

Design and Development of a Tea Processing, Sorting and Grading System that Converts Secondary-grade Tea into Primary-grade Tea

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Abstract - The tea industry generates significant quantities of undervalued secondary-grade teas, including Broken Mixed Fannings (BMF), Pekoe Fannings 2 (PF2), Fannings 1 (F1), and Dust 2 (D2), which typically constitute 15–20% of total production and are sold at substantially lower prices or discarded as waste. This paper presents the design and development of an optimized tea processing, sorting and grading system specifically engineered to convert these secondary-grade teas into higher-value primary-grade teas (Broken Pekoe 1, Pekoe Fannings 1, Pekoe Dust, and Dust 1). Pilot plant experiments were conducted to establish critical design parameters, evaluating the effects of milling (150–500 μm particle size), moisture content (40–70% in 10% increments), and fermentation duration (0–120 minutes) on conversion efficiency and final tea quality. Results demonstrated that milling secondary teas to 150–500 μm , adjusting moisture content to $60\pm 2\%$, and applying no additional fermentation yielded optimal conversion, achieving sensory scores of 4.6–4.8 for taste (against ITCs benchmark of 4.6) and leaf appearance score of 4. Based on these findings, a modular processing system was designed comprising: (i) a dual 40 HP hammer mill (450 kg/hr throughput, 4,500 rpm rotor speed) achieving target particle size reduction; (ii) a 500 mm diameter Stairmand-type cyclone separator ($\geq 95\%$ efficiency for particles $\geq 150 \mu\text{m}$); (iii) a pulse-jet deduster (2,400 m^3/hr , 25 filter bags) for fine dust control; (iv) a 230 mm diameter screw conveyor (225 kg/hr capacity) for material handling; and (v) a 0.9 m^3 buffer hopper with 60° discharge angle ensuring continuous feeding. The system achieved $69\pm 1\%$ conversion of secondary-grade teas into primary grades, improving overall primary-grade output from 80% to 94% when integrated with existing CTC processing lines. This integrated design represents the first dedicated engineering solution for secondary tea grade valorization, transforming what was previously considered waste into commercially viable primary-grade tea products.

Keywords—Tea Processing; System Design; Process Development; Pilot Plant; Secondary-grade Tea; Primary-grade Tea; Hammer Mill; CTC Tea; Moisture Content; Fermentation; Cyclone Separator; Deduster; Hopper; Tea Grading; Sensory Scores; Optimization; Value Addition

I. INTRODUCTION

Tea (*Camellia sinensis*) stands as one of the world's most economically significant cash crops, with black tea dominating global consumption, particularly in key producing nations such as Kenya, India, and Sri Lanka [1]. The conventional Crush, Tear, Curl (CTC) processing method transforms tender green leaf shoots—comprising two leaves and a bud—into granular black tea through a sequence of carefully controlled operations: withering to $70\pm 2\%$ moisture content, maceration, CTC cutting (8–10 teeth per inch), fermentation at $22\pm 1^\circ\text{C}$ for approximately two hours, drying at 130°C , and finally sorting and grading into various commercial categories [2] as shown in Fig. 1 below:

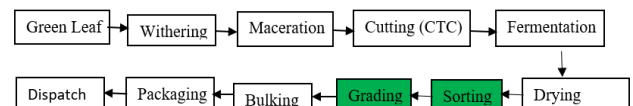


Fig. 1 Black Tea Manufacturing Process [2]

This processing regimen yields two distinct product classifications: primary-grade teas, including Broken Pekoe 1 (BP1), Pekoe Fannings 1 (PF1), Pekoe Dust (PD), and Dust 1 (D1), which command premium prices (USD 3.00–4.98/kg) in international auctions due to their superior sensory characteristics and uniformity [3, 4]. Conversely, secondary-grade teas, comprising Broken Mixed Fannings (BMF), Pekoe Fannings 2 (PF2), Fannings 1 (F1), Dust 2 (D2), and Balls, images as shown in Plate 1 below, typically constitute 15–20% of total production and are sold at substantially lower prices (USD 1.50–2.60/kg) or discarded as waste [5]. This persistent generation of undervalued secondary grades represents both an economic inefficiency and an environmental concern for tea processors worldwide.

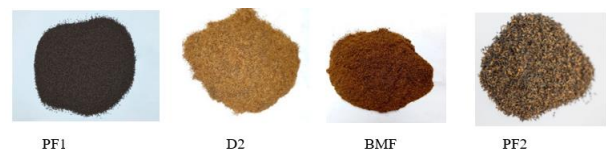


Plate 1 CTC Black tea images [6, 7].

