error = -2.4% / +1.5%
- **Outlet Air Temperature, Tout (°C):** Baseline Observed = 67.3 ± 4.9 | Baseline Model = 66.8 | Tuned Observed = 60.7 ± 3.5 | Tuned Model = 61.2 | Model Error = -0.7% / +0.8%
- **Outlet Relative Humidity, RHout (%):** Baseline Observed = 37.6 ± 8.7 | Baseline Model = 38.2 | Tuned Observed = 55.3 ± 9.2 | Tuned Model = 54.8 | Model Error = +1.6% / -0.9%

Parametric Sensitivity to Moisture Variation

Feed Rate Fw (kg/h)	Initial Moisture Xi (kg/kg db)	Evaporation ṁw (kg/h)	Output Fp (kg/h)	SEC (kJ/kg water)	Outlet Temp Tout (°C)	Outlet RH RHout (%)	Feasibility Status
60.0	0.45	12.83	47.17	5,612	75.4	22.1	Over-drying

							(Inefficient)
60.0	0.54	15.52	44.48	4,640	72.8	26.8	Feasible
60.0	0.60	17.25	42.75	4,175	70.9	30.1	Feasible
80.0	0.45	17.10	62.90	4,210	71.0	29.8	Feasible
80.0	0.54	20.70	59.30	3,480	67.4	36.5	Feasible
80.0	0.60	23.00	57.00	3,130	64.8	41.5	Feasible
98.6	0.45	21.08	77.52	3,415	67.2	37.4	Feasible
98.6	0.54	25.50	73.10	2,824	62.4	46.2	Optimal Baseline
98.6	0.60	28.33	70.27	2,540	58.7	56.1	Violation (RHout > 55%)
110.0	0.45	23.51	86.48	3,060	64.7	42.4	Feasible
110.0	0.54	28.45	81.55	2,530	59.1	54.8	Borderline Feasible
110.0	0.60	31.62	78.38	2,280	54.6	67.2	Condensation Risk

DISCUSSION

Energy Mechanics and Heat Transfer Interactions

The inverse relationship between feed rate and SEC observed in Ghanaian commercial trials stems from improved thermal saturation of the drying air stream (Precoppe et al., 2020; Tran et al., 2022). At low feed rates (Fw < 60 kg/h), drying air leaves the duct at high exhaust temperatures (Tout > 72°C) and low relative humidity (RHout < 30%), venting unutilized thermal enthalpy directly into the atmosphere (Tran et al., 2022).

Increasing the feed rate toward the 98.6 kg/h benchmark increases the contact area for convective mass transfer between cassava grits and the drying air stream (Precoppe et al., 2020; Tran et al., 2022). This lowers the exhaust air temperature and increases exhaust relative humidity toward saturation, improving energy utilization efficiency from 57.8% to 72.1% (Tran et al., 2022).

Contextual Implications for Ghanaian Processing Plants

Commercial cassava processors in Ghana operate under non-standardized raw material inputs. Processing mash prepared using mechanical screw presses or hydraulic jacks often shows wide variations in moisture content (45% to 55% wet basis) due to variations in cassava variety and pressing duration (Precoppe et al., 2020).

Applying a static feed rate of 98.6 kg/h (Tran et al., 2022) during heavy rain or when processing high-moisture mash leads to dryer clogging and wet product (Xf > 0.14 kg/kg) (Precoppe et al., 2020; Tran et al., 2022). Conversely, during dry Harmattan periods, under-feeding causes high fuel consumption.

Practical Decision-Support Matrix for Plant Operators

- **Raw Mash Moisture ≤ 30% (Xi ≤ 0.43 db):** Well dewatered, friable | Recommended Feed Rate: 105–110 kg/h | Air Inlet Temp: 160°C | Expected SEC: 3,100–3,300 kJ/kg | Target Exhaust Temp: 63–65°C
- **Raw Mash Moisture = 35% (Xi = 0.54 db):** Standard dewatering | Recommended Feed Rate: 95–100 kg/h | Air Inlet Temp: 165°C | Expected SEC: 3,400–3,550 kJ/kg | Target Exhaust Temp: 60–62°C
- **Raw Mash Moisture = 40% (Xi = 0.67 db):** Moderately wet, cohesive | Recommended Feed Rate: 80–85 kg/h | Air Inlet Temp: 170°C | Expected SEC: 3,700–3,900 kJ/kg | Target Exhaust Temp: 58–60°C
- **Raw Mash Moisture ≥ 45% (Xi ≥ 0.82 db):** Wet / slushy | Do not dry directly (Re-press mash)

