Improving Production Efficiency in a Quinoa Exporting Company through an Integrated FEFO, Standardized Work, and TPM Approach

Mario Alberto Chumbe-Sausa, Arelys Karen Casas-Apolinario, Gino Viacava-Campos and Jorge Antonio Corzo-Chavez
Carrera de Ingeniería Industrial
Universidad de Lima
Lima, Peru
20200531@aloe.ulima.edu.pe, 20202714@aloe.ulima.edu.pe, geviacav@ulima.edu.pe, jacorzo@ulima.edu.pe

Abstract

The agro-industrial quinoa sector in Peru shows operational efficiency levels below 85%, largely affected by high reprocessing, grain breakage, and variability in microbiological quality during storage. Although Lean and Total Productive Maintenance (TPM) have demonstrated benefits in agro-industrial environments, their integration with inventory-rotation methods such as the First Expired, First Out (FEFO) approach remains limited—particularly in processes where microbiological stability is critical. This study proposes an integrated improvement model for quinoa-exporting companies, combining FEFO-based inventory management, Standardized Work (SW), and TPM to intervene in critical stages of the production flow. Validation followed a hybrid approach: FEFO and SW were evaluated through pilot implementation using real production cycles and cross-checked operational records, while TPM was validated through an Arena simulation model parameterized with plant data and tested across multiple replications to ensure statistical consistency. This multi-method validation strengthens the robustness of the findings and reduces the likelihood that improvements result from random process variation. The integrated model substantially reduced reprocessing, improved operational consistency, and stabilized equipment performance, offering a scalable and replicable framework for enhancing efficiency, minimizing waste, and ensuring quality control in food industries handling short-shelf-life products.

Keywords
Lean Manufacturing, TPM, FEFO, Standardized Work, Agro-exportation.

1. Introduction
Quinoa (Chenopodium quinoa Willd.) has become one of the most relevant crops in the Peruvian agro-industrial sector due to its high nutritional value, gluten-free properties, and sustained growth in global demand. Peru is currently the world's leading quinoa exporter, accounting for 46.6% of global quinoa exports in 2023 (OEC, 2025). In the same year, Peru exported quinoa for US$ 99.4 million, mainly to the United States (US$ 41.7 million) and Canada (US$ 9.7 million), confirming quinoa's strategic relevance for export competitiveness and rural value chains (CIEN-ADEX, 2024).

Beyond market growth, quinoa exporters face increasingly strict quality and safety requirements. Internationally, the Codex Standard for Quinoa (CXS 333-2019) establishes key specifications for processed quinoa, including maximum moisture content of 13.0%, maximum saponin content of 0.12%, and limits for defects such as broken grains (≤ 3.0%), directly linking commercial compliance to effective conditioning, storage, and handling practices (Codex Alimentarius Commission, 2019). These requirements are especially relevant because quinoa processing typically includes pericarp

removal to reduce saponins (debittering), cleaning, and sorting—operations where variability and mechanical action can increase breakage and quality losses. Evidence shows that abrasive processing influences kernel integrity and the distribution of nutrients and proteins within the grain, highlighting the need for controlled parameters and equipment calibration during polishing stages (D'Amico et al., 2019). Likewise, scientific reviews emphasize that quinoa saponins are concentrated in outer layers, meaning insufficient removal affects acceptability, while over-processing can intensify physical damage and yield losses (El Hazzam et al., 2020). In parallel, microbiological compliance remains a core challenge in food export chains; recent experimental work with Peruvian quinoa varieties found that combined disinfection treatments can significantly reduce microbial loads (log reductions in mesophilic aerobic bacteria and enterobacteria), supporting the relevance of robust conditioning and sanitation controls when non-conformities arise (García-Torres et al., 2025). Additionally, Peru's quinoa supply chains involve multiple actors and processing paths (collectors, processors, exporters), often creating coordination gaps that make standardization and inventory control more difficult (Mercado & Ubillus, 2017).

Despite its economic relevance, quinoa processing industries face operational challenges related to product quality preservation, compliance with international standards, and minimization of waste across production stages. The company analyzed in this study reports a production yield of 84.13%, which is significantly below the sector benchmark of 93.8%, resulting in a technical gap of 9.7%. Diagnostic indicators reveal that 37% of reprocessing is associated with inadequate inventory rotation, 63% is linked to microbiological non-conformities during raw material conditioning, and 21.8 tons of grain breakage occur during the polishing stage, contributing to an overall waste rate of 15% in the production line. These inefficiencies directly affect cost structure, productivity, and product quality, limiting the company's ability to remain competitive in international markets.

In agro-industrial environments, Standardized Work has shown the ability to reduce variability and stabilize production tasks. Calderón Morales (2024) demonstrated this by applying standardized work and the 5S methodology in an artichoke-processing line, achieving higher productivity and reducing raw-material losses. Lean-based quality-control approaches also enhance process reliability in food manufacturing; Cabrera (2020) reported that the integration of Lean tools with the hazard analysis and critical control point system reduced non-conformities and strengthened quality assurance. Additionally, Total Productive Maintenance contributes to improving equipment performance, with Abdelwahab (2018) showing that autonomous and planned maintenance increase the average operating time before a failure occurs, reduce downtime, and improve continuity in food-industry operations.