Previous investigations by (Peterson, et al. and Taşar & Özer [8, 9], have demonstrated that

secondary-grade teas retain significant quantities of bioactive compounds, including polyphenols and catechins, which contribute to antioxidant activity, flavour development, and the characteristic sensory attributes of black tea. Owuor and Reeves [10] established that optimal fermentation conditions and processing parameters critically influence theaflavin and thearubigins formation, which directly impact liquor colour, taste, and mouthfeel. However, these studies primarily focused on biochemical characterization or waste valorisation pathways, such as bioenergy production, fertilizer manufacturing, or functional food ingredients, [11, 12] rather than developing engineering solutions capable of upgrading secondary teas back into the primary-grade market stream.

Research by Johnson [13] and Kaushik [14] explored automation strategies and real-time monitoring systems for tea processing, yet these efforts remained confined to laboratory-scale prototypes without addressing the specific challenges of secondary-grade reprocessing. Temple, Clifford, and Robins [15] identified that particle size distribution critically influences black tea quality, with optimal infusion characteristics occurring within the 150–500 μm range, a finding particularly relevant for secondary tea conversion. Furthermore, uncontrolled milling can generate excessive temperatures exceeding 45°C, accelerating degradation of volatile flavour compounds [15]. Despite these insights, no integrated, industrially scalable system has been developed specifically engineered to convert secondary-grade teas into marketable primary-grade products.

The present study addresses this technological gap through the design and development of an optimized tea processing, sorting, and grading system for secondary-grade tea valorisation.

This integrated design represents, to the authors' knowledge, the first dedicated engineering solution specifically conceived for secondary tea grade conversion, transforming what has historically been considered waste or low-value byproduct into commercially viable primary-grade tea products while maintaining sensory quality standards defined by the International Tea Categorization System (ITCS) [16]. Pilot plant experiments were systematically conducted to establish critical design parameters, evaluating the effects of milling intensity (150–500 μm particle size), moisture content (40–70% in 10% increments), and fermentation duration (0–120 minutes) on conversion efficiency and final tea quality. These experimental findings informed the engineering design of a modular processing system comprising:

- (i) a dual 40 HP hammer mill achieving 450 kg/hr throughput with 4,500 rpm rotor speed;
- (ii) a 500 mm diameter Stairmand-type cyclone separator demonstrating $\geq 95\%$ collection efficiency for particles $\geq 150 \mu\text{m}$;
- (iii) a pulse-jet deduster (2,400 m^3/hr , 25 filter bags) for fine dust control;

- (iv) a 230 mm diameter screw conveyor (225 kg/hr capacity) ensuring controlled material handling; and

- (v) a 0.9 m^3 buffer hopper with 60° discharge angle facilitating continuous feeding.

II. MATERIALS AND METHODS

A. Study Location and Raw Materials

The research was conducted at Browns Plantations Pilot Plant facility in Kericho County, Kenya. Secondary-grade tea raw materials, comprising Broken Mixed Fannings (BMF), Pekoe Fannings 2 (PF2), Fannings 1 (F1), and Dust 2 (D2), were sourced from routine CTC production runs from various factories. These materials were combined at standard factory production ratios by mass to create representative feedstocks for all experiments.

B. Equipment and Experiments Set up - Pilot Plant Experimental Design

A factorial experimental design was employed to evaluate the effects of three key processing parameters on secondary-grade tea conversion:

- i) Milling treatment: Samples were milled using a laboratory-scale hammer mill (Model DF-15, capacity 15 kg/hr, rotor speed 4,200 rpm) fitted with 0.5 mm, 0.8 mm, and 1.0 mm screens to achieve particle size distributions of 150–300 μm , 300–500 μm , and $>500 \mu\text{m}$ respectively. Particle size analysis was conducted using a mechanical sieve shaker with ISO 565 test sieves.
- ii) Moisture content: Milled samples were conditioned to target moisture contents of 40%, 50%, 60%, and 70% ($\pm 1\%$) by calculated water addition. Moisture content was verified using a moisture analyzer (Mettler Toledo HX204, $\pm 0.01\%$ accuracy).
- iii) Fermentation duration: Samples at optimal moisture content (determined from initial trials) were subjected to fermentation periods of 0, 30, 60, and 120 minutes in a controlled environment chamber maintained at $22 \pm 1^\circ\text{C}$.

