# Ultracongelation and IoT to Improve Energy Efficiency and Working Conditions in the Cold Chain of a Food MSME: A Mixed-Methods Study with a Gender Perspective

**Leonardo José España-Barraza[1]*, Efraín Javier De-la-Hoz-Granadillo[2], Katia Ninozca Flores-Ledesma[3]**

[1] Universidad de Cartagena. Cartagena, Colombia. Email lespanab@unicartagena.edu.co
[2] Universidad de Cartagena. Cartagena, Colombia. Email: edelahozg@unicartagena.edu.co
[3] Universidad César Vallejo, Perú. Email: knfledesma@hotmail.com

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**ABSTRACT:**
Thermal efficiency in the cold chain is a critical challenge for micro, small, and medium-sized enterprises (MSMEs) in the food sector, especially in contexts where temperature variability affects product quality, increases waste, and raises energy consumption. This study evaluated the impact of implementing Industry 4.0 technologies, specifically a deep-freezing system and an IoT (Internet of Things) monitoring platform, at PASTELART SAS, commercially known as Pastel de Oro, a Colombian food MSME whose operational workforce is composed of 70% women. A mixed-methods approach was adopted, integrating technical-operational analysis, statistical modeling, and qualitative assessment of labor perceptions. The results show substantial improvements in the thermal performance of the cold system, including a reduction in freezing time, greater temperature stability in the cold room, and a 67% reduction in waste. Energy consumption per unit also decreased significantly, which was confirmed through an interrupted time series model that showed an immediate change of –39.43 COP per unit after the intervention ($R^2 = 0.93$). Likewise, interviews revealed perceived improvements in workload, thermal comfort, and safety, especially among women directly exposed to high temperatures.
The findings demonstrate that the combination of deep freezing and IoT not only optimizes energy and operational performance but also enhances labor well-being in highly feminized contexts. This study provides applied evidence of the potential of Industry 4.0 technologies to strengthen productive and social sustainability in food MSMEs.

Keywords: Cold chain; Industry 4.0 technologies; IoT; Deep freezing; Energy efficiency; Gender; Food MSMEs.

**Introduction**

The cold chain plays an essential role in assuring food safety and stability during the entire food production, storage and distribution process. James and James (2010) and Koutsoumanis et al. (2020) reported that proper management will prevent microbial growth, maintain sensory quality, and ensure a longer product shelf life. Technological limitations, thermal fluctuations, manual operations and absence of traceability are common drawbacks in food MSMEs that contributes to losses of economic value and the quality of the final product.

Over the last few years, digital technologies have started to radically change thermal control in the industry. Badia-Melis, Carvajal and Garcia-Hierro (2018) state that the Internet of Things (IoT) enables real-time tracking of critical variables, the generation of predictive warnings that avert deviations that impact food safety, and a decrease in variability. Nevertheless, the implementation of Industry 4.0 technologies in MSMEs is still limited because of financial resources, lack of qualified people, and the resistance to change among the organisations, according to Horváth and Szabó (2019). It highlights the need for applied studies of real experiences of implementation in small businesses.

The bakery company studied in this work had a continuous cold chain production problem, mainly due to the slow freezing speed, thermal instability of the cold rooms and quality deterioration of the cheese products, especially costeño. To overcome these constraints, a process innovation on the basis of two complementary interventions was developed. The first intervention was the installation of a deep freezer, which was able to decrease the freezing-time from 8-10 hours to 90 minutes, in accordance with Bevilacqua et al. (2018) who state that "rapid freezing" is beneficial. The second intervention was the implementation of an IoT monitoring system in the cold room, storing already frozen products. This system allowed for the real-time recording of temperature and temperature changes as well as higher stability and increase in thermal stability by about 4°C.

This study not only has a technical analysis but also, has an organizational and human approach. The firm employs 70% women in operational roles directly handling products, freezing and storing the products. Multiple research has demonstrated that digitalization processes have different impacts on different labour groups along production chains, with potential benefits for improved working conditions, perception change and learning opportunities (FAO, 2022; ILO, 2021). Therefore, a qualitative part was added with semi-structured interviews analyzed by Atlas.ti software to better comprehend the workers' perception of the technological change and its impact on the day-to-day job.

This article presents the evidence of the implementation of Industry 4.0 technologies in the cold chain of a food MSME, which includes technical and organizational outcomes. It is also a practical case which can be replicated by other companies in the sector and adds to the literature on process innovation and digitalisation in production contexts where there are predominantly women.

