# Proposed based on TPM, Process Standardization and Circular Economy tools to reduce the waste in a spinach production line

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***Abstract*— The agro-industrial sector is crucial for the Peruvian economy, contributing significantly to exports and GDP growth. However, it faces challenges, particularly high production waste due to machinery failures, lack of preventive maintenance, and non-standardized processes, which reduce productivity and profitability. This study focuses on excessive waste in a spinach production company and proposes a solution using Total Productive Maintenance (TPM). Emphasis is placed on preventive maintenance to enhance machinery efficiency and process standardization to improve production. Additionally, a FIFO system is suggested for better inventory management, alongside a circular economy approach to reduce waste. The research primarily targets the post-harvest stage, where waste is most critical, but addresses the full production chain. Implementation will follow the PDCA methodology, starting with planning and training staff in preventive maintenance and process standardization. Progress will be tracked through key performance indicators, and a pilot plan will assess the real-world impact of proposed changes. The goal is to improve sustainability and competitiveness in Peruvian agri-food businesses while addressing critical industry challenges.***

***Keywords*—TPM; process standardization; FIFO; circular economy; PDCA**

## I. INTRODUCTION

The agro-industrial sector is an integral part of the Peruvian economy, significantly contributing to the gross domestic product (GDP) and being a key driver of the country's exports. However, this sector faces several critical challenges, such as inefficient production management and high levels of waste. Agro-industrial companies often suffer significant losses due to a lack of adequate maintenance processes and inefficiencies in supply chain management, directly affecting the profitability and competitiveness of these organizations [1]. Additionally, the lack of process standardization in operations leads to variations in product quality and increases in waste generation [2].

In particular, the spinach production chain in Peru faces significant losses due to recurring machinery failures and the absence of a preventive maintenance plan, resulting in high waste rates, affecting approximately 15% of the total annual production [3]. In many agro-food companies, the lack of control over downtime and errors in machinery management are responsible for up to 30% of the increased operating costs, further aggravating the economic difficulties of these companies [4]. In the case of companies that handle perishable products, such as spinach, this problem is even more critical due to the short shelf life of the products, which generates an immediate impact on product availability for markets [5].

In addition to mechanical failures, another significant challenge is the lack of integration in production processes. In the agro-industrial sector, imbalances in production processes often result in delays that exacerbate waste generation, affecting an average of 12% of productive time [6]. Weather conditions and poor post-harvest process planning also affect product quality and subsequent commercialization, resulting in a reduction of up to 20% of the produced volume [7]. Inadequate storage conditions, both during production and transportation, contribute to the degradation of fresh products, leading to significant economic losses estimated in millions of dollars annually [8].

The need to solve these problems has become imperative to ensure the sustainability and growth of the agro-industrial sector. Research has identified that the implementation of tools such as Total Productive Maintenance (TPM) and process standardization can drastically reduce waste generated by machinery failures and improve operational efficiency by up to 25% [9]. In a similar case study, a 34% reduction in equipment failures in an agro-food company was achieved by applying TPM, resulting in a significant improvement in production efficiency and reduced downtime [10]. This evidence suggests that TPM can be an effective tool to address maintenance issues in companies that, like this study, handle highly perishable products.

Another key aspect in solving the problem is the implementation of circular economy-based approaches, which allow for maximizing resource use and minimizing waste. The reuse of by-products generated during production can reduce waste by 20% and increase overall system efficiency [11]. This approach has not only economic but also environmental implications, as it contributes to more sustainable resource management and reduces the environmental impact of agro-industrial operations, decreasing the carbon footprint by 10% [12].

This research focuses on analyzing the problem of high waste rates in the production of spinach in a Peruvian agro-industrial company. The company in question has reported alarming waste levels, particularly in the post-harvest stage, due to frequent machinery failures and the lack of standardized processes that ensure efficient product handling [13]. The lack of flexibility in supply chains also plays a crucial role in waste generation, highlighting the need to implement comprehensive solutions that address both operational efficiency and inventory management [14].

For this reason, this study proposes a solution model based on the principles of TPM, process standardization, and the circular economy. The implementation of these tools will reduce waste by 20%, improve machinery efficiency by 25%, and promote more sustainable resource management [15]. These improvements will not only positively impact the company's profitability but also contribute to strengthening the competitiveness of the Peruvian agro-industrial sector [16].

## II. Literature Review

### *2.1 How Problems Are Solved*

Techno-organizational problems in industrial settings often arise from inefficiencies in production processes, failure in machinery, and lack of standardized procedures. To address these challenges, various tools and methodologies have been proposed in the literature, focusing on improving operational efficiency and reducing downtime. One widely employed approach is root-cause analysis (RCA), used to identify the underlying causes of problems. Tools such as the Ishikawa (fishbone) diagram and Pareto analysis are often applied in this context. Studies have identified the effectiveness of RCA tools in quality management, highlighting the seven classic quality tools as essential for identifying process inefficiencies and equipment failures [17].

Other research emphasizes the behavioral aspect of problem-solving. It has been shown that defining problems too narrowly or too broadly can hinder the effectiveness of subsequent solutions, suggesting a balanced approach is needed [18]. Additionally, studies have found that effective problem formulation is crucial for implementing organizational changes, particularly in fields like transportation planning [19].

Further, some methodologies combine both qualitative and quantitative approaches to ensure thorough analysis. A novel tool for decision-support based on cause-and-effect analysis integrates qualitative insights with quantitative data, offering a more comprehensive understanding of root causes and facilitating more effective decision-making [20]. In the manufacturing sector, methods like cause-effect chain analysis plus (CECA+) have been introduced to solve manufacturing problems by integrating a systematic approach with real-time data analysis. This method is particularly effective in identifying complex interdependencies between operational variables, significantly reducing production downtime and improving efficiency [21].