Each experimental condition was replicated five times ($n=5$) with independent batches, yielding a total of 140 experimental runs, plus unmilled controls which failed processing and were excluded from full factorial analysis).

C. Processing Protocol

For each experimental run, 5 kg of secondary-grade tea feedstock was processed as follows:

- i) Pre-milling (where applicable): Material was milled to target particle size distribution (150–500 μm) using the laboratory hammer mill. Airflow (450 m^3/hr) was maintained to prevent thermal degradation, with mill outlet temperature monitored continuously (Type K thermocouple, $\pm 0.5^\circ\text{C}$) and maintained below 40°C following Temple et al. [15].

- ii) Moisture conditioning: Milled material was transferred to a laboratory-scale ribbon blender (Model RB-25, capacity 25 L) and calculated water volume was atomized into the tumbling mass over 10 minutes at 20 rpm. Conditioned samples were held for 4 hours in sealed polyethylene containers at 20±2°C to ensure uniform moisture distribution.
- iii) CTC processing: Moisture-conditioned samples were fed through a laboratory-scale CTC machine 200 mm roller width, 8 teeth per inch, roller speed 700 rpm) at a feed rate of 15 kg/hr.
- iv) Fermentation (where applicable): The CTC-cut dhool was spread uniformly (2 cm depth) on perforated stainless-steel trays and placed in the controlled environment chamber for the specified duration. Dhool temperature was monitored every 15 minutes.
- v) Drying: Fermented dhool was dried in a laboratory-scale fluidized bed dryer 130±2°C inlet air temperature, 21 minutes residence time) to achieve final moisture content of 2.5±0.2%.
- vi) Sorting and grading: Dried tea was separated using a laboratory sorter (Model GS-1, 2.0 mm, 1.4 mm, 1.0 mm, and 0.5 mm mesh screens) to obtain grade fractions: BP1 (>1.4 mm), PF1 (1.0–1.4 mm), PD (0.5–1.0 mm), D1 (<0.5 mm), and residual secondary-grade material.

D. Instrumentation and Equipment

- i) Hammer mill, DF-15, 15 kg/hr, 4,200 rpm, for Particle size reduction
- ii) Moisture analyzer, Mettler Toledo HX204, for Moisture determination
- iii) Sieve shaker, Endecotts Octagon 200, for Particle size analysis
- iv) CTC machine, CTC-L2, 200 mm diameter, for Leaf maceration
- v) Environment chamber, Binder KBF 720, for fermentation control
- vi) Fluidized bed dryer, FBD-200, 130°C, for final drying
- vii) Temperature logger, OMEGA RDXL4SD, for process monitoring
- viii) Balance, Mettler Toledo MS6002S, for mass measurement

E. Tea Quality Evaluation

Processed tea samples were evaluated by a panel of professional tea tasters from Africa Tea Brokers Association using the International Tea Categorization System (ITCS) methodology [16].

F. Data Collection and Statistical Analysis

For each experimental run, the following data were deviations from standard recorded:

- i) Initial and final mass of each grade fraction (BP1, PF1, PD, D1, secondary residue)
- ii) Processing parameters: milling screen size, moisture content, fermentation duration, CTC roller temperature, drying time and temperature

- iii) Sensory evaluation scores (taste, hue, mouthfeel, leaf) for PF1, PD, and D1 grades
- iv) Process observations: material flow characteristics, equipment performance, any operating conditions

G. Design of a Milling System

Used pilot plant data to design a milling machine to mill the secondary tea grades (Fig. 2) and used the milling machine to mill the secondary tea grades for full scale factory trials.

Design requirements were defined as follows:

- i) Determined the required throughput (e.g., kg/hour) for processing secondary tea grades.
- ii) Specified the desired particle size in microns.
- iii) Identified power requirements and operational constraints (e.g., motor capacity, energy efficiency and other components).
- iv) Design various components required for the milling system as follows:
 - a. Milling Power Requirements, Hammer Mill and Airflow System.
 - b. Buffer Hopper Design for Mill Feeding Systems.
 - c. Milling Power Requirements, Hammer Mill and Airflow System - Motor, Hammer Mill, Airflow and Belt/Pulley System.
 - d. Buffer Hopper Design for Mill Feeding System.
 - e. Centrifugal Fan from Hammer Mill to Cyclone
 - f. Cyclone Design for Milling System (Fig. 3).
 - g. Design of Dust Exhaust Fan for Tea Milling System.
 - h. Deduster System Sizing for Tea Milling (Fig. 4).
 - i. Screw Conveyor System Design
 - j. Sprocket & Chain Drive Design for Screw Conveyor.