Therefore, this study proposes an integrated improvement model based on three complementary tools: Standardized Work (SW) to reduce operational variability, the FEFO method to optimize warehouse rotation and prevent deterioration, and Total Productive Maintenance (TPM) to calibrate polishing equipment and minimize grain breakage. The objective of this research is to reduce reprocessing levels, minimize waste, and increase overall production efficiency while ensuring compliance with international quality and microbiological safety standards. The approach provides a practical, scalable, and replicable framework for small and medium-sized agro-industrial companies.

1.1 Objectives
This study aims to achieve the following objectives:
1. To diagnose the current production process and identify the main sources of inefficiency, waste, and variability affecting production yield.
2. To implement Standardized Work (SW) and the First Expired, First Out (FEFO) methodology to improve operational consistency and optimize inventory rotation practices.
3. 3. To apply Total Productive Maintenance (TPM- Autonomous Maintenance & Planned Maintenance) in the polishing stage to improve equipment performance and reduce grain breakage and reprocessing.
4. To evaluate the impact of the integrated improvement model through pilot implementation and simulation, and to propose a scalable framework for adoption in similar agro-industrial companies.

2. Literature Review
Lean Manufacturing has been recognized as an effective approach to improve operational efficiency and reduce waste in the agri-food sector. In processing environments with biological variability, Lean enables greater control of flows, reduction of losses, and improvements in product consistency (Dora et al., 2013). The application of Lean principles in food production also contributes to stabilizing process conditions and improving quality outcomes, particularly when operational decisions directly affect product integrity (Vlachos, 2015).

As global food supply chains require strict traceability and control, Lean tools have proven beneficial in reducing variability and enhancing performance in small and medium-sized enterprises (Vanichchinchai, 2019). Within this framework, inventory rotation plays a critical role. The FEFO (First Expired, First Out) principle has been applied to ensure that storage and dispatch decisions prioritize product stability, minimizing deterioration and avoiding

reprocessing. Visual rotation systems and consistent monitoring support correct execution of FEFO in agro-industrial environments (Castro-González & Montero-Vargas, 2022).

In addition, process standardization is essential to achieving operational stability. Standardized Work establishes a repeatable and optimized procedure for each task, helping to reduce operator-dependent variability. Its implementation in food processing environments has demonstrated improvements in material conditioning, hygiene control, and reduction of non-conformities (Cecconello et al., 2017). Standardization therefore supports both quality assurance and production flow continuity.

On the other hand, equipment reliability is fundamental in mechanical transformation stages such as polishing. Total Productive Maintenance (TPM) seeks to ensure process continuity and product integrity by incorporating preventive maintenance routines and operator involvement in routine checks (Chan et al., 2005).

Finally, simulation has been used as a means to validate Lean and TPM strategies before full implementation. Discrete-event simulation allows the evaluation of production performance under different maintenance and operational conditions without interrupting production lines, supporting data-driven decision-making. Integrating Lean tools such as FEFO, Standardized Work, and TPM allows addressing simultaneously three sources of inefficiency: inventory degradation, procedural inconsistency, and equipment instability, improving productivity and reducing waste (Singh & Ahuja, 2017).

3. Methods

The research followed an applied and quantitative approach, aiming to improve production performance in a Peruvian quinoa export company. The methodology combined direct observation, time studies, and structured pilot testing of three tools: First Expired, First Out (FEFO), Standardized Work, and Total Productive Maintenance (TPM). These tools were selected after a diagnostic stage that identified high reprocessing rates, operational variability, and machine-related defects as key inefficiency drivers.

In addition, the methodological framework was supported by international standards to ensure applicability and replicability. The FEFO method was aligned with ISO 22000:2018, guaranteeing food safety during storage and distribution. Standardized Work was designed in accordance with ISO 9001:2015, emphasizing quality management and process consistency. For TPM, references were taken from ISO 55000 (asset management) and ASTM E2608-20 (preventive maintenance practices), in addition to ISO 16793:2018 for polishing machine pressure monitoring. Previous studies such as Chan et al. (2005) have shown that integrating international standards with TPM practices enhances process reliability and facilitates broader industry adoption, while Singh & Ahuja (2017) highlight their effectiveness in food processing industries.

The validation approach followed a hybrid design:

- Pilot implementations were conducted in the plant for FEFO and Standardized Work, assessing short-term improvements in reprocessing and consistency.

- TPM—through its Autonomous Maintenance and Planned Maintenance pillars—was validated through simulation in Arena, comparing AS-IS and TO-BE scenarios.

- The process was structured in three phases: preparation, implementation, and evaluation, including operator training, checklists, and control routines.