### *2.2 Similar Problems Solved*

In the field of industrial production, particularly in the agro-industrial sector, many companies face issues similar to those analyzed in this study. Failures in machinery, lack of a preventive maintenance plan, and poor process standardization have been identified as primary causes of inefficiencies across various companies. For example, in the metalworking sector, the implementation of Total Productive Maintenance (TPM) and Lean tools reduced downtime by up to 34%, proving their effectiveness in similar contexts [22].

Another relevant case study applied value stream mapping (VSM) to an unbalanced food processing line, identifying inefficiencies in production flow. By optimizing process flows and incorporating preventative maintenance schedules, the study achieved a significant reduction in waste generation and downtime [23]. Additionally, research in the textile industry showed that combining Lean Manufacturing with TPM led to a reduction of waste by 20% and an increase in operational efficiency by 18% [24]. A broader approach combining Lean Manufacturing principles with a focus on circular economy models, resulting in a more sustainable production system that minimizes waste and optimized resource use. This is particularly relevant for agro-industrial companies dealing with perishable goods, where reducing waste is crucial for maintaining profitability and environmental sustainability [25]. A case study in the food processing industry demonstrated that implementing these models could lower production waste by up to 25% while improving the overall sustainability of the operations [26].

Finally, the application of predictive maintenance models has been gaining traction in recent years. Predictive maintenance strategies can effectively forecast equipment failures before they occur, leading to significant reductions in unscheduled downtime and waste [27]. This aligns with the solutions proposed in this paper, where a predictive and preventive maintenance plan is integrated into the operational strategy of the spinach production company.

## III. Methodology

The methodology adopted in this study focuses on identifying and analyzing the core issues related to high waste rates in the post-harvest process of spinach production.

Initially, a thorough diagnostic phase was conducted, in which the root causes of inefficiencies in production were identified. Data collection involved reviewing historical records of production processes and machinery failures to pinpoint the most frequent issues, especially those related to equipment breakdowns and waste generation. The data collected were analyzed to categorize the problems into areas such as human errors, machinery failures, and environmental factors.

Once the root causes were identified, the PDCA cycle (Plan, Do, Check, Act) was employed to structure the continuous improvement phases and manage the implementation of solutions [28]. Pareto analysis was used to prioritize the most impactful factors, ensuring that efforts to reduce waste focused on the problems contributing most to inefficiencies. This phase included evaluating the effectiveness of current preventive maintenance practices and standardization procedures. Additionally, circular economy practices were adopted in selected areas of the process, focusing on reducing waste through the reutilization of by-products generated within the production cycle [29].

## IV. Problem Analysis

### *4.1 The Case*

The case focuses on a Peruvian agro-industrial company specializing in the cultivation of vegetables using soil-less methods in greenhouses, specifically hydroponic systems. The company is a pioneer in Peru for this innovative approach to agriculture. The facilities are in the district of Lurín, in Lima, where the company operates on 10 hectares of land. This land houses greenhouses equipped with a drip irrigation system for the efficient production of vegetables.

The company distributes its products, including spinach, to major national markets such as Metro, Wong, Vivanda, Plaza Vea, and Tottus. The company is recognized for its strict quality policy, which emphasizes continuous process improvement by employing specialized human capital, ensuring ergonomic standards, and maintaining a healthy work environment. Its mission is to provide customers with healthy, natural products rich in nutrients. The vision is to become the first choice for greenhouse vegetables in Peru, being present in the main markets and recognized for enhancing the quality of life of its consumers.

### *4.2 The Process*

The production process under analysis revolves around the spinach production line, which is divided into several key phases: cultivation, post-harvest handling, washing, quality control, packaging, and storage. The company employs hydroponic cultivation in greenhouses, using a drip irrigation system that ensures optimal growth conditions for spinach. Once harvested, the spinach undergoes a post-harvest process where it is sorted and inspected for any defects or irregularities.

After the initial sorting, the spinach is transported to the washing area. Here, the product is cleaned using a specialized washing system designed to remove dirt, pesticides, and other residues. The washing phase is a crucial step in maintaining food safety standards, and it involves several cycles of washing and rinsing. The washed spinach is then moved to a drying conveyor, where excess water is removed to prepare it for packaging.

Following the drying process, the spinach enters the quality control stage, where a final inspection is carried out. This step ensures that the spinach meets the company's strict quality standards before packaging. The packaging process involves weighing the product, placing it into sealed bags, and using an automated sealing machine to ensure that the packaging is airtight and tamper-proof. Once packaged, the spinach is transferred to the cold storage facilities. The storage process is key to maintaining the freshness and quality of the spinach before it is distributed to national supermarkets.

### *4.3 The Problem*

The key issue identified within the company is the excessive waste generated during the post-harvest processes of the spinach production line. This waste is concentrated in various stages, including washing, sealing, quality control, and storage. Each stage plays a crucial role in ensuring product quality and efficiency, yet failures and inefficiencies at these critical points have led to a compounding waste problem. The waste rate is particularly concerning, with a total waste percentage of 21.07% for the year 2023, significantly higher than the regional agro-industrial benchmark of 5% [30] (See Fig. 2).