Motor Power:

Calculated the required motor power based on the material properties (density, hardness) and throughput.

$$P = \frac{Q \cdot E}{\eta} \dots\dots\dots (1)$$

Where:

- P = Motor power (kW)
- Q = Throughput (kg/h)
- E = Specific energy consumption (kWh/kg)
- η = Efficiency of the motor (%)

Rotor Speed:

$$N = \frac{60 \cdot v}{\pi \cdot D} \dots\dots\dots (2)$$

Where:

- N = Rotor speed (rpm)
- v = Peripheral speed (m/s)
- D = Rotor diameter (m)

Power, $P=T\omega$ (3)

Where:

- T - Torque (Nm).
- P – Power (kW)

$\omega = \frac{2\pi N}{60}$ (4)

- N = rotor speed in rpm

Airflow System:

Airflow rate required for effective material transport and dust collection and control.

Continuity equation:

$Q_{air} = A \cdot v_{air}$ (5)

Where:

- Q_{air} : Airflow rate (m^3/h) (1,600 – 1,800 m^3/h required for optimal pneumatic conveying for target particle size of 150–500 μm round (95% at 300 μm round, 5% others oblong, straight, insignificant after milling) [17], chosen mid-point of 1,700 m^3/hr).
- A: Duct cross-section
- v_{air} : Air velocity (30 m/s for pneumatic conveying). Optimal peripheral velocity for milling to target particle size (150–500 μm round) (95% at 300 μm round, 5% others oblong, straight, insignificant after milling) is 20–40 m/s [17], (chosen mid-point of 30 m/s).

Load & Life Calculation:

Basic Rating Life (L_{10}) for Double row self-aligning ball bearings:

$L_{10} = \left[\frac{C}{P} \right]^3 \times 10^6$ revolutions (6)

Where:

- p - exponent = 3 for ball bearings [18].
- P - Equivalent Load = 5 kN (radial only) [18].
- C - Dynamic load rating = 25kN for for 70mm inner diameter SKF bearing 2314 [18]

Hopper Volume, $V = \frac{w}{\rho}$ (7)

Where:

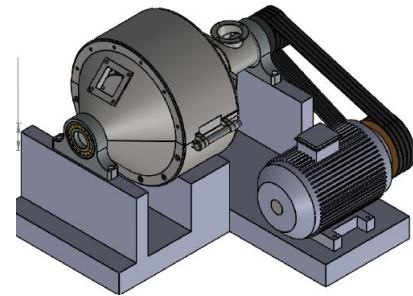
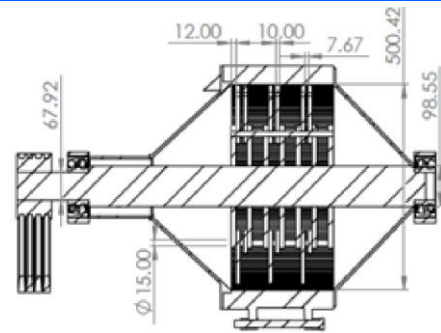
- ρ - Bulk Density (kg/m^3)
- w – capacity (Kg)

Friction Loss (Straight Duct), $\Delta P_{friction}$:

$\Delta P_{friction} = \lambda \cdot \left[\frac{L}{D} \right] \left[\frac{\rho v^2}{2} \right]$ (8)

Where:

- λ - Friction factor - for 5m duct length, $\lambda \approx 0.02$ (smooth SS duct) [17]
- L- Length of pipe/duct = 5 metres (available space).
- D – Duct inner diameter (140mm – design calculation).
- ρ - Fluid density (air density = 1.2 kg/m^3 at 20°C and 1 atm [17])
- v - Speed of fluid in the pipe = 30.66m/s – design calculation.