**2. Theoretical Framework**

**2.1 The cold chain in the food industry**

The cold chain is a continuous preservation system which ensures safe food production, storage and distribution at appropriate temperatures. It is primarily used to prevent microbial proliferation, to maintain physicochemical and sensory qualities, mainly in high-moisture food matrices or those with fatty and dairy products. James and James (2010) point out that differences in temperature exceeding 2 degrees can speed up deterioration process and affect food safety. This vulnerability is more evident in prepared foods, refrigerated bakery products and fresh dairy products, according to Koutsoumanis et al. (2020).

The cold chain is an important problem in food MSMEs, as it is common there to have heterogeneous equipment, lack of systematic records, empirical processing and lack of automation. Such situations create difficulties in production standardization and contribute to

economic losses due to thermal variations and storage failures. The literature highlights that such businesses generally have limited resources, limiting their capacity to invest in more sophisticated refrigeration technologies, (Montoya-Torres et al., 2021).

In this context freezing is an important stage and the efficiency of this stage depends on the rate at which the product is cooled to stability temperature. According to Bevilacqua et al. (2018), slow freezing induces the growth of large crystals that disrupt internal structures, result in water loss during thawing and have a negative effect on texture. Conversely, fast and controlled processes minimize structural damage, enhance shelf life and ensure the quality of the final product is stable.

### 2.2 Industry 4.0 technologies applied to thermal control and traceability

The food sector has embraced the digitalization of the industry 4.0 era by using connected sensors, data analysis, automation, cloud-based technology, etc. The Internet of Things is one of these tools, as it allows real-time recording of variables such as temperature, generation of alerts and identification of behavioral patterns in refrigeration systems. Badia-Melis et al. (2018) showed that IoT systems help to increase the traceability in cold rooms and decrease the chance of thermal deviations, which is beneficial for food safety and waste reduction.

Digital monitoring is especially advantageous for MSMEs that endure fluctuations due to the frequent opening and closing of doors, products overloading and human oversight mistakes. According to Montoya-Torres et al. (2021), connected sensors help to make operational decisions based on the available evidence, optimize energy use, and increase process reliability. Furthermore, they offer the possibility for thermal trend analysis, evaluation for system recovery, and early detection of anomalies.

But the use of these technologies is still limited in MSMEs. Horváth and Szabó (2019) list some of the common obstacles, including insufficient technical expertise, initial implementation costs, lack of trained staff, and reluctance to change. Hence, the value of case studies and applied research to help illustrate how small companies can incrementally and cost-effectively introduce digital solutions that are suitable for their operations.

### 2.3 Rapid Freezing and Ultra-Freezing as Process Innovation

Ultra-freezing is a process in which the time of reaching deep negative temperatures is reduced drastically so that the structural damage is minimised and product preservation is improved. Laguerre et al. (2019) describe that the speed of the freezing process creates small crystals that maintains the internal integrity of the product; decrease syneresis, and improves the product's shelf life. This is why ultra-freezing is one of the most promising process innovations for temperature-sensitive products, like doughs, dairy products and classic bakery products.

It is generally agreed that the new freezing times that are less than 2 hours are a significant improvement in quality and energy efficiency. Bevilacqua et al. (2018) reported that rapid freezing would be advantageous in maintaining the texture, color and moisture content of the food, and would minimize losses in storage and distribution. The findings add to the importance of the use of ultra-freezers in MSMEs where loss due to temperature fluctuation is a concern and sensitive products need to be stabilized.

### 2.4 Gender Approach in Technological Adoption in MSMEs

Women participate at a high level in the food sector, particularly in production, handling and packaging. The International Labour Organization (ILO, 2021) notes that the feminisation of employment within the food sector has a bearing on the way innovations are implemented, as technology can affect the skills needed for food operations, physical workloads and work practices.

Similarly, the FAO (2022) has documented that women often occupy operational positions where exposure to temperature variations, repetitive physical effort, and direct product handling is higher. Therefore, process innovations that improve thermal stability, reduce losses, and

facilitate product handling can have a direct impact on their working conditions and well-being.