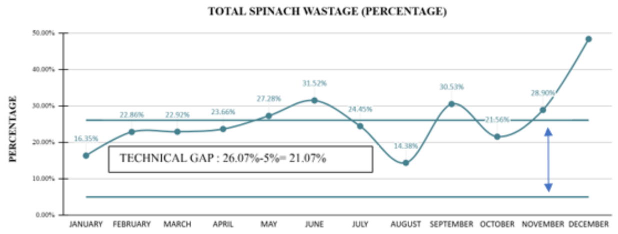


Fig. 1 Monthly percentage of amount lost in spinach in the year 2023

Additionally, it was determined that the spinach production line has the highest rate of product returns, further highlighting the severity of the inefficiencies in the post-harvest processes. The rejection and return rates have led to substantial financial losses due to unfulfilled orders and customer dissatisfaction [31]. These returns not only represent lost revenue but also damage the company's reputation with clients, who expect consistent product quality.

This technical gap of 20.13% reflects a substantial loss in efficiency and leads to financial impacts on the company. The economic loss contributed to the waste issue in the spinach line amounted to S/. 145,613.70, primarily from rejected orders and billing losses due to product quality issues [32]. The root causes of this problem stem from several factors, including equipment failures, particularly with the sealing machines, and inefficient washing processes. Furthermore, the lack of proper storage conditions exacerbates the situation by accelerating product degradation during handling and distribution [33].

In fact, the company faces significant challenges in fulfilling 100% of its customer demand due to the high waste levels found in the spinach production line. This issue is particularly acute with spinach, as it generates the highest percentage of waste compared to other products produced by the company. In terms of overall waste, the company registered a total of 58,390 units rejected across all products, leading to a total financial loss of S/. 227,453.48. However, spinach stands out as the product with the highest number of rejected units, accounting for 31.42% of all rejected units and 30.74% of the total financial losses due to waste.

TABLE I
TOTAL FINANCIAL LOSSES DUE TO WASTE BY PRODUCT FAMILY

| Product Family | Quantity (units) | Quantity (%) | Total Amount (S/.) | Total Amount (%) |
|---|---|---|---|---|
| Spinach Family | 18,344 | 31.42% | S/ 69,924.01 | 30.74% |
| Lettuce Family | 17,551 | 30.06% | S/ 65,537.11 | 28.81% |
| Tomato Family | 6,742 | 11.55% | S/ 25,089.05 | 11.03% |
| Other products | 15,753 | 26.98% | S/ 66,903.31 | 29.41% |
| Total | 58,390 | 100.00% | S/ 227,453.48 | 100.00% |

The spinach production line includes three main product variations: "Spinach Baby," "Spinach 360 grams," and "Spinach 500 grams."

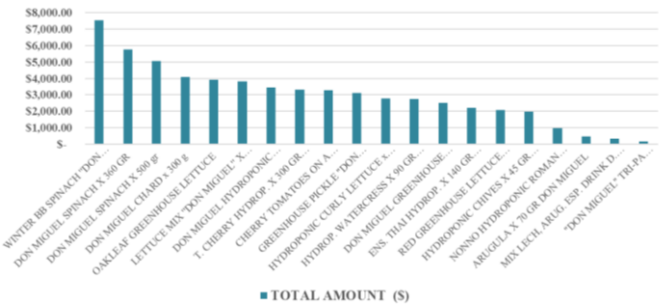


Fig. 2 Total Waste (non-accepted products) in 2023 (in $)

Among these, “Spinach Baby” presents the highest waste, with 6,834 units rejected in 2023, resulting in financial losses of S/. 28,703.16 from waste generation alone. This product is particularly vulnerable to poor post-harvest handling, given its delicate nature and shorter shelf life. Any delays or inefficiencies in the handling and packaging process further increases the likelihood of product rejection.

This disproportionate impact of spinach waste on the company's overall performance makes it the focal point of this study. The decision to focus on spinach was driven by its significant contribution to both sales and waste. By addressing the inefficiencies in the spinach production line, the company aims to achieve the most impactful reduction in waste and financial losses, thereby improving overall productivity and competitiveness. The resolution of these issues is critical not only for reducing operational costs but also for meeting customer expectations, maintaining product quality, and ultimately ensuring the company’s position in an increasingly competitive agro-industrial market.

*4.4. Root-cause analysis*

The root-cause analysis revealed that the post-harvest stage in the spinach production line was the most significant contributor to the overall waste, accounting for 86% of the total waste generated in the entire process. This finding highlights the critical nature of post-harvest inefficiencies in driving waste within the production line and demonstrates the need for targeted improvements in this stage.

The total production of spinach for the year was 259,808 units. Within the production chain of this product, the spinach goes through the phases of planting and subsequent harvesting. In these phases, the amount that was not processed due to waste amounted to 401 and 949 units, respectively. Continuing with the post-harvest phase, this stage includes the processes of washing, quality control, sealing, and storage. In total, these processes resulted in 15,077 units of spinach being unprocessed due to waste. Finally, within the distribution phase, an additional 1,100 units were also wasted.

This high percentage of waste is primarily linked to inefficiencies in key processes such as washing, sealing, and storage. Within the post-harvest stage, the sealing process was responsible for 45% of the total waste, making it the single largest contributor. The washing process contributed 19% of the waste, while storage-related issues accounted for an additional 15%. These numbers indicate that nearly all of the waste in the spinach production line stems from inefficiencies that occur after the spinach is harvested. Addressing these specific areas is essential to reducing waste and improving overall operational efficiency.