Dimensions in mm

Fig. 1 Hammer Mill

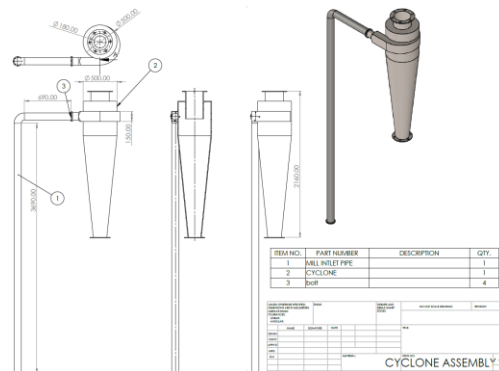
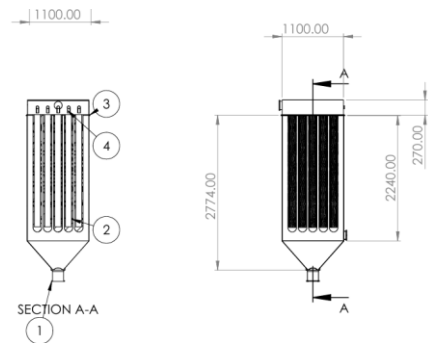


Fig. 3 Cyclone Design for Milling System



ITEM NO.	PART NUMBER	QTY.
1	de-duster main	1
2	filter bag	25
3	de-duster cover	1
4	pressure tip	5

Dimensions in mm

Fig. 4 Deduster System

III. RESULTS AND DISCUSSIONS

A. Pilot Plant Trials Tea Tasting Results

Direct use of un-milled teas proved ineffective, as they clogged in the CTC machine, thus was not considered in the design.

i) Moisture Content Variation:

Most reprocessed samples from 60% moisture content and above, with no fermentation, achieved taste scores of 4.6 – 4.8 and Leaf appearance scores of 4 (Fig. 5), which is above the benchmark ITCS value of 4.6 taste and score 4 for leaf, the minimum threshold for marketable tea quality thus were categorized as commercial primary grades. This compares well to Normal CTC teas scores of 4.8 – 5.2 taste and score 4 – 5 for leaf. The 60% MC trials yielded the highest sensory scores and the most favourable grade distribution. This suggests that 60% MC is optimal for maintaining tea quality during processing. Samples from below 60% scored ITCS value below 4.6 thus not marketable.

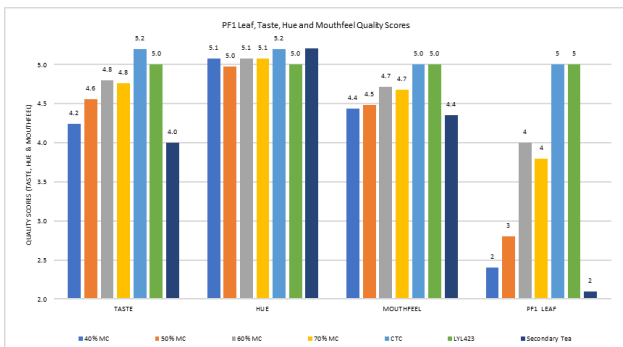


Fig. 5 PF1 Taste, Hue, Mouthfeel and Leaf Quality Scores for

ii) Fermentation Duration Variation

All fermentation durations from 0 to 120 minutes at a constant moisture content of 60% showed no significant difference in made tea quality (taste – 4.8 and leaf scores - 4) (Fig. 6). Extended fermentation did not significantly improve made tea quality; thus, no fermentation is optimal for reprocessed tea. This is so because the tea had undergone full fermentation for CTC tea processing and showed that reprocessed teas retain structural integrity without further oxidation.

The commercial design was therefore based on milling secondary-grade teas at normal production ratios to 150-500 microns and reprocessing at 60% moisture content with no additional fermentation before drying and sorting.

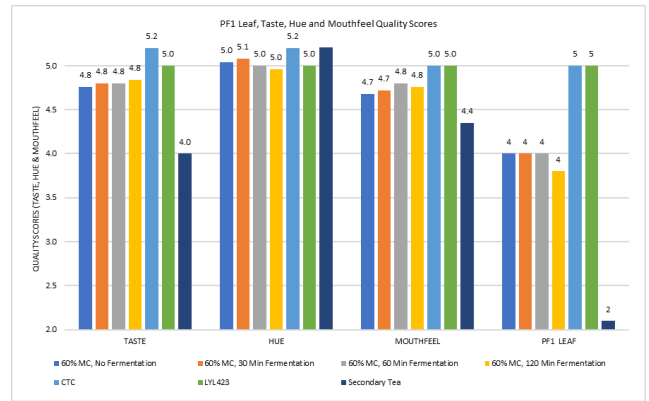


Fig. 6 PF1 Taste, Hue and Mouthfeel Taste Scores for fermentation duration variation

iii) Grade Profile

Pilot Plant trials gave the following Primary-Grade Tea grade profile percentages, after conversion from Secondary Tea (Fig. 7):