Furthermore, to ensure a rigorous evaluation of the improvements achieved, specific indicators were defined for each root cause and tool. For Standardized Work, the indicators included the percentage of reprocessed products due to poor storage and pre-cleaning practices and the compliance rate with standardized procedures. For FEFO, the metrics considered were inventory rotation time, percentage of expired products, and volume of reprocessing associated with microbiological non-conformities. Finally, for TPM, the indicators comprised the percentage of grain breakage, Overall Equipment Effectiveness (OEE), and average downtime per shift. These indicators enabled an objective comparison between the AS-IS and TO-BE scenarios, ensuring that each improvement could be quantitatively validated and directly linked to its corresponding root cause.

3.1 Component 1: Optimize Production Yield through TPM (Autonomous Maintenance & Planned Maintenance)

The TPM model was developed for the polishing machine, identified as a critical point due to its significant influence on the percentage of broken grains. The approach included three components: autonomous maintenance, which involved daily inspection and basic adjustments by operators; pressure monitoring, with visual logs of daily readings to ensure compliance with ISO 16793:2018 pressure ranges (80–100 kPa); and preventive maintenance, scheduling short,

periodic stops to inspect and adjust the equipment. Similar TPM frameworks were successfully applied in manufacturing sectors by Singh & Ahuja (2017), reporting substantial improvements in OEE and defect rates.

Direct studies were conducted in the plant to capture actual durations of key tasks in the polishing process. The recorded times included machine operation cycles, bag transitions, pressure adjustment intervals, and minor stoppages. This empirical data was processed using Arena Input Analyzer to determine the most appropriate statistical distributions for each sub-process. In particular, NORM(5.06, 0.29) was applied for polishing times and TRIA (3.74, 4.12, 5.19) for sack transfer.

To ensure robustness, two scenarios were tested: one reflecting the AS-IS condition with reactive maintenance, and another incorporating TPM measures such as operator inspections and preventive shutdowns. Preventive maintenance was scheduled for every 50 sacks processed, which allowed a more stable system and reduced cycle times. The scenario was simulated using 38 replications, ensuring statistical robustness. The purpose was not only to compare production efficiency, but also to validate that the TPM improvements could be reliably maintained under dynamic production conditions. Furthermore, the simulation confirmed that under the TPM-enhanced scenario, machine utilization increased, and grain breakage decreased, reinforcing the role of systematic maintenance in minimizing waste and stabilizing process variability.

The following diagram summarizes the proposed production efficiency improvement model, starting from the main problem identified in the quinoa processing operation: the failure of some products to meet the required microbiological standards for export, mainly due to poor control during initial conditioning and excessive waste generated in the polishing stage. Three key problem areas are highlighted: the lack of standardized procedures during pre-cleaning and conditioning, inefficient product rotation in the finished goods warehouse, and inadequate calibration of the polishing machine. To address these issues, the model integrates three improvement actions: the implementation of Standardized Work to ensure consistent and controlled conditioning processes, a FEFO pilot to improve inventory rotation and prevent quality deterioration over time, and a TPM-based simulation to evaluate and reduce grain breakage and waste caused by machine settings. Together, these solutions aim to reduce reprocessing and waste, leading to a comprehensive improvement in production efficiency (Figure 1).
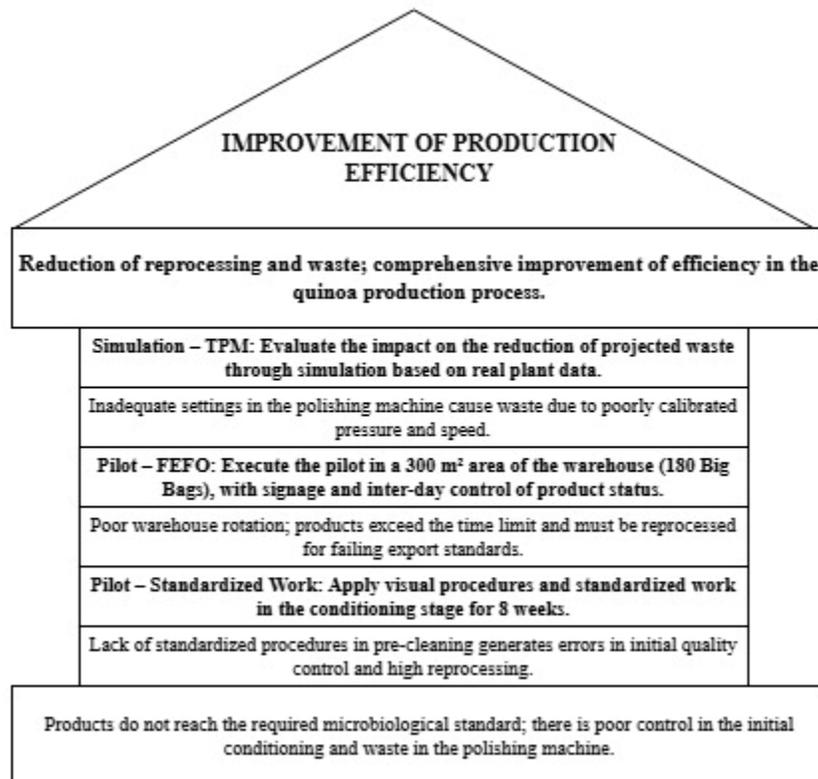