TABLE 2
WASTE INDEX

| Process | Waste (units) | Waste (%) |
|---|---|---|
| Sealing | 7,840 | 45% |
| Washing | 3,317 | 19% |
| Storage | 2,567 | 15% |
| Quality Control | 1,357 | 8% |
| Distribution | 1,100 | 6% |
| Harvesting | 949 | 5% |
| Planting | 401 | 2% |
| Total | 17,527 | 100% |

The percentage of waste generated within each production area of the spinach product was represented, which included not only the post-harvest phase, but also the previous and subsequent phases.

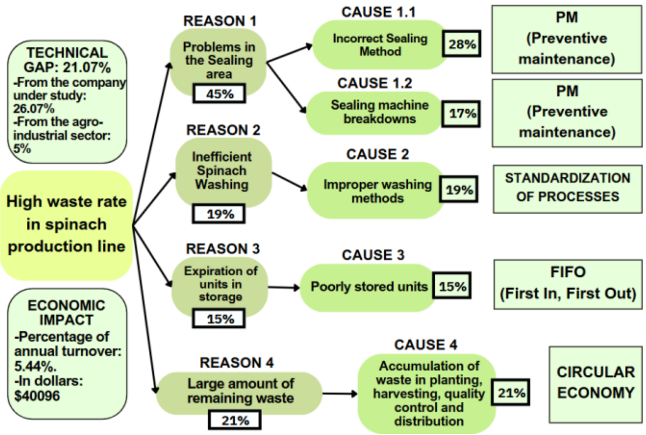

Fig. 3 Problem Tree

The significant proportion of waste generated during sealing can be attributed to frequent machinery malfunctions and improper packaging techniques. Sealing machines, which are responsible for ensuring that spinach is securely packed and ready for distribution, frequently malfunction, leading to improperly sealed products. These products often get spoiled before reaching the market, contributing significantly to the high waste rates. The lack of preventive maintenance exacerbated these issues, as equipment failures were not addressed proactively, resulting in costly downtime and increased waste generation.

In the washing stage, problems such as inadequate removal of contaminants and poor control over water quality further aggravated the waste issue. Spinach that did not meet the required cleanliness standards was discarded during quality control, adding to the overall waste. The washing process was not sufficiently standardized, resulting in inconsistent washing practices across shifts. This inconsistency made it difficult to ensure that all spinach was washed to the same quality standard, leading to additional product rejections.

Storage conditions also played a critical role, with insufficient temperature regulation and inadequate handling practices causing premature spoilage of spinach during storage and distribution. Poor temperature control during storage, combined with frequent delays in transportation, meant that spinach was often exposed to suboptimal conditions, leading to rapid deterioration. Inadequate staff training on proper handling techniques also contributed to this problem, as spinach was often mishandled during the packing and loading stages, increasing the likelihood of spoilage.

These findings underscore the importance of implementing targeted solutions in the post-harvest stage. By addressing the root causes of waste in sealing process, washing, and storage, the company can significantly reduce the overall waste percentage and improve the quality and shelf life of the spinach products. Implementing a more robust maintenance plan, standardizing washing procedures, and improving storage conditions will be key steps in achieving these improvements.

*4.5. Findings*

The analysis of the spinach production line identified key inefficiencies leading to a significant waste rate of 25.13% during 2023, which is considerably higher than the regional industry benchmark of 5%. The technical gap of 20.13% resulted in substantial economic losses, particularly in the post-harvest stages of the process, where sealing, washing, and storage accounted for most of the waste. The impact of these inefficiencies translated into an estimated economic loss of S/. 145,613.70 due to product rejections and customer dissatisfaction.

In addition to the waste percentage, it was found that the spinach product family contributed the highest portion of rejected units, accounting for 31.42% of all discarded products, and 30.74% of the total financial loss related to waste. These figures illustrate the critical impact of the spinach production line on the company's overall operational performance.

Through the root-cause analysis, equipment malfunctions in the sealing machines, inefficient washing processes, and improper storage conditions were identified as the primary factors contributing to the waste. The study demonstrated that addressing these root causes could significantly reduce waste and improve overall process efficiency.

By implementing a Total Productive Maintenance (TPM) system, process standardization, and circular economy practices, it is expected that the waste generated during the post-harvest phase can be reduced by at least 20%, aligning the company's performance with industry standards and yielding substantial economic benefits [34].

## V. Innovative Proposal

*5.1 Proposed Model*

After a thorough analysis of the literature and identifying the root causes of the waste problem, a model was developed that integrates four key components: Total Productive Maintenance (TPM), process standardization, FIFO (First In, First Out) inventory management, and circular economy principles. This model is built on the foundation of the PDCA (Plan-Do-Check-Act) cycle to ensure continuous improvement and long-term effectiveness [35].

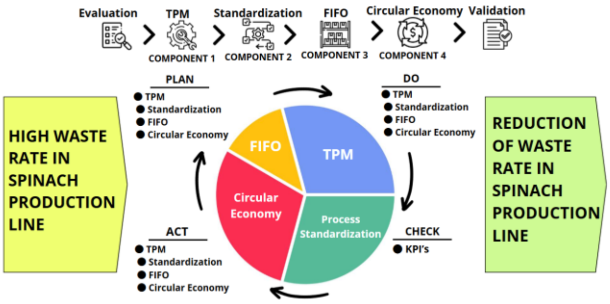


Fig. 4 Proposed Solution Model

The TPM component will focus on preventing machinery failures, particularly in the sealing machines, which account for a large proportion of the waste. Process standardization will be applied to the washing and sealing processes to ensure uniformity and reduce human errors. FIFO will be implemented in storage management to prioritize the oldest stock, minimizing spoilage due to improper rotation. Finally, the circular economy approach will be introduced to repurpose waste generated during the production process into usable resources such as compost.