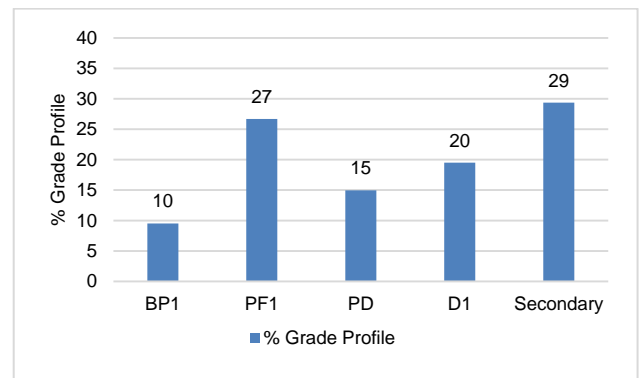


Fig. 7 Pilot Plant Trials: Primary-Grade Tea Grade Profile after conversion from Secondary Tea

Reprocessed tea achieved less percentage primary-grade profiles of 71% compared with normal tea grade profile of 80- 85%. Reprocessed Secondary-grade residue gave 29% average which is significantly higher than normal tea grade profile of 15- 20% due to inherent higher composition of fibrous materials in the secondary teas raw materials. However, the reprocessing improves overall primary grades to 94% thus reducing secondary grades to 6% as illustrated in Fig. 8 below:

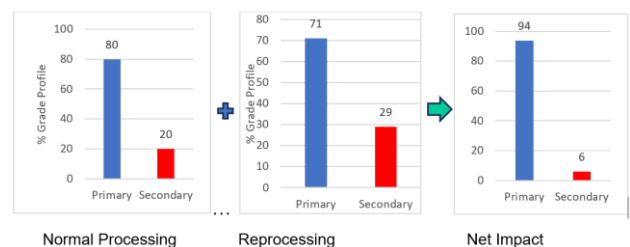


Fig. 8 % Net Grade Profile after reprocessing

B. Summary of design parameters

The design parameters resulted in the tea milling parameters (Table 1.1) and tea milling system for secondary-grade tea conversion to primary-grade teas (Fig. 9).

Table 1 Design Parameters Summary for Tea Milling System

Component	Formulae	Key Specifications	Citation
Milling Machine	$P = \frac{Q \cdot E}{\eta}$ (1);	Throughput: 2 x 225 kg/hr (matches existing drier capacity) Power: 2 x 40 HP motors, Speed: 3,000 rpm Rotor: 4,500 rpm (1.5:1 pulley ratio, B-Section 4-groove V-belts). Motor Shaft: 60 mm diameter, Torque: 71.24 Nm Particle Size: 150–500 µm round (95% average 300 µm) Rotor Tip Speed: 33 m/s Airflow Requirement: 1,700 m³/hr at 30 m/s (duct diameter: 140 mm). 6 plates (142×38×10 mm) Bearings: SKF 2314 (self-aligning double roller ball bearings). Lifespan: ~14,000 hours (3.6 years 24/5) Shaft Diameter: 70mm	[2, 19, 20, 21, 18, 22, 23, 24]
	$N = \frac{60 \text{ vs}}{\pi \cdot D}$ (2);		
	$P = T \omega$ (3);		
	$\omega = \frac{2\pi \cdot N}{60}$ (4);		
	$Q_{\text{air}} = A \cdot V_{\text{air}}$ (5)		
	$L_{10} = \left[\frac{C}{P} \right]^p \times 10^6$ (6)		
Buffer Hopper	$V = \frac{\text{Capacity}}{\text{Bulk Density}}$ (7)	Volume: 0.9 m³ (2-hour capacity) Inlet/Outlet: 840x850 mm / 140x140 mm Slope: 60° to prevent bridging	[25, 22]
Cyclone	$Q_{\text{air}} = A \cdot V_{\text{air}}$ (5); $\Delta P_{\text{friction}} = \lambda \cdot \left[\frac{L}{D} \right] \cdot \left[\frac{\rho v p^2}{2} \right]$ (8)	Type: Stairmand high-efficiency Diameter: 500 mm Airflow: 2,000 m³/hr Efficiency: >95% for ≥150 µm particles	[26, 17]
Deduster & Exhaust Fan / Filter	$Q_{\text{air}} = A \cdot V_{\text{air}}$ (5); $\Delta P_{\text{friction}} = \lambda \cdot \left[\frac{L}{D} \right] \cdot \left[\frac{\rho v p^2}{2} \right]$ (8)	Type: Pulse-jet bag filter Airflow: 2,400 m³/hr; Pressure drop: ~653 Pa; Fan: Centrifugal, 1 HP (Backward-curved centrifugal fan), Includes HEPA filter Filter Area: 23.5 m² (25 bags)	[26, 17]
Screw Conveyor	$P = T \omega$ (3)	Capacity: 225 kg/hr Diameter: 230 mm Motor: 4 HP (at 50 rpm) Pitch: 120 mm	[27, 28]
Bearings	$L_{10} = \left[\frac{C}{P} \right]^p \times 10^6$ (6)	Type: SKF 2314 (self-aligning ball bearings) Lifespan: ~14,000 hours (3.6 years 24/5) Shaft Diameter: 70 mm	[21]
Material	-	All food-contact parts: AISI 304 stainless steel (corrosion-resistant, food-grade)	[22, 20]