Figure 1. Conceptual Model of the project

3.2 Component 2: Reduce Storage Time and Quality Risk through FEFO

To reduce the high reprocessing rate associated with poor inventory rotation, a pilot implementation of the FEFO (First-Expire, First-Out) method was conducted over a two-month period. During this pilot, operators were trained to use a color-coded labeling system (red, yellow, and green) to visually identify the remaining shelf life of packaged quinoa. Red labels indicated products with less than five days of remaining shelf life and were prioritized for immediate dispatch, while yellow and green labels represented medium- and long-term storage conditions, respectively.

As part of the implementation, the warehouse layout was reorganized to position products approaching expiration in more accessible locations, reducing handling time and decision-making uncertainty. Visual signaling systems were installed across storage zones to facilitate rapid identification of dispatch priorities and to support operator compliance. Initial implementation challenges were observed, particularly delays in updating label colors due to limited supervisor availability. However, as the pilot progressed, standardized daily update routines were established, resulting in improved traceability, better inventory visibility, and a noticeable reduction in reprocessing linked to storage time exceedance.

It is important to note that this FEFO system was intentionally implemented as a manual and visual pilot to validate its operational feasibility and impact under real plant conditions. For large-scale deployment, a more robust and scalable solution is recommended. Future improvements may include the integration of FEFO logic into an inventory management or ERP system, allowing automatic tracking of product shelf life, real-time prioritization of dispatch orders, and system-generated alerts when critical thresholds are reached. Such digital integration would reduce reliance on manual updates and individual judgment, enabling the system to automatically indicate which specific Big Bag or storage location should be dispatched when an order is registered, thereby further minimizing quality risks and inventory-related reprocessing.

3.3 Component 3: Standardize Work Operations to Reduce Variability

To reduce the high rate of reprocessing caused by inconsistent task execution, a Standardized Work (SW) system was developed. This included the creation and distribution of standard operating procedures (SOPs), visual guides, and printed manuals across workstations. The methodology was explicitly aligned with ISO 9001:2015, ensuring that operational consistency was embedded into the company's quality management system. As shown by Cecconello et al. (2017) and Ahmadi (2023), standardization practices significantly reduce process variability, enhance quality compliance, and improve operator training efficiency in manufacturing environments.

Initial adoption by workers was limited; however, during the second month, reinforcement strategies such as peer-led engagement, progressive training sessions, and the distribution of both printed and digital SOP copies were implemented. These strategies improved adherence to standardized practices and strengthened coordination among operators.

The standardized work sheets included checklists for raw material inspection, parameter ranges for machine settings, and explicit defect classification criteria. These parameters not only provided clarity in execution but also facilitated compliance with international quality standards. The SW model was validated in the Arena simulation by incorporating reduced variability parameters, which projected measurable improvements in productivity and a significant decrease in defect rates.

4. Data Collection

Data collection was conducted on-site in the quinoa processing plant during regular production shifts to ensure the representativeness of operating conditions. Primary operational data were obtained through direct observation, operator interviews, and standardized operational records, allowing cross-verification of information from independent sources. Key indicators—production yield, reprocessing volumes, grain breakage, and microbiological non-conformities—were extracted from monthly production and quality-control reports covering multiple production cycles, providing statistically stable trends rather than isolated observations. Inventory rotation data were gathered from warehouse batch records and storage-time logs, enabling analysis of rotation behavior across a sufficiently large sample of batches.

To support TPM calibration, real-time monitoring of polishing parameters—including pressure, rotational speed, and sack throughput—was recorded continuously over a two-month period, ensuring variability capture for reliable parameter estimation. For the Standardized Work assessment, execution times and operator-sequence variability were measured using time-motion study techniques across repeated trials, enhancing the statistical reliability of task-uniformity measurements.

In the validation phase, the Arena simulation model was parameterized using averaged processing rates, historical downtime distributions, and preventive maintenance intervals derived from multi-cycle plant data. Data validity was further reinforced through triangulation between warehouse databases, quality-inspection reports, and equipment-

performance logs. This multi-source, multi-cycle, and cross-validated data collection strategy strengthens the statistical robustness of both the diagnostic findings and the validation outcomes.

5. Results and Discussion

This section presents the outcomes of the FEFO and Standardized Work (SW) pilot implementations, along with the TPM validation conducted through Arena simulation. The results demonstrate significant reductions in reprocessing, waste generation, and grain breakage, contributing to a notable increase in overall production efficiency.

5.1 Numerical Results

This section presents the numerical results obtained from the evaluation of the AS-IS and TO-BE scenarios. The analysis aims to quantify the operational inefficiencies observed in the initial system and to assess the impact of the proposed improvement model on productivity, waste reduction, and overall process efficiency (Table 1).