Incorporating a gender perspective in studies on Industry 4.0 technologies in MSMEs is relevant because it allows for the analysis of how digitalization affects the majority workforce, how change is perceived, and what opportunities emerge in terms of learning, operational improvement, and working conditions. This is particularly important in companies such as the one analyzed in this study, where approximately 70 percent of the operational staff is composed of women who directly interact with critical stages of the cold chain.

### 2.5 Conceptual Framework Integration

This conceptual framework articulates three central dimensions. First, the technical importance of the cold chain and rapid freezing in the preservation of bakery products. Secondly, the increasing significance of Industry 4.0 technologies for real-time thermal monitoring and for making operational decisions. Third, the importance of taking into account the composition of the workforce to grasp the implications of technological innovations in terms of practical and organizational benefits, particularly in the case of predominantly female workforces. The dimensions are fundamental when discussing the analysis of this article further.

## 3. Materials and Methods

### 3.1 General Research Approach

The research in this study is a mixed method research using a technical-operational analysis and qualitative analysis. The hybrid approach enabled the assessment of measurable outcomes of the redesign of the cold chain, perceptions and experiences of operational staff who are directly involved in freezing/storage processes. This type of design has been developed to address research questions that focus on how technological interventions can be introduced into real productively contexts and technical and organisational impacts can be analysed at the same time.

### 3.2 Description of the Production Context

This research was carried out in a traditional bakery MSME located in Colombia. Prior to intervention, the company was experiencing thermal fluctuations of the product in cold storage and longer freezing times. As the majority of the workforce is female (70% of the operational staff), it is important to consider a gender perspective in the analysis of technological adoption and in understanding the labour dynamics linked to the labour transformation process.

### 3.3 Technical Intervention in the Cold Chain

The process innovation consisted of two parts to be performed in order:

#### a. Installation of the ultra-freezer

An ultra-freezing unit was installed to quickly lower the product temperature to below –19°C. The average freezing time before the intervention was between 8 and 10 hours. With the ultra-freezer, this time was reduced to 90 minutes. This improvement allowed for more stable internal temperatures, decreased the formation of macrocrystals, and better texture and stability in the products, particularly in those with local cheese (queso costeño).

#### b. Integration of the IoT temperature monitoring system

Digital monitoring was only installed in the cold storage room where the products are stored after processing in the ultra-freezer. The system consisted of a network of sensors that could be connected together, capturing real-time data, raising alerts and storing historic data in the cloud. This allowed the analysis of thermal patterns, identification of variations associated with product load, and improved system recovery after door openings.

Temperature data were analyzed before and after the intervention to determine differences in thermal stability and cooling efficiency. The improvement recorded was approximately a 4°C reduction in the average temperature of the cold room after implementing ultra-freezing.

### 3.4 Technical Indicators Evaluated

To assess the impact of the intervention, the following indicators were analyzed:

1. Freezing time

Total time required for products to reach the target temperature.

2. Minimum temperature and thermal stability

Measurement of cold room internal temperature and average variation per door-opening cycle.

3. Reduction of losses (waste/spoilage)

Comparison of the volume of deteriorated products before and after the intervention.

Data were collected using sensors, direct observation, and internal production records.

### 3.5 Qualitative Methodology

Given that operational staff are the group directly affected by technological changes, a qualitative methodology was applied to understand perceptions, learning outcomes, changes in work routines, and evaluations of the innovation.

a. Participants

Semi-structured interviews were conducted with 8 operational workers from the plant. The group consisted of both women and men, with a predominance of female participants. Most had completed secondary education, and some had technical training, reflecting the typical profile of the food sector in MSMEs.

b. Data Collection

The interviews were conducted in person within the company. Open-ended questions were used, focusing on:

- Previous experience with the freezing process
- Perception of the new ultra-freezer
- Observed changes in product quality
- Use and usefulness of digital monitoring
- Improvements in working conditions
- Feelings of well-being, workload, and performance
- Perceptions of technological change

The average duration of each interview was 20 to 30 minutes.

c. Analysis using Atlas.ti

The interview transcripts were processed and coded using Atlas.ti software. The analysis included:

- Open coding
- Category development
- Co-occurrence analysis
- Construction of semantic networks

The main codes found were: 1) improvement of thermal control, 2) reduction of losses, 3) incorporation of Industry 4.0 technologies, 4) organizational learning, 5) institutional pride, 6) perception of performance, 7) thermal well-being. The codes were formed based on excerpts of texts, as in the Atlas.ti quotation report.