*5.2 Model Details*

*A. Component 1 - TPM (Total Productive Maintenance)*

The primary objective of TPM is to reduce equipment failures, especially in the sealing machines, by implementing regular preventive maintenance. The steps for TPM implementation include forming a dedicated TPM team, evaluating the current state of equipment, and developing maintenance schedules. Continuous supervision and staff training are essential to ensure machinery operates at optimal capacity.

*Phase 1: Formation of the TPM team. A dedicated team will be assembled to oversee the implementation and ongoing management of TPM practices within the facility.*

*Phase 2: Equipment assessment. The current state of all critical machinery, particularly the sealing machines, will be evaluated to identify areas of frequent failure and inefficiency.*

*Phase 3: Development of a preventive maintenance plan. Based on the equipment assessment, a detailed schedule for regular maintenance tasks will be established to minimize downtime and prolong the lifespan of the machines.*

*Phase 4: Ongoing supervision and staff training. Continuous oversight will ensure that* maintenance tasks are performed on time, and all relevant personnel will receive training on TPM practices to maintain equipment performance.

*B. Component 2 - FIFO (First In, First Out)*

FIFO is a critical component for managing the freshness of perishable goods. It ensures that older stock is used before newer stock, reducing waste due to spoilage. The system will be designed using color-coded labels to visually distinguish product entry dates. Staff will be trained to organize products by entry date and follow FIFO policies strictly, which will reduce waste by improving stock rotation.

*Phase 1: Design of the FIFO system.* The system will utilize color-coded labels to differentiate between product entry dates, ensuring older stock is prioritized for use.

*Phase 2: Staff training on FIFO procedures.* Employees will be trained to understand and implement FIFO policies effectively, ensuring proper stock rotation to prevent spoilage.

*Phase 3: Implementation of FIFO in daily operations.* The system will be integrated into the company's inventory management, with specific attention to the handling and storage of perishable goods like spinach.

*Phase 4: Continuous monitoring and adjustments.* The FIFO system's effectiveness will be evaluated regularly, and adjustments will be made to improve stock management and reduce waste.

*C. Component 3 - Process Standardization*

Standardizing the washing and sealing processes will help reduce variability and errors, ensuring consistent quality across the production line. By establishing clear operational procedures and training staff to follow the best practices, the company can significantly reduce waste and improve efficiency. Regular audits will be conducted to monitor compliance and adjust the standards as necessary.

*Phase 1: Documentation of current washing and sealing processes.* All steps within these processes will be recorded to identify inconsistencies and areas for improvement.

*Phase 2: Development of standardized operating procedures.* Clear and concise standards will be established to ensure uniformity in the washing and sealing stages, reducing errors and variability.

*Phase 3: Staff training in new procedures.* Employees will be trained in the newly standardized processes to ensure consistency in quality and efficiency.

*Phase 4: Regular audits and performance monitoring.* Continuous audits will be conducted to ensure compliance with the new standards, and adjustments will be made as necessary to maintain process integrity.

*D. Component 4 – Circular Economy*

This component focuses on transforming the waste generated during production into valuable resources, such as compost. The waste audit will identify the volumes and types of waste produced, and a composting system will be designed to handle the organic material.

*Phase 1: Waste evaluation.* A detailed audit will be conducted to quantify the types and amounts of waste generated during the production process, focusing on organic waste from spinach production.

*Phase 2: Design of a composting system.* A composting program will be created to repurpose organic waste into valuable resources like compost, reducing the company's overall environmental footprint.

*Phase 3: Staff training in waste management and composting.* Employees will be educated on the correct procedures for waste segregation and composting to maximize the efficiency of the circular economy initiative.

*Phase 4: Implementation and ongoing evaluation.* The composting system will be integrated into daily operations, and its effectiveness in reducing waste and creating valuable outputs will be assessed regularly.

Additionally, as part of the non-economic impacts, the Leopold Matrix was used as a qualitative tool to analyze the environmental and social effects associated with the proposal. This methodology enabled a structured identification of the expected positive impacts related to environmental conservation, efficient resource use, and local community well-being. By doing so, the technical approach is complemented by a long-term sustainability perspective, reinforcing the overall value of the proposal and its alignment with sustainable development goals.

## 5.3 KPI's

*A. Non-Conforming Product*

This indicator plays a critical role in maintaining the quality standards of the spinach production line, especially during the sealing process. It measures the percentage of products that do not meet the required quality specifications, such as poorly sealed spinach bags that may spoil before reaching consumers. The current non-conforming product rate is 4.45%, which is a significant concern as it surpasses the industry standard for food products, which is below 3%. Reducing the percentage of non-conforming products is essential to improving the company's overall product quality and customer satisfaction. The implementation of preventive maintenance and process standardization is expected to address this issue by minimizing defects in the production process.

$$\%Non-Conforming\ Product = \frac{Defective\ Units}{Total\ Units} \times 100\% \qquad (1)$$

Equation (1) shows this formula. The company's goal is to lower this percentage to align with the industry benchmark, which will not only reduce waste but also improve operational efficiency by ensuring that more units meet quality standards on the first pass [36].

*B. Availability*

Availability is a crucial performance indicator that reflects the operational efficiency of the sealing machines, which are key to the entire spinach packaging process. This metric measures the percentage of time the machines are functional and ready for use, compared to the total time they should be operational. Currently, the availability rate is 78.13%, which is well below the 90% target. This figure indicates that frequent machine downtimes are affecting the production process, leading to delays and reduced output. By implementing TPM and focusing on regular maintenance, the company aims to reduce equipment failures and increase machine availability.

$$\%Availability = \frac{MTBF}{MTBF+MTTR} \times 100\% \qquad (2)$$

Equation (2) shows this formula. Improving this rate will directly impact on the company's ability to meet production targets, as higher machine availability means more products can be processed in a timely and efficient manner [37].