Table 1. Key results by indicator

Indicator	Tool	AS-IS (Before Pilot)	TO-BE (Expected Results)	Pilot Results (Actual)
Production Yield (%)	—	84.13%	$\geq 90\%$	88.5% (Pilot Est.)
Reprocessing Rate – Inventory Rotation (%)	FEFO	37% (311.52 tons/year)	15% (126.3 tons/year)	12% (40 tons/year)
Reprocessing Rate – Initial Control Failures (%)	Standardized Work	63% (530 tons/year)	25% (210 tons/year)	24% (126 tons/year)
Waste Rate (%) – Excessive Machine Pressure	TPM	15%	5% – 11%	7% (Pilot Est.)
Broken Grain Rate (%) – Improper Speed Settings	TPM	9%	3%	4.1% (Pilot Est.)

Under the AS-IS scenario, the company exhibited several structural inefficiencies that negatively affected production performance. Poor inventory rotation in the finished goods warehouse led to frequent reprocessing activities, as products often exceeded acceptable storage times before sealing and dispatch. This situation resulted in a production yield below the sector benchmark and increased operational pressure to meet customer orders. Reprocessing activities were mainly demand-driven rather than efficiency-driven, which caused unplanned machine usage, frequent reallocations of labor, higher energy consumption, and the need for overtime work. In addition, the absence of specialized personnel focused on process improvement limited operational control and reduced visibility over inefficiency sources.

Waste generation, particularly grain breakage during the polishing process, was considered a normal outcome of operations and was not closely monitored. Although broken grains were sold to secondary markets, the accumulated volume of waste was higher than expected on an annual basis. The economic and operational impact of this waste became evident only after the waste rate indicator was analyzed in detail. Furthermore, gradual misconfigurations in polishing machine parameters, such as pressure and speed, increased grain breakage over time; however, these deviations were not systematically corrected due to the lack of preventive maintenance practices. Overall, the AS-IS system lacked structured monitoring of reprocessing frequency, waste generation, and machine performance, operating reactively based on order fulfillment rather than proactively improving efficiency (Table 2).

Table 2. Summary of key results

Tool	AS-IS Tons	TO-BE Tons	% Reduction
FEFO	311.52	126.3	59.5%
Standarized Work	530	126	75%
TPM	21.8	<10	54%

The numerical results of the TO-BE scenario reflect the improvements achieved after implementing the proposed FEFO, Standardized Work, and TPM-based interventions. These results demonstrate a reduction in reprocessing activities and waste levels, along with an improvement in production yield and process stability. The comparison between AS-IS and

TO-BE scenarios highlights the effectiveness of addressing inventory rotation, operational standardization, and machine reliability in an integrated manner to enhance overall production efficiency.

5.2 Graphical Results

The comparative analysis of performance indicators (AS-IS vs. TO-BE vs. Pilot Results) demonstrates how the improvements introduced by each component—inventory rotation through FEFO, operational consistency through Standardized Work, and equipment optimization through TPM—collectively enhanced production efficiency in the quinoa processing line. FEFO significantly reduced inventory-related reprocessing by improving the prioritization and flow of stored products, while Standardized Work minimized microbiological reprocessing by stabilizing operator tasks and reducing variability in early processing stages. TPM contributed to lowering waste and broken grain rates by ensuring appropriate machine calibration and pressure control. As shown in the Figure 2, the combined effect of these interventions increased production yield from 84.13% to 88.5%, while sharply decreasing reprocessing rates, waste, and equipment-related defects. These results confirm that addressing bottlenecks across inventory, operations, and machinery simultaneously generates a synergistic improvement in overall process efficiency.
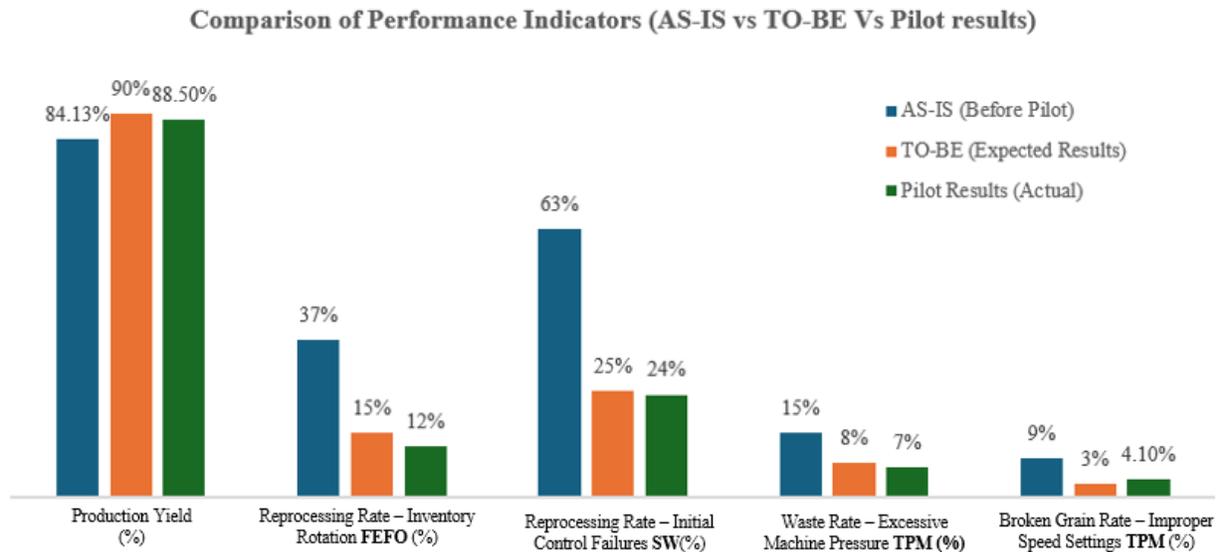