### 3.6 Ethical Considerations

Informed verbal consent was obtained from all participants. Anonymity, confidentiality and exclusive use of the data for research was ensured. No worker's name or age or nature of work was identified. The study was compiled as per the ethical principles of the Declaration of Helsinki for research involving human participants and no physical risk.

### 3.7 Integration of Methods

Triangulation of technical and qualitative data was done in the mixed-method approach. The quantitative indicators are compared to the perceptions of operating personnel for a comprehensive interpretation of the effects of the process innovation.

## 4. Results

### 4.1 Technical Improvements in the Freezing Process

The thermal stabilization process of the products was significantly affected by the installation of ultra-freezer. Prior to intervention, freezing time ranged from 8 to 10 hours, with many temperature swings and observable loss in quality and quantity of

sensitive products like queso costeño. Following implementation, the freezing time was shortened to 90 minutes, or more than 80% improvement.

This reduction enabled products to be loaded at a cooler and more consistent internal product temperature into the cold room to reduce the thermal load of the storage room. The mean storage temperature was therefore brought to a steady level, and is now 4 to 5°C lower than the preceding years. Such action is in line with research indicating that the proper pre-freezing of products can enhance the efficiency of cold storage and lessen fluctuations caused by door-opening cycles.

**4.2 Thermal Stability and Energy Efficiency**

The IoT system allowed the internal temperature of the cold room to be monitored at all times. The following data was recorded:

1. Reduction in thermal variations during recovery cycles
2. Improved stability of minimum temperature levels
3. Greater operational reliability

This behavior is regarded as an indicator of refrigeration equipment's maturity of operation because it is operating under less thermal stress and better energy efficiency.

As far as energy efficiency is concerned, Figure 1 shows a three-dimensional analysis which compares, among the three main variables, the number of units produced, monthly sales and energy intensity, measured as COP per unit. This representation enables the observation of the evolution of energy efficiency both as a function of production volume and of commercial activity. In the first month, there are considerable variations in energy intensity, which exceed 300 COP/unit, indicating the situation before the technology was introduced. A downtrend in energy use/unit is evident from May, particularly from month 6 (when the cold system improvements were implemented). Despite rising production levels in the second half of the study period, values continue to fall and reach c. 245 COP per unit.

This behaviour shows that the adopted intervention increased the process thermal stability and improved the use of energy. As production increased, the energy intensity of the systems decreased, indicating better system efficiency, which is in line with lower losses and better refrigeration system performance. In general, the figure confirms that the process optimization resulted in benefits in both terms of production and energy efficiency.