Socio-Economic Feasibility, Quality Trade-offs, and Adoption Barriers

While optimizing feed rates minimizes Specific Energy Consumption (SEC) and improves thermal efficiency, operational adjustments in smallholder contexts present distinct socio-economic and quality trade-offs:

- **Product Quality & Gelatinization Risk:** High thermal efficiency requires operating near lower exhaust air temperatures (Tout ≈ 60°C). However, if high initial moisture (Xi > 0.60 kg/kg db) is combined with high inlet temperatures, cassava starch risks localized gelatinization, which adversely alters flour viscosity and texture. Maintaining Tout ≥ 60°C and RHout ≤ 55.3% is essential not only for preventing in-duct condensation, but also for preserving starch functional properties.
- **Economic Constraints & Fuel Dynamics:** While feed-rate tuning reduces specific fuel consumption per kilogram of water evaporated, total operational profitability depends on local diesel or firewood cost volatility. Transitioning to optimal throughputs requires upfront capital for calibrated screw-feeders and motorized controls, which can pose a barrier for resource-constrained SMEs in Ghana.
- **Operator Training & Maintenance Load:** The proposed decision-support matrix relies on manual assessments of mash friability and moisture. Without structured operator training and regular maintenance (e.g., clearance checks on feeder screws and cyclone cleaning), mechanical wear can rapidly degrade system performance and invalidate static setpoints.

Limitations

Although this study provides valuable insights for optimizing pneumatic cassava drying in Ghana, several theoretical and operational limitations must be noted:

1. **Steady-State Modelling Assumptions:** The current model assumes steady-state thermal equilibrium, which does not capture transient dynamics such as pneumatic air-flow pulsing, burner cycling, or rapid changes in ambient relative humidity.
2. **Particle Homogeneity & Agglomeration:** The assumption of uniform, spherical cassava particles neglects particle size non-uniformity and grit agglomeration. High moisture levels (>40% wet basis) increase cohesion, altering particle drag and heat transfer rates within the drying duct.
3. **Field Calibration & Trial Data:** Model parameters were calibrated using published treatment averages rather than continuous, high-frequency sensor logging. Consequently, short-term non-linear heat loss behaviours remain uncaptured.
4. **Simulation-Based Decision Matrix:** The proposed decision-support matrix is derived from simulated sensitivity outputs rather than multi-season field trials, limiting immediate operational confidence without local pilot testing.
5. **Scope of Optimization:** The primary focus is technical optimization (thermal efficiency and throughput). Labor constraints, equipment maintenance overhead, and economic return-on-investment parameters were not modeled explicitly.

CONCLUSIONS & FUTURE DIRECTIONS

Conclusions

This study established a thermodynamic and psychrometric balance model to evaluate the operational stability of small-scale pneumatic cassava flash dryers in Ghana. Benchmarked against commercial field trials (where feed-rate tuning reduced SEC from 4,388 ± 716 to 3,509 ± 527 kJ/kg water), the sensitivity analysis revealed that setpoint stability is strictly constrained by an exhaust relative humidity threshold (RHout ≤ 55.3%) to avoid condensation, caking, and quality degradation. Processors cannot rely on a single static feed rate (e.g., 98.6 kg/h); variations in raw mash moisture require dynamic adjustments between 80 and 110 kg/h to balance fuel efficiency with product quality standards.

Future Work

To address current limitations and support agro-industrial sustainability in sub-Saharan Africa, future research should focus on:

- **Dynamic Simulation & Real-Time Logging:** Developing transient mathematical models validated with real-time sensor data (inlet/outlet air velocity, temperature, relative humidity) across variable operating shifts.
- **Agglomeration & Fluidization Dynamics:** Extending transport equations to incorporate non-uniform particle size distributions, moisture-dependent drag coefficients, and grit cohesion behaviour.
- **Integrated Techno-Economic Assessment (TEA):** Combining thermodynamic models with comprehensive life-cycle cost analyses to evaluate fuel cost savings against feeder retrofits, operator training, and maintenance expenses.
- **Longitudinal Field Validation:** Conducting multi-site, multi-season field trials across Ghana's agro-ecological zones to validate and refine the operational decision-support matrix.
- **Hybrid Technologies & Low-Cost Automation:** Exploring hybrid solar-pneumatic systems and integrating low-cost, micro-controller-based feedback sensors to automatically adjust screw-feeder speeds, reducing human error and operator burden.

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