Figure 2. Comparison of performance indicators (AS IS vs TO-BE vs Pilot Results)

5.3 Proposed Improvements

Although the pilot implementation of FEFO, Standardized Work, and TPM demonstrated substantial improvements in production efficiency and waste reduction, several enhancements are required to sustain and scale the results across the full quinoa processing line.

First, the FEFO system should transition from a manual, color-coded tag updating process to a more decentralized and autonomous model. During the pilot, delays in supervisor-led updates were identified as a limitation that affected inventory rotation speed. Implementing a digital or barcode-based batch tracking mechanism, accompanied by responsibility delegation to multiple trained operators, would ensure consistent product turnover and mitigate the risk of reprocessing due to aging inventory.

Second, while Standardized Work significantly reduced reprocessing caused by initial control failures, the adoption process revealed the need for continuous reinforcement. Training should evolve toward micro-learning modules, periodic hands-on refresh sessions, and visual audits to strengthen long-term operator compliance. Embedding these practices into daily supervision routines would help stabilize process variability and maintain microbiological quality performance.

Third, the TPM strategy—validated in simulation—must be transferred into real operating conditions to confirm its long-term effectiveness. Autonomous maintenance routines should be introduced gradually, beginning with basic operator inspections, lubrication tasks, and critical parameter verification (e.g., pressure and rotational speed). Additionally, integrating preventive maintenance scheduling into regular production planning would reduce downtime while ensuring optimal machine performance.

Finally, establishing a unified performance monitoring dashboard that consolidates indicators such as yield, reprocessing rates, breakage levels, and equipment utilization would support real-time decision-making and increase accountability. This would help maintain the improvements observed during the pilot phase and allow for proactive corrective actions rather than reactive responses.

5.4 Validation

The validation process focused on determining whether the improvements obtained in the TO BE scenario were statistically significant relative to the AS IS baseline. For this purpose, the Arena simulation was executed with multiple replications, allowing the estimation of 95% confidence intervals for key indicators. The AS IS scenario exhibited an average system time of 7.8 minutes, with a confidence interval of (7.55; 8.05), while the TO BE scenario reduced this metric to an interval of (6.05; 6.45). Since these intervals do not overlap, the reduction in processing time is statistically significant and cannot be attributed to random variation. In addition, running multiple replications reduces the risk that results are driven by isolated outliers or a single favorable production run, strengthening the internal validity of the comparison between scenarios.

Similarly, machine utilization improved from an AS IS interval of (89.1%; 90.3%) to (92.2%; 93.5%) in the TO BE scenario, confirming that TPM interventions stabilized equipment performance and increased effective capacity. Product quality indicators also showed significant improvement: the percentage of conforming sacks increased from 125–133 units in AS IS to 140–148 units in TO BE, while non-conforming sacks decreased from 4–7 units to 1–3 units, demonstrating a clear and statistically supported shift toward higher-quality outputs. Together, these results indicate that the TO BE scenario improves both efficiency (time and utilization) and output quality simultaneously, rather than achieving gains through a trade-off between speed and conformance.

The AS IS descriptive statistics reinforce this conclusion: the system exhibited a mean loss rate of 15% with a wide interval of (10%; 20%), reflecting high variability driven by excessive polishing pressure. In contrast, the TO BE configurations supported by calibrated preventive maintenance and standardized settings produced narrower intervals across all indicators, evidencing improved process stability. This reduction in variability is particularly relevant for agro-industrial environments, where incoming raw-material heterogeneity can amplify process fluctuations and make consistent execution essential for maintaining export-grade quality.

Overall, the non-overlapping confidence intervals, the reduction in standard deviations, and the narrower ranges in the TO BE scenario confirm that the improvements observed are statistically robust. These results validate that the proposed Lean–TPM model generates real, replicable performance gains rather than stochastic fluctuations inherent to production variability. Nevertheless, since FEFO and Standardized Work were validated through on-site pilots and TPM primarily through simulation, future work should complement these findings with longer-term shop-floor TPM monitoring to confirm sustained performance under routine operating conditions.