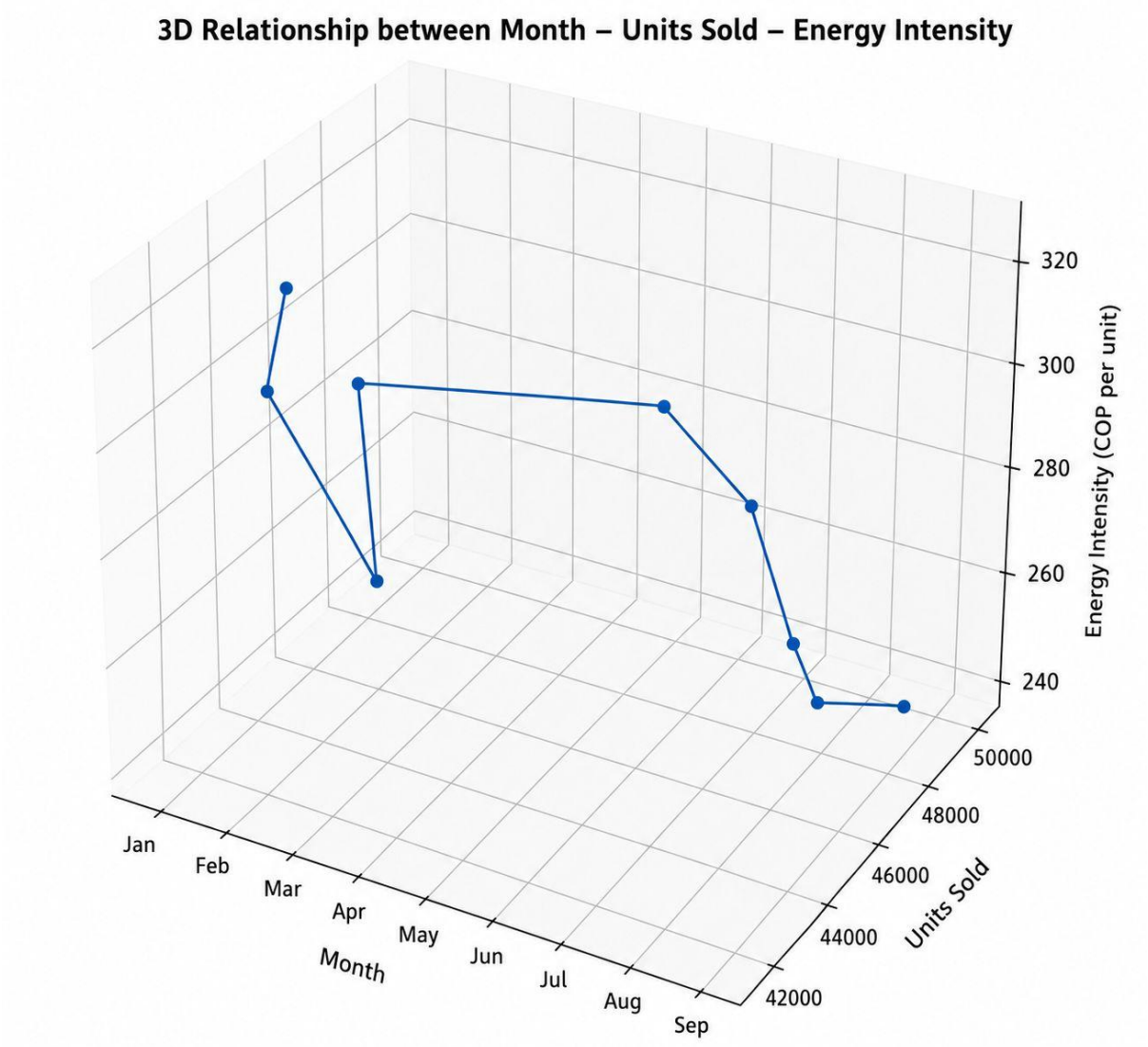



**Figure 1.** Monthly relationship between units produced, sales, and energy consumption
*Source: Own elaboration based on the company's operational data.*

**Statistical Model of the Impact of the Technological Intervention on Energy Efficiency**

To quantify the impact of the technological intervention (installing the ultra-freezer and the IoT monitoring system on the process energy efficiency), Interrupted Time Series (ITS) analysis was used. This way, people can estimate the direct change caused by the intervention, as well as the change that was taking place before and after the intervention. The dependent variable was energy consumption per unit (COP/unit) which shows the energy intensity of the process regardless of the production volume.

The below equation is the estimated model:

$$COP_t = \beta_0 + \beta_1\,(\text{Tiempo}) + \beta_2\,(\text{Intervencion}) + \beta_3\,(\text{TiempoDespues}) + \varepsilon_t$$

In the last equation, **Time** represents the pre-intervention trend before the technological change, **Intervention** takes the value of 0 before month 6 and 1 from that point onward, **Post Time** counts the months elapsed since implementation, and **εt** represents the error term.

Model results are very close to the observed data and the model has a high level of fit ($R^2 = 0.93$),

meaning that the energy efficiency observed can be best explained by the proposed model structure. A coefficient $\beta_1$ of –3.96 is seen in the pre-intervention trend with a slight downward trend in COP per unit, thus showing a gradual improvement even prior to the intervention. Most importantly, the immediate changes from installing the ultra-freezer and IoT system created the largest effect as seen in a coefficient $\beta_2$ value of –39.43. This value shows that energy efficiency levels have jumped up suddenly, with an estimated decrease in COP per unit of approximately 39 COP per unit with the immediate implementation of the intervention. Last, the coefficient of the post-intervention trend, $\beta_3 = 0.68$, indicates a post-intervention trend (and maintenance) that remained stable after the process was implemented, and that the reduction realized remained stable over time. Such a trend has been observed with the reduction in loses and the increase of thermal stability and decrease in workload for the operators. The results above, as a whole, validate the direct, considerable and permanent effect of the technological intervention on the performance of the cold chain system.