Note: Components designed for seamless feed to CTC tea process.

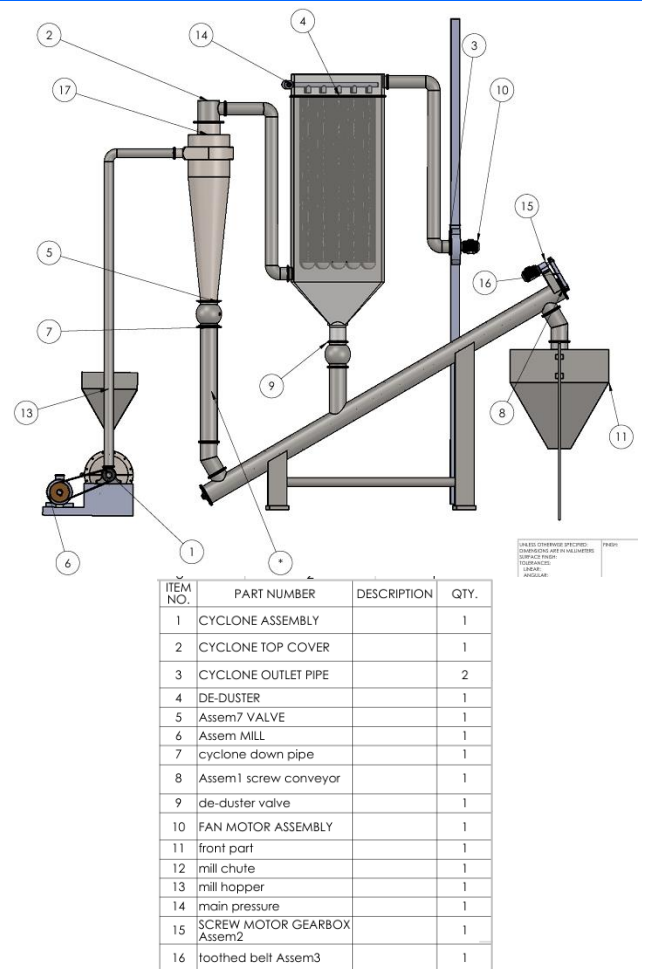


Fig. 9 Tea Milling System Components

C. Comparison of proposed design with previous studies

The proposed design represents a significant advancement over previous work in the field of secondary tea usage. Earlier research by [13] developed a lab-scale hammer mill prototype limited to a bench-top pulverizer with manual batch feeding and no airflow system, rendering it not scalable and lacking industrial compatibility. Similarly, [12] conducted waste-focused studies incorporating components like shredders and digesters, but their systems relied on manual feeding and, while conceptually scalable, were primarily concerned with secondary tea reuse rather than direct grade conversion. Biochemical assessments by [8, 10] focused on polyphenol retention using only mesh components in static batch setups, remaining purely experimental with no physical design work. In contrast, this study presents a full system design specifically engineered for secondary tea conversion. The system integrates a 450 kg/hr hammer mill powered by dual 40 HP motors, complemented by a cyclone separator achieving 95% efficiency and a 2,400 m³/hr pulse jet deduster for comprehensive dust and particle management. Material handling is automated through a 230 mm screw conveyor driven by a 4 HP motor, and the overall design is modular and factory-scalable. Unlike previous laboratory-

scale or conceptual approaches that addressed waste disposal, animal feeds, or biochemical properties, this work directly upgrades secondary-grade waste into sellable primary-grade tea. By incorporating airflow optimization, dust control, automated material handling, and durability considerations, the proposed design transforms secondary tea conversion from a research concept into an operational, factory-ready system, filling a critical market gap through practical value addition via grade conversion.