6. Conclusion

This study addressed the low operational efficiency of a Peruvian quinoa-exporting company by designing and validating an integrated improvement model based on FEFO, Standardized Work (SW), and Total Productive Maintenance (TPM). The findings show that the model effectively reduced reprocessing, stabilized critical operations, and improved production yield, confirming that Lean-based approaches can be adapted to agro-industrial contexts characterized by biological variability and strict quality requirements. Beyond productivity, the model also has clear economic and sustainability implications: reducing reprocessing loops and grain breakage decreases unnecessary machine runtime, electricity consumption, and labor hours devoted to non-value-added activities, while lowering overall material losses and associated environmental impacts. In addition, because the approach targets universal drivers of agro-food inefficiency (rotation discipline, task standardization, and equipment stability), it can be adapted to other food-processing lines—particularly grains, pulses, flours, and similar products—by recalibrating shelf-life rules, critical quality parameters, and equipment-control standards.

Regarding the research objectives, the diagnostic stage (Objective 1) successfully identified inventory rotation failures, microbiological non-conformities, and equipment-related grain breakage as the main sources of inefficiency. The subsequent implementation of SW and FEFO (Objective 2) reinforced the core aim of the study: both tools proved particularly effective in reducing operational variability and quality-related reprocessing. SW strengthened task discipline in raw material handling and conditioning, improving microbiological control and process consistency. In parallel, FEFO enhanced warehouse rotation practices and decision-making in dispatch sequencing, reducing the risk of product deterioration during storage and directly supporting inventory-related objectives.

TPM (Objective 3) contributed by improving the behavior of the polishing process, especially when pressure and maintenance routines were controlled according to predefined standards. The Arena simulation evidenced a more stable operating pattern, lower grain damage, and better machine utilization when TPM practices were applied. However, this pillar also revealed the greatest risk at the model level: its validation was primarily conducted through simulation rather

than full-scale, long-term implementation on the shop floor. This means that, while the potential of TPM is clear, its sustained performance depends on continuous operator involvement, disciplined execution of preventive tasks, and the integration of maintenance planning into daily production management.

Overall, the integrated validation (Objective 4) confirmed that combining FEFO, SW, and TPM in a coordinated framework can significantly reduce waste and strengthen operational performance in quinoa processing. The most robust contribution of the model lies in the synergy between process standardization and inventory rotation, which delivered consistent and tangible improvements during the pilot. At the same time, the dependence on manual label updates in FEFO and the need for ongoing training and reinforcement in SW highlight that behavioral and organizational aspects remain critical for long-term sustainability.

From a real-world deployment perspective, scaling the integrated model beyond a pilot introduces practical constraints that can weaken long-term performance if not proactively managed. At scale, the effectiveness of FEFO and SW is sensitive to workload pressure during peak demand, storage-layout complexity, workforce turnover, and execution drift (e.g., delayed label updates, incomplete records, or non-compliance with standard procedures). Likewise, TPM sustainability depends on reliable spare-parts availability, disciplined routine inspections, and preventive tasks fully synchronized with production planning to avoid reverting to reactive maintenance. Therefore, broader implementation should be supported by stronger governance (clear roles, daily audits, and KPIs), cross-functional alignment between production–quality–warehouse–maintenance, and progressive digitalization (barcode/ERP traceability and real-time dashboards) to reduce manual errors and accelerate decision-making.

Future efforts should therefore focus on reinforcing the weakest elements of the model. In particular, TPM should be progressively migrated from a simulated scenario to a fully operational one, with clear routines for autonomous maintenance, systematic data recording, and scheduled interventions integrated into production planning. Likewise, digital tools for real-time inventory tracking and performance monitoring would reduce the risk associated with manual FEFO execution and enable faster decision-making. Extending the model to downstream stages such as packaging and distribution could amplify its impact at the value-chain level.

In summary, the study demonstrates that an integrated Lean-based framework—centered on FEFO, Standardized Work, and TPM—can substantially improve efficiency, reduce waste, and enhance quality control in agro-industrial systems handling short-shelf-life products. The strongest results emerged from the objectives related to process standardization and inventory rotation, while the maintenance pillar, although promising, still requires further consolidation to fully secure the long-term robustness of the model.

References

Abdelwahab, S. A., Application and performance measurement of Total Productive Maintenance: Case study of a food industries company in Egypt, *Eng. Res. J.*, vol. 160, pp. 1–25, 2018.

Cabrera, J. L., et al., Improving quality by implementing lean manufacturing, SPC and the hazard analysis and critical control point system in the food industry: A case study, *S. Afr. J. Ind. Eng.*, vol. 31, no. 4, pp. 194–207, 2020.

Calderón Morales, A., Modelo de gestión de producción para mejorar la productividad en el saneamiento de alcachofas mediante la aplicación de trabajo estándar y 5S, Universidad de Lima, Facultad de Ingeniería Industrial, 2024.

Castro-González, S. and Montero-Vargas, J. A., Building first expired first out models to predict food losses at retail due to cold chain disruption in the last mile, *Front. Sustain. Food Syst.*, vol. 6, Art. no. 1018807, 2022.

Chan, F. T. S., et al., Implementation of Total Productive Maintenance: A case study, *Int. J. Prod. Econ.*, vol. 95, no. 1, pp. 71–84, 2005.