### 4.3 Reduction in Product Losses

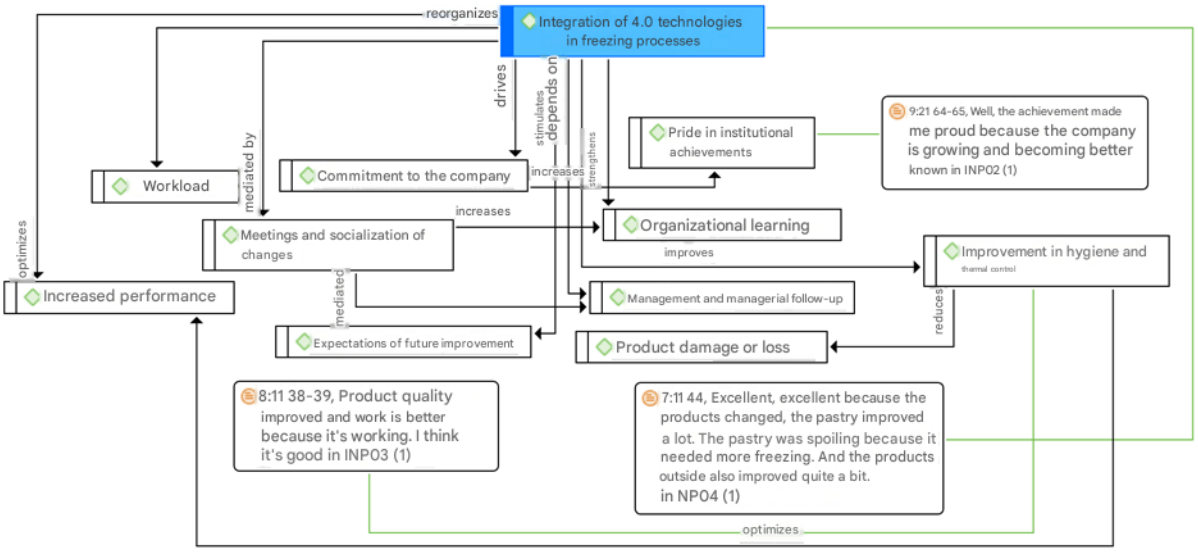
The company saw a loss reduction of almost 67% due to the thermal degradation. The highest reduction was seen for products prepared with queso costeño, a queso that is very sensitive to textural changes, moisture loss and deformation related to unstable temperatures. This improvement is due to the introduction of ultra-frozen products in the cold room, along with the improvement of the thermal stability. In addition, the estimated shelf life of products was found to be increased and internal returns were reduced because of sensory failures.

### 4.4 Improvements in Product Quality

Staff always reported improvements in texture, appearance, firmness and resistance to thaw. These observations are consistent with those reported in the literature for the advantages of a rapid freezing in decreasing the formation of macrocrystals, moisture loss and structural deformation. Products are stated to be more solid, easier to handle, and to have a better shape retention today compared to products in the past, being stated by workers. These perceptions fit the technical data, and provide greater confidence in the observed improvements.

### 4.5 Qualitative Results: Perceptions of Operational Staff

When the interviews were analysed clear patterns in the perceptions of staff members that have direct contact in the process emerged. The verbatim extracts gathered from Atlas.ti show the improvements in working conditions, thermal comfort, confidence in the product and overall satisfaction in the job.



#### 4.5.1 Perception of Improvement in Product Quality and Preservation

The following fragments indicate that the performance of the ultra-freezer is viewed positively:

"Excellent, excellent because the products changed, the pastry improved a lot. The pastry was getting damaged because it needed more freezing. And the products outside also improved significantly."

Another worker stated:

"Yes, the products we prepare are better preserved, and it is no longer so stressful to store them in the cold rooms. Because of the temperatures, the products used to get damaged and melt from the heat."

These perceptions validate the relationship between thermal stability and reduced losses.

#### 4.5.2 Reduction of Work-Related Stress Associated with Product Deterioration

Before the intervention, frequent product deterioration created operational pressure and a sense of wasted effort. A representative statement noted:"One feels exhausted, fainting from so much heat here in the company."

After the intervention, staff perceived lower risk of product damage and greater safety during storage activities.

#### 4.5.3 Integration of Industry 4.0 Technologies and Perception of Change

Digital monitoring of the cold room was perceived as an operational improvement: "No, it was wonderful, we were all happy because it is a great help since we all store the products here and they freeze and are preserved there." This testimony reflects the technical acceptance of the innovation

#### 4.5.4 Organizational Learning and Culture of Improvement

Perceptions related to strengthened teamwork and learning were observed:

"It has influenced performance quite a bit because colleagues store everything in the ultra-freezer, and there it freezes a bit faster before being taken to the cold rooms, where it is better preserved." These narratives align with the observed pattern of improved efficiency and internal coordination.