*C. Obsolescence Rate*

The obsolescence rate measures the efficiency of inventory management by assessing the proportion of stock that becomes obsolete due to expiration or damage before it can be used or sold. In the case of spinach, the current obsolescence rate is 1.52%, which exceeds the industry recommendation of 1% for perishable food products. This metric is particularly important for a product like spinach, which has a limited shelf life. Poor inventory management can result in unnecessary financial losses, as spoiled products must be discarded. The introduction of a more structured inventory system, such as FIFO, aims to reduce the obsolescence rate by ensuring older stock is used first.

$$\%Obsolescence = \frac{MTBF}{MTBF+MTTR} \times 100\% \qquad (3)$$

Equation (3) shows this formula. Lowering this rate will ensure better resource utilization, minimizing waste and improving the overall profitability of the production line [38].

*D. Quality Indicator (Q)*

Maintaining high product quality is a top priority in the food industry, especially in the case of perishable products like spinach. The quality indicator measures the percentage of correctly processed units during the washing process, ensuring the spinach meets cleanliness standards before packaging. Currently, the quality indicator is 98.17%, falling just short of the food industry's target of 99%. This shortfall suggests that inconsistencies in the washing process are leading to a small percentage of spinach being rejected. Standardizing this process and implementing better quality control measures will help raise this percentage, ensuring a higher proportion of the product meets the required quality specifications.

$$\%Quality = \left(\frac{Processed\ units - Incorrect\ units\ processed}{Processed\ units}\right) \times 100\% \quad (4)$$

Equation (4) shows this formula. The goal is to achieve at least a 99% quality rate, which will lead to fewer rejections and less waste, ultimately enhancing product satisfaction and reducing costs [39].

### *E. Waste Collection Rate (QCR).*

The waste collection rate is a key metric for evaluating the effectiveness of the company's initiatives. It measures the percentage of vegetable waste collected for composting or other recycling processes, reducing the environmental impact of the company's operations. Currently, the waste collection rate is 0%, as the company has not yet implemented a system to collect and repurpose organic waste. The target is to reach a 97% collection rate, which will significantly reduce the company's waste output and improve its sustainability efforts.

$$\%QCR = \frac{Amount\ of\ waste\ collected}{Total\ amount\ of\ wate\ generated} \times 100\% \quad (5)$$

Equation (5) shows this formula. Achieving a high waste collection rate will not only benefit the environment but also align the company with global sustainability trends, potentially opening up new market opportunities for eco-friendly products [40].

## VI. CONCLUSIONS

In conclusion, this article addresses the significant waste and inefficiency in the spinach production li0ne of a Peruvian agro-industrial company, where a waste rate of 25.13% is caused by machine breakdowns (45%), inefficient washing processes (19%), and improper storage conditions (15%), leading to rejected products and financial losses.

To mitigate these problems, a comprehensive model is proposed based on Total Productive Maintenance (TPM), FIFO inventory management, process standardization, and the adoption of circular economy practices. The effectiveness of this solution will be validated through the implementation of a pilot program, the results of which will provide a clear view of the actual impact of the proposed modifications. Additionally, as part of the non-economic impact assessment, the Leopold Matrix was used to qualitatively analyze expected environmental and social benefits, reinforcing the long-term sustainability perspective of the proposal.

Compared to other TPM-based waste reduction initiatives in agro-industrial contexts, our proposal stands out for its comprehensive and integrated approach tailored specifically to the spinach production process. While some studies applied Lean Six Sigma and TPM to reduce raw material waste in nectar production [33], they focused mainly on process metrics and did not incorporate FIFO or circular economy practices, and others examined the relationship between TPM practices and operational performance in the soft drinks manufacturing industry [41], but omitted elements such as process standardization, personnel training, and organic waste valorization, making their scopes more limited. In contrast, our project addresses machinery failures, such as those in the sealing process, and integrates process standardization, a FIFO system, and circular economy strategies to drive systemic waste reduction, operational efficiency, and environmental sustainability across the entire post-harvest stage.

Additionally, this innovative proposal can be extrapolated to other relevant cases as appropriate, allowing for broader generalization of its application and verification. The analysis of key performance indicators will enable detailed monitoring of progress, while the pilot plan will assess the impact of the changes in a real production environment. In a future article, the detailed results of this validation phase will be presented.

## REFERENCES


[1] Ortiz-Porras, J. E., Bancovich-Erquínigo, A. M., Candia-Chávez, T. C., Huayanay-Palma, L. M., Moore-Torres, R. K., & Gomez, O. R. T. (2023). Green Lean Six Sigma model for waste reduction of raw material in a nectar manufacturing company of Lima, Peru. Journal of Industrial Engineering and Management, 16(2), 169–185. https://doi.org/10.3926/jiem.4916

[2] Ramos, E., Coles, P. S., Chavez, M., & Hazen, B. (2022). Measuring agri-food supply chain performance: insights from the Peruvian kiwicha industry. Benchmarking, 29(5), 1484–1512. https://doi.org/10.1108/BIJ-10-2020-0544

[3] Liu, Q., Yang, H., & Xin, Y. (2020). Applying value stream mapping in an unbalanced production line: A case study of a Chinese food processing enterprise. Quality Engineering, 32(1), 111–123. https://doi.org/10.1080/08982112.2019.1637526