Codex Alimentarius Commission, Standard for Quinoa (CXS 333-2019), Codex Alimentarius, FAO/WHO, 2019.

Centro de Investigación de Economía y Negocios Globales – CIEN-ADEX, Granos Andinos: Evolución del Mercado Internacional y Nacional, Nota de Inteligencia Comercial, ADEX/CIEN, Mayo 2024.

D'Amico, S., et al., Abrasive milling of quinoa: Study on the distribution of selected nutrients and proteins within the quinoa seed kernel, *J. Cereal Sci.*, vol. 86, pp. 132–138, 2019, https://doi.org/10.1016/j.jcs.2019.01.007

Dora, M., et al., Lean practices for reducing food waste in food processing SMEs: A case study, *Prod. Plann. Control*, vol. 24, no. 16, pp. 1–13, 2013.

El Hazzam, K., et al., An insight into saponins from quinoa (Chenopodium quinoa Willd): A review, *Molecules*, vol. 25, no. 5, Art. no. 1059, 2020, https://doi.org/10.3390/molecules25051059

García-Torres, S. M., et al., A comparative study of disinfection methods to reduce microbial contamination in different quinoa varieties from Peru, *Foods*, vol. 14, no. 18, Art. no. 3196, 2025, https://doi.org/10.3390/foods14183196

Mercado, W. and Ubillus, K., Characterization of producers and quinoa supply chains in the Peruvian regions of Puno and Junin, *Sci. Agropecuaria*, vol. 8, no. 3, pp. 251–265, 2017, https://doi.org/10.17268/sci.agropecu.2017.03.08

Nguyen, T., et al., Shelf life modelling for first-expired-first-out warehouse management, *Int. J. Refrigeration*, vol. 45, pp. 231–245, 2014.

Observatory of Economic Complexity (OEC), Cereals: Quinoa (Chenopodium quinoa) — International Trade Data (2023), OEC, 2025.

Singh, T. P. and Ahuja, I. S., Evaluating manufacturing performance through strategic TPM implementation in a food processing industry, *Int. J. Prod. Qual. Manag.*, vol. 21, no. 4, pp. 429–442, 2017.

Vanichchinchai, A., Lean practices and performance: The role of supply chain integration, *Sustainability*, vol. 11, no. 20, Art. no. 5751, 2019.

Vlachos, I., Applying lean thinking in the food supply chains: A case study, *Prod. Plann. Control*, vol. 26, no. 16, pp. 1351–1367, 2015, https://doi.org/10.1080/09537287.2015.1049238

Biographies

Mario Chumbe is a Bachelor of Industrial Engineering from the Universidad de Lima (Perú). He currently works as a Junior Business Specialist in the financial sector, where he has accumulated two years of professional experience leading and supporting nationwide high-impact projects within the alternative channels and correspondent tellers network. He has participated in university research and improvement projects related to operational efficiency, process optimization, and continuous improvement in agro-industrial and service environments. His professional background includes experience in project coordination, data analysis, operational management, and strategic support for commercial and service processes in the banking industry. His main areas of academic and professional interest include lean manufacturing, process simulation, operations management, logistics systems, and continuous improvement applied to medium and large-scale organizations.

Arelys Casas is a Bachelor of Industrial Engineering from the Universidad de Lima (Perú). She currently works in the retail sector at Tai Loy, where she has one year of experience supporting commercial operations and sales management processes. Her professional background includes coordination of point-of-sale activities, product assortment management, customer service improvement, and commercial performance monitoring. She has also participated in academic and applied projects related to process optimization and operational efficiency. Her main areas of interest include retail operations, commercial strategy, continuous improvement, and supply chain management in high-demand environments.

Gino Viacava-Campos is currently a professor in industrial engineering career at Universidad de Lima. He holds a Master in Operations and Logistics from Universidad Peruana de Ciencias Aplicadas (UPC) (Perú) and is Industrial Engineer from the Universidad de Lima (Perú). He has experience in industrial and service companies to improve productivity, development of business models and structure compensation systems. He has worked in human resources area, operations and logistics areas of a transnational company, locally and overseas. As consultant he has experience with construction, manufacturing, services, mining, commercial, finance and education sector. His main research interests are lean manufacturing, master production schedules, logistics, compensation systems for small and medium-sized enterprises.

Jorge Antonio Corzo-Chavez is currently a professor in industrial engineering career at Universidad de Lima, chief executive officer at Conquista Lab, and associate consultant at Manpower Group for multinational companies. He holds a Master in Business Administration from Universidad ESAN (Perú), a Master in Marketing Science from ESIC Business & Marketing School (Spain) and is Industrial Engineer from the Universidad de Lima (Perú). He has experience in advising industrial and service companies to improve productivity and development of business models. He has worked in areas of entrepreneurship and innovation, marketing and commercial for the construction, metalworking, mining, services, and education sectors. His main research interests are lean manufacturing, master production schedules, logistics, machine learning, and innovation for small and medium-sized enterprises.