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(Research Article)

Longitudinal analysis of industrial water consumption by process: Empirical evidence from a brewery case study (2022–2024)

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Abstract

Industrial water efficiency is a critical component of sustainable manufacturing, particularly in water-intensive sectors such as beverage production. This study analyzes longitudinal water consumption patterns in a brewery plant between 2022 and 2024, using validated daily operational records disaggregated by process. Descriptive statistics, interannual comparisons, and inferential tests were applied to identify structural trends and critical consumption nodes. Results show that two processes consistently accounted for more than 70% of total water use, confirming structural concentration. Consumption increased significantly in 2023 (+24.8%), followed by a reduction in 2024 (−8.1%), coinciding with the implementation of an operational efficiency intervention. The packaging process exhibited the largest decrease (−23.9%), supported by statistically significant differences ($p < 0.01$). Variability indicators revealed improved operational stability after intervention. Findings demonstrate that process-level monitoring enables precise identification of inefficiencies and supports targeted strategies for resource optimization. This study contributes empirical evidence to industrial water management literature by providing high-resolution longitudinal data from a real production environment and highlighting the value of process-based analysis for sustainability decision-making.

Keywords: Industrial Water Use; Process Efficiency; Longitudinal Analysis; Brewery Industry; Sustainability

1. Introduction

Water management has become a strategic priority for industrial sustainability, especially in sectors with intensive consumption such as food and beverage manufacturing. Global water stress, regulatory pressure, and corporate sustainability commitments require companies to move from reactive monitoring to systematic management approaches [1], [6], [8]. Previous research shows that industrial water consumption is rarely uniform across processes; instead, it tends to be concentrated in specific operational stages. Identifying these critical nodes is essential for improving efficiency [2], [7]. However, most available studies rely on aggregated annual data, limiting the ability to detect structural variability and operational patterns. This study addresses this gap by analyzing daily water consumption records from a brewery plant over a three-year period (2022–2024). The objective is to identify structural consumption patterns, evaluate interannual variability, and determine whether targeted operational interventions can produce measurable efficiency improvements.

2. Materials and Methods 2.1 Study design

A quantitative longitudinal case study design was applied, using operational records from a beverage production facility. The analysis covered three consecutive years to capture structural trends and temporal variability.

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2.1. Data source

Daily water consumption records were obtained from validated internal monitoring systems. Data were organized by process:

- Packaging
- Cold rooms
- Brewing
- Utilities
- Administrative use

Total consumption was calculated as the sum of all processes.

2.2. Variables analyzed

Main variables included:

- Daily consumption (m^3/day)
- Annual totals
- Process contribution (%)
- Standard deviation (SD)
- Coefficient of variation (CV)

2.3. Statistical analysis

The analytical strategy included:

- Descriptive statistics
- Interannual comparisons
- Welch t-tests for pre/post comparisons
- ANOVA for multi-year differences

Significance level $\alpha = 0.05$

3. Results

3.1. Structural concentration of consumption

Across all years, water use was highly concentrated in two processes, which together accounted for more than 70% of total consumption. This confirms structural dependence on specific operational stages.

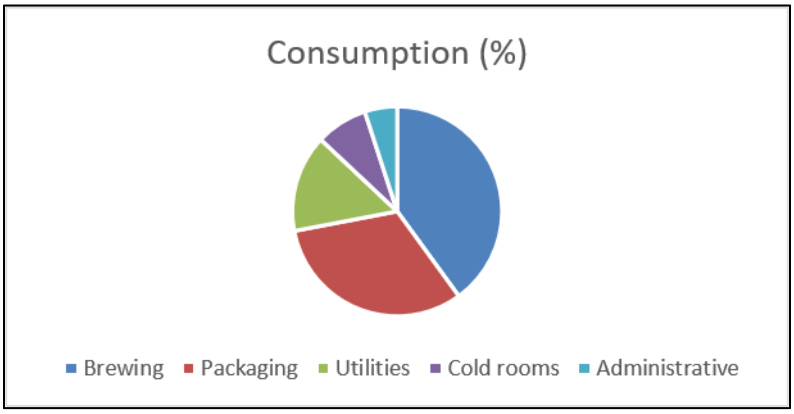

Figure 1 Structural concentration of water consumption by process

3.2. Interannual evolution

Table 1 Annual water consumption and interannual variation (2022–2024)

Year	Total Consumption (m^3)	Interannual Variation (%)	Operational Phase
2022	1,250,500	-	Baseline year
2023	1,560,624	+ 24.8%	Peak consumption
2024	1,434,213	- 8.1%	Reduction phase

Total water consumption showed a non-linear pattern:

- 2022: baseline year
- 2023: peak consumption (+24.8%)
- 2024: reduction phase (−8.1%)

The increase in 2023 was associated with higher production intensity and operational variability, whereas the reduction in 2024 coincided with the introduction of a targeted efficiency strategy.