[4] Liu, H. (2020). Measurement Research on Influential Effect of Standardization on Technological Innovation. IOP Conference Series: Earth and Environmental Science, 527(1). https://doi.org/10.1088/1755-1315/527/1/012020

[5] Taghikhah, F., Voinov, A., Shukla, N., Filatova, T., & Anufriev, M. (2021). Integrated modeling of extended agro-food supply chains: A systems approach. European Journal of Operational Research, 288(3), 852–868. https://doi.org/10.1016/j.ejor.2020.06.036

[6] Almeida, P., Garcia, R., & Fonseca, A. (2022). Advances in Modelling of the Integrated Production Logistics in Sugarcane Harvest | Avanços na Modelagem da Logística de Produção Integrada na Colheita de Cana. Promet - Traffic - Traffico, 34(4), 595–608. https://doi.org/10.7307/ptt.v34i4.4012

[7] Sadi, M., & Arabkoohsar, A. (2020). Techno-economic analysis of off-grid solar-driven cold storage systems for preventing the waste of agricultural products in hot and humid climates. Journal of Cleaner Production, 275. https://doi.org/10.1016/j.jclepro.2020.124143

[8] Melo, C., Campos, R. C., Al-Hadrami, A., Pathare, P. B., Al-Dairi, M., & Al-Mahdouri, A. (2023). Investigation of Bruise Damage and Storage on Cucumber Quality. AgriEngineering, 5(2), 855–875. https://doi.org/10.3390/AGRIENGINEERING5020053

[9] Au-Yong, C. P., Azmi, N. F., & Myeda, N. E. (2022). Promoting employee participation in operation and maintenance of green office building by adopting the total productive maintenance (TPM) concept. Journal of Cleaner Production, 352. https://doi.org/10.1016/j.jclepro.2022.131608

[10] Xiang, Z. T., & Feng, C. J. (2021). Implementing total productive maintenance in a manufacturing small or medium-sized enterprise. Journal of Industrial Engineering and Management, 14(2), 152–175. https://doi.org/10.3926/jiem.3286

[11] Martins, A. D. O., dos Anjos, F. E. V., & da Silva, D. O. (2023). The Lean Farm: Application of Tools and Concepts of Lean Manufacturing in Agro-Pastoral Crops. Sustainability (Switzerland), 15(3). https://doi.org/10.3390/su15032597

[12] Lelicińska-Serafin, K., Manczarski, P., & Rolewicz-Kalińska, A. (2023). An Insight into Post-Consumer Food Waste Characteristics as the Key to an Organic Recycling Method Selection in a Circular Economy. Energies, 16(4). https://doi.org/10.3390/en16041735

[13] Anichkina, O., Chen, T. C., Sivakov, S. I., Voronkova, O. Y., Gorovoy, S. A., & Davidyants, A. A. (2022). A novel mathematical model to design an agile supply chain for perishable products. International Journal of Industrial Engineering and Management, 13(2), 88–98. https://doi.org/10.24867/IJIEM-2022-2-303

[14] Anichkina, O., Chen, T. C., Sivakov, S. I., Voronkova, O. Y., Gorovoy, S. A., & Davidyants, A. A. (2022). A novel mathematical model to design an agile supply chain for perishable products. International Journal of Industrial Engineering and Management, 13(2), 88–98. https://doi.org/10.24867/IJIEM-2022-2-303

[15] Soltanali, H., Khojastehpour, M., & Torres Farinha, J. (2021). Measuring the production performance indicators for food processing industry. Measurement: Journal of the International Measurement Confederation, 173. https://doi.org/10.1016/j.measurement.2020.108394

[16] Dziuba, S., & Szczyrba, A. (2023). Agile management in Polish organic food processing enterprises. Production Engineering Archives, 29(1), 101–107. https://doi.org/10.30657/pea.2023.29.12

[17] Barsalou, M. (2023). Determining which of the classic seven quality tools are in the quality practitioner's RCA tool kit. Cogent Engineering.

[18] Choo, A. (2014). Defining Problems Fat and Slow: The U-shaped Effect of Problem.

[19] Gralla, E., Goentzel, J., et al. (2016). Problem Formulation and Solution Mechanisms: A Behavioral Study of Humanitarian Transportation Planning.

[20] Jawwad, A. (2020). A novel qualitative-quantitative cause-and-effect tool for analysis, presentation, and decision-support.

[21] Lee, M-G., et al. (2018). Introduction to cause-effect chain analysis plus with an application in solving manufacturing problems.

[22] Xiang, Z. T., & Feng, C. J. (2021). Implementing total productive maintenance in a manufacturing small or medium-sized enterprise. Journal of Industrial Engineering and Management, 14(2), 152–175. https://doi.org/10.3926/jiem.3286

[23] Liu, Q., Yang, H., & Xin, Y. (2020). Applying value stream mapping in an unbalanced production line: A case study of a Chinese food processing enterprise. Quality Engineering, 32(1), 111–123. https://doi.org/10.1080/08982112.2019.1637526

[24] Tortorella, G. L., Saurin, T. A., Fogliatto, F. S., Tlapa, D., Moyano-Fuentes, J., Gaiardelli, P., et al. (2021). Integration of Industry 4.0 technologies into Total Productive Maintenance practices. International Journal of Production Economics, 240. https://doi.org/10.1016/j.ijpe.2021.108224