#### 4.5.5 Institutional Pride and Perception of Growth

The staff expressed feelings of satisfaction and belonging: "Well, the achievement made me feel proud because the company is growing and becoming more recognized every day."

This result suggests that the innovation contributed to strengthening the organizational climate.

### 4.6 Results from a Gender Perspective

Given that 70% of the operational workforce is composed of women, the improvement in the cold chain had direct effects on their workload, thermal well-being, and confidence in product handling. The interviewed workers highlighted that handling more stable products under improved and more controlled cold conditions and with a reduced risk of product damage decreased operational pressure during storage, packaging, and handling activities.

The evidence indicates that technological development has improved the efficiency of processes and has been positive for the experience of the mainly female workforce employed in crucial operations within the production process.

## 5. Discussion

The results obtained from the study validate the significant improvement in thermal and energy efficiency achieved by the use of the ultra-freezer and the IoT monitoring system in the cold chain. The decreased freezing time and increased stability of the cold room are in line with previous research on digital control systems, which provide a stable operation of compressors and minimize critical fluctuations (Badia-Melis et al., 2018), and with previous research that shows the contribution of ultra-freezing in reducing initial thermal load during cold room storage (Zhu et al., 2018). The results confirm the possibility of providing corrective solutions to existing manual operations structural inefficiencies, as well as thermal variability, which is

also a common issue in the field of agriculture and food processing.

The interrupted time series analysis revealed that there was a large immediate energy consumption change following the intervention (beta2 = –39.43) with a very good overall model fit (R2 = 0.93). This improvement is comparable with other studies that reported the use of ultra frozen products reduced the compressor workload, hence the overall refrigeration efficiency (James and James, 2010). Furthermore, the fact that the overall trend after intervention has become steady indicates that the system has stabilized at a new structural efficiency level, thus implying that the improvement is not a short-term gain due to production volume.

Qualitative measures revealed by operational staff perceptions validated relevant changes in working conditions. Less physical work, exposure to less cold conditions and more predictable of the process were common themes in the interviews. The fact that 70% of the cold room staff is comprised of females is also significant since the International Labour Organization (2021) reported that cold-chain handling activities significantly impact the female workforce and could lead to fatigue and ergonomic risk. In this context, technology was used as not just an efficiency tool, but also as a tool of intervention in the context of occupational well-being.

In conclusion, the technical, statistical and qualitative outcomes strengthen the notion of the digital transformation in MSMEs not just being based on the acquisition of equipment, but also the convergence of infrastructure, data and practices. Accessible technologies can yield substantial benefits in terms of productivity, quality and working conditions and this study offers real-world proof of this in an organization with limited resources.

## 6. Conclusion

The application of the ultra-freezer and the IoT monitoring system at the cold chain of the MSME PASTELART SAS, in the food sector, resulted in very significant improvements in terms of operations, energy and labor use. The results indicate that using ultra-freezing decreased the freezing time, stabilized the cold room temperature and decreased product losses by 67%, which increased the company's ability to maintain the quality of the product and reduce losses. The interrupted time series model also showed an immediate decrease of 39.43 COP/unit in energy costs and high model fit, with results that suggested the intervention led to a structural and sustainable improvement in energy efficiency.

In human terms the technology proved to be a work saver and enhanced the work experience for employees, mainly women. This implies that the use of technologies in Industry 4.0 may also bring positive effects other than technical efficiency, potentially improving thermal stress and creating a better working environment for workers in jobs that are traditionally considered physically demanding.

In general, the results showed that the use of digital technologies in the cold chain is a promising approach to enhance productive and social sustainability in the food sector MSMEs. The research demonstrates that there can be substantial transformation in the learning process when even relatively low-cost interventions are used in a way that is well integrated into the process and using real-time monitored data as the basis for support.

Recommendations are for other comparable companies to implement the same solutions with the help of ultra-freezing and IoT solutions, providing staff training and monitoring of thermal and energy indicators, and slowly upgrading equipment. This model is replicable and may serve as a reference for public policies aimed at technological modernization and strengthening working conditions in small food-sector enterprises.

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