3.3. Process-level changes

The packaging process showed the largest reduction between 2023 and 2024 **(see Figure 2)**

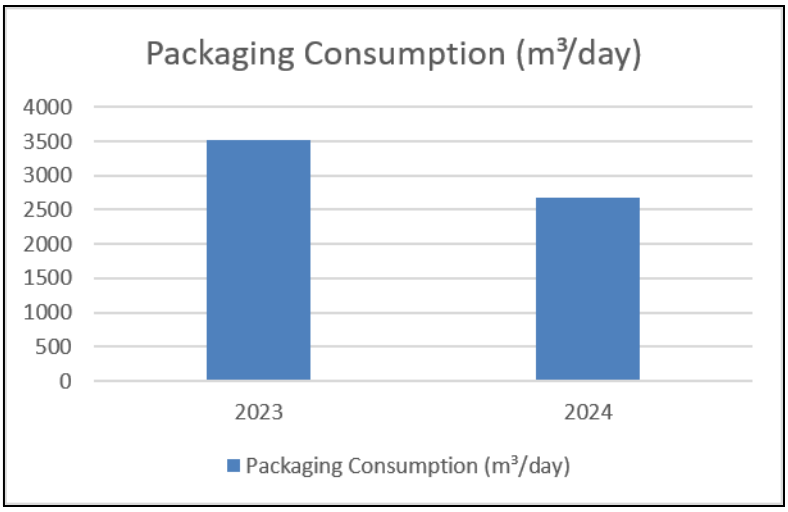

Figure 2 Average daily water consumption reduction in the packaging process

- Absolute decrease: -840 m^3/day
- Relative decrease: −23.9%
- Statistical significance: $p < 0.01$

Other processes exhibited minor variations, confirming that most of the global reduction was driven by the targeted area.

3.4. Variability analysis

The coefficient of variation decreased across major processes, indicating improved operational stability. This suggests that efficiency gains were not only quantitative but also structural.

4. Discussion

The results confirm that industrial water consumption is structurally concentrated in specific processes rather than uniformly distributed. This finding aligns with previous studies in industrial resource efficiency showing that targeted interventions are more effective than generalized strategies **[4], [5], [9]**. The sharp increase observed in 2023 illustrates how production growth without systematic monitoring can lead to resource inefficiencies. Conversely, the reduction observed in 2024 demonstrates that operational control mechanisms can rapidly reverse such trends. The statistically significant decrease in the packaging process provides empirical evidence that process-focused interventions can produce measurable improvements. Importantly, the simultaneous reduction in variability indicates improved process standardization, which is a key indicator of operational maturity. These findings highlight the importance of high-resolution monitoring and confirm that daily process-level data provide stronger analytical value than aggregated indicators.

5. Conclusions

This study demonstrates that longitudinal process-level analysis is a powerful tool for identifying inefficiencies in industrial water consumption. The results confirm that:

- Water use is structurally concentrated in specific processes.
- Consumption trends respond to operational conditions rather than random variation.
- Targeted interventions can generate statistically significant reductions.
- Efficiency improvements are accompanied by greater operational stability.

The findings support the adoption of process-based monitoring systems as a core strategy for industrial sustainability and provide empirical evidence applicable to other water-intensive sectors.

Compliance with ethical standards

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Disclosure of conflict of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work the author(s) used Gemini in order to translate the original manuscript from Spanish to English and improve readability. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

CRediT authorship contribution statement

- **Ana Karen Córdoba Schettino:** Conceptualization, Methodology, Formal analysis, Writing - original draft, Visualization.
- **Samantha San Basilio Guillén:** Data curation, Validation.
- **Xavier Contreras Calvario:** Software, Investigation.
- **Samantha Conde Sanchez:** Resources, Data curation.
- **Carlos Navarrete Enriquez:** Writing - review & editing.
- **Salvador Nava Rodriguez:** Supervision, Project administration, Writing - review & editing.

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