[25] Massaro, A., & Galiano, A. (2020). Re-engineering process in a food factory: an overview of technologies and approaches for the design of pasta production processes. Production and Manufacturing Research, 8(1), 80–100. https://doi.org/10.1080/21693277.2020.1749180

[26] Fikry, I., Gheith, M., & Eltawil, A. (2021). An integrated production-logistics-crop rotation planning model for sugar beet supply chains. Computers and Industrial Engineering, 157. https://doi.org/10.1016/j.cie.2021.107300

[27] Singh, S., Agrawal, A., Sharma, D., Saini, V., Kumar, A., & Praveenkumar, S. (2022). Implementation of Total Productive Maintenance Approach: Improving Overall Equipment Efficiency of a Metal Industry. Inventions, 7(4). https://doi.org/10.3390/inventions7040119

[28] Rangel-Sánchez, M.-Á., Urbina-González, J.-D.-J., Carrera-Escobedo, J.-L., Guirette-Barbosa, O.-A., Murillo-Rodríguez, V.-A., Celaya-Padilla, J.-M., Durán-Muñoz, H.-A., & Cruz-Domínguez, O. (2024). Enhancing Scrap Reduction in Electric Motor Manufacturing for the Automotive Industry: A Case Study Using the PDCA (Plan–Do–Check–Act) Approach. Applied Sciences (Switzerland), 14(7). https://doi.org/10.3390/app14072999

[29] Massaro, A., & Galiano, A. (2020). Re-engineering process in a food factory: an overview of technologies and approaches for the design of pasta production processes. Production and Manufacturing Research, 8(1), 80–100. https://doi.org/10.1080/21693277.2020.1749180

[30] MIDAGRI. (2022). Boletín Estadístico Mensual: El Agro en Cifras. Ministerio de Desarrollo Agrario y Riego. https://siea.midagri.gob.pe/portal/phocadownload/datos_estadisticas/mensual/Agro/2022/Agro_en_cifras_08_2022.pdf

[31] MIDAGRI. (2022). Boletín Estadístico Mensual: El Agro en Cifras. Ministerio de Desarrollo Agrario y Riego. https://siea.midagri.gob.pe/portal/phocadownload/datos_estadisticas/mensual/Agro/2022/Agro_en_cifras_08_2022.pdf

[32] Gomero-Campos, A., Mejia-Huayhua, R., Leon-Chavarri, C., Raymundo-Ibañez, C., & Dominguez, F. (2020). Lean Manufacturing Production Management Model using the Johnson Method Approach to Reduce Delivery Delays for Printing Production Lines in the Digital Graphic Design Industry. IOP Conference Series: Materials Science and Engineering, 796(1). https://doi.org/10.1088/1757-899X/796/1/012002

[33] Ortiz-Porras, J. E., Bancovich-Erquínigo, A. M., Candia-Chávez, T. C., Huayanay-Palma, L. M., Moore-Torres, R. K., & Gomez, O. R. T. (2023). Green Lean Six Sigma model for waste reduction of raw material in a nectar manufacturing company of Lima, Peru. Journal of Industrial Engineering and Management, 16(2), 169–185. https://doi.org/10.3926/jiem.4916

[34] Singh, S., Agrawal, A., Sharma, D., Saini, V., Kumar, A., & Praveenkumar, S. (2022). Implementation of Total Productive Maintenance Approach: Improving Overall Equipment Efficiency of a Metal Industry. Inventions, 7(4). https://doi.org/10.3390/inventions7040119

[35] Rangel-Sánchez, M.-Á., Urbina-González, J.-D.-J., Carrera-Escobedo, J.-L., Guirette-Barbosa, O.-A., Murillo-Rodríguez, V.-A., Celaya-Padilla, J.-M., Durán-Muñoz, H.-A., & Cruz-Domínguez, O. (2024). Enhancing Scrap Reduction in Electric Motor Manufacturing for the Automotive Industry: A Case Study Using the PDCA (Plan–Do–Check–Act) Approach. Applied Sciences (Switzerland), 14(7). https://doi.org/10.3390/app14072999

[36] Singh, S., Agrawal, A., Sharma, D., Saini, V., Kumar, A., & Praveenkumar, S. (2022). Implementation of Total Productive Maintenance Approach: Improving Overall Equipment Efficiency of a Metal Industry. Inventions, 7(4). https://doi.org/10.3390/inventions7040119

[37] Soltanali, H., Khojastehpour, M., & Torres Farinha, J. (2022). Measuring the production performance indicators for food processing industry. Measurement: Journal of the International Measurement Confederation, 173. https://doi.org/10.1016/j.measurement.2020.108394

[38] Çalışkan, C. (2022). A Comparison of Simple Closed-Form Solutions for the EOQ Problem for Exponentially Deteriorating Items. Sustainability (Switzerland), 14(14). https://doi.org/10.3390/su14148389

[39] Soltanali, H., Khojastehpour, M., & Torres Farinha, J. (2021). Measuring the production performance indicators for food processing industry. Measurement: Journal of the International Measurement Confederation, 173. https://doi.org/10.1016/j.measurement.2020.108394

[40] Lelicińska-Serafin, K., Manczarski, P., & Rolewicz-Kalińska, A. (2023). An Insight into Post-Consumer Food Waste Characteristics as the Key to an Organic Recycling Method Selection in a Circular Economy. Energies, 16(4). https://doi.org/10.3390/en16041735

[41] Singh, A. P., & Awoke, N. F. (2023). Relationship between TPM practices and operational performance in soft drinks manufacturing industry. Journal of Quality in Maintenance Engineering. https://doi.org/10.1108/JQME-10-2022- 0067