IV. CONCLUSIONS AND RECOMMENDATIONS

A. Conclusions

- i) **Feasibility of Secondary-Grade Reprocessing:** Pilot plant trials conclusively demonstrated that secondary-grade teas (BMF, PF2, F1, D2) can be successfully upgraded to primary-grade teas (BP1, PF1, PD, D1). This feasibility is attributed to the confirmed presence of bioactive compounds retained in secondary grades after initial processing, providing the biochemical foundation for redesign.
- ii) **Essential Milling Requirement:** Design validation established that milling secondary-grade teas to a particle size range of 150–500 microns is a critical prerequisite for compatibility with CTC machinery. Un-milled teas consistently caused clogging in CTC rollers and were determined to be non-processable, establishing the non-negotiable requirement for size reduction in the system design.
- iii) **Optimal Process Parameters for System Design:** The pilot plant investigations established definitive design specifications:
 - a) **Moisture Content:** 60±2% identified as optimal, achieving target sensory scores
 - b) **Fermentation:** No additional fermentation required, as secondary teas retain sufficient biochemical properties from initial processing, eliminating the need for extended fermentation chambers in the design
 - c) **Quality Outcomes:** Achieved Taste scores of 4.6–4.8 and Leaf appearance score of 4 on the International Tea Categorization System (ITCS), meeting primary-grade marketable quality standards
 - d) **Grade Distribution:** 71% conversion of secondary inputs to primary-grade tea, with overall primary-grade output improved to 94% when integrated with existing production
- iv) **Integrated Milling System Design:** A modular, optimized milling system was successfully designed with a throughput capacity of 225 kg/hr specifically for processing secondary-grade teas (BMF, PF2, D2, F1, Balls) into primary-grade teas (BP1, PF1, PD, D1). The design achieves target particle size of 150–500 µm through an integrated configuration comprising:

- a) Hammer mill (primary size reduction unit)
- b) Cyclone separator with deduster (particulate management)
- c) Screw conveyor (controlled material handling)
- d) Buffer hopper (continuous feeding)

The modular design enables seamless integration with existing CTC processing lines without disrupting conventional production workflows, representing the first dedicated engineering solution for secondary tea grade valorization.

B. Recommendations:

- i) **Adoption of Established Design Parameters:** Tea processing facilities should implement the established design parameters, particularly milling to 150–500 µm particle size and moisture adjustment to 60±2%, as these factors critically influence conversion efficiency and final tea quality. System designs must incorporate these specifications as non-negotiable performance requirements.
- ii) **Integration with Existing CTC Lines:** The modular design approach facilitates retrofitting into both smallholder and large-scale tea factories. System integration should position the milling and reprocessing unit upstream of existing CTC lines, enabling continuous processing of secondary grades without disrupting conventional production.
- iii) **Material Selection for Food Safety:** All system components in contact with tea product must be fabricated from food-grade materials, preferably AISI 304 stainless steel, ensuring corrosion resistance, hygiene compliance, and durability under continuous industrial operation.
- iv) **Design Provision for Process Monitoring:** System design should incorporate provisions for routine monitoring of critical parameters, particularly particle size distribution and moisture content, to ensure consistent system performance and product quality.

C. Recommendations for Further Work

- i) **Extended Multi-Site Design Validation:** Future design research should validate system performance across different geographical factories, seasonal conditions, varying secondary-grade conditions to assess design adaptability and establish location, specific design modifications.
- ii) **Long-Term Quality Stability Studies:** Investigate the sensory and chemical stability of reprocessed teas over extended storage periods to ensure no degradation in marketability, informing potential design modifications for product handling and storage integration.
- iii) **Adaptive Automation Integration:** Research the integration of IoT sensors and machine learning algorithms to enable real-time adjustment of

milling parameters (intensity, moisture, airflow) based on feedstock variability. Explore variable-speed drive designs for conveyors to adjust throughput dynamically based on downstream demand.

- iv) Secondary Grade Blending Design: Investigate design configurations for controlled blending of reprocessed secondary teas with withered green leaf, assessing quality impacts and potential design modifications for integrated blending systems.

ACKNOWLEDGMENT

I am profoundly thankful to the Multimedia University of Kenya for providing an enabling academic environment and the essential resources needed to pursue the research.

Special appreciation goes to Browns Plantations for their collaboration, co-sponsorship and allowing trials at their pilot plant. Their willingness to grant access to their facilities, approve and fund proposed experiments and trials, significantly enhanced the practical and industrial relevance of this publication.

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