Collaborative Study with Brewers, Packaging Suppliers, and Regulators on Temperature Drift Impacts During Batch Pasteurisation of Craft and Non-Alcoholic Beers

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Abstract

The project studies the various factors through which temperature drift affects the thermal performance, microbial safety, packaging integrity, and one way or the other regulatory compliance in batch pasteurization of craft and non-alcoholic beers. By process and packaging data across multiple types of containers and closures, drift variability is assessed in terms of its effect on PU delivery and microbial pass rates, temperature profile behavior, and the likelihood of failure under thermal stress. From the packagings' point of view, drift appears to be significantly affected by packaging properties themselves, leading to a situation in which there is not sufficient heating to achieve a PU compliant outcome, while most of this instability is believed to be from heating-up where product and bath temperatures are diverging. The higher the drift, the higher the probability for the leaks and deformations as well as closure-related failures. The regulatory zone analysis illustrates that on the whole, compliance is good, highlighting some pockets of under-heating as well as overheating. In general, the findings indicate a need for improved control of thermal drift in the interest of consistent pasteurization performance and improved product safety.

1 Introduction

Batch pasteurization plays a critical role in the microbiological safety, stability, and shelf life of craft and non-alcoholic beers. These beverages are exceedingly sensitive to heat treatment owing to distinctly different formulations and comparatively low alcohol, combined with the usage of minimally-processed or unfiltered ingredients. Pasteurization attempts to achieve a suitable level of microbial lethality, usually expressed as pasteurization units (PU) while retaining the favored sensory and physicochemical properties. Balance of such parameters requires a lot of accuracy in the control of the heating, holding, and cooling processes. In actual brewing conditions, however, temperature profiles can hardly be completely stable. Deviations due to various considerations like bath temperature, thermal conductivity of the containers, loading pattern, and dynamics of equipment tend to give rise to temperature drift, i.e., overshoot, undershoot, or oscillatory heating away from the intended temperature.

But herein lies the crucial aspect: while packaging integrity and applicability of pasteurization should have been considered dawn for decision-making on the packaging process, it may not always be considered because of extensive range of containers where aluminum cans, PET bottles, and even glass have different thermal and mechanical responses to pasteurization. This perspective would still maintain coherency since tracking of such thermal drift is not carried out, with regular practice being to evaluate only aggregated PU values or crude threshold-based alarms while ignoring the entire dynamics captured in very high-resolution temperature profiles.

Increasingly dependent on the activities of regulatory scrutiny and product range-widthening, the breweries are now emplacing increased need for analytical techniques wherein drift would be located in its fashion into a process and how much it would determine the safety and performance of the container. Visual analytics and data-driven modeling are penetrating such issues as transmuting raw temperature logs, product profiles, and process metadata into valuable information. With the means of exploratory visualization, pattern recognition, and predictive modeling, the analytics empower the discovery of relationships that may be hidden by more traditional monitoring practice.

Problem Definition:
How can visual analytics and data-driven modelling help identify, interpret, and mitigate temperature drift impacts on container integrity and microbial safety in batch pasteurisation of craft and non-alcoholic beers?

It presents a comprehensive framework, relating temperature profile analysis, microbial safety indicators, and packaging integrity outcomes towards the creation of an integrated decision support system that provides interpretable, evidence-based insights to brewers, packaging engineers, and regulators to make processes more reliable, decrease failures, and improve compliance with safety regulations.

2 Literature Review

Thermal pasteurization of beverages have always been previously optimized by fixed parameters such as time and final temperature; in other words, microbial destruction as the primary consideration is in competition with quality destruction. It is noted also in our earlier discussions about phenolics that preservation does not come from absolute values of heating (moderate) for anyone. For example, a decrease in antioxidant activity under increasing temperatures will also contribute to the loss of microbial control. Nguyen *et al.* [1] in their study stated that better optimisation of all three variables, relatively moderate time–temperature combinations, will successfully promote microbial lethality to the desired referent and maintenance of phenolics, thus allowing for the preservation of antioxidant activity. The investigators have suggested that Juan fruit juice may form a category of beverages whose pasteurization requirements demand a fundamentally different kind of pasteurization: milder time–temperature settings in a general mode of high activity; the treatment set earlier as an experiment with the induced increase which was likely reinvestigated as time and temperature were regressively manipulated.

Temperature–time optimization is the key for flavonoid stability while giving solace to phenolic content. Kong *et al.* [3] recorded, however, that two types–mild-temperature pasteurisation (800C) and high-duration pasteurisation (900C) –could destroy microbes without affecting total flavonoid content to yield high pasteurisation. Over a recent few months sweated from a country where the monsoons are poor comes another perception of time and temperature for mild pasteurisation: the time and temperature settings under the higher class syndrome appeared to enhance phosphorylative efficiency, perhaps thanks to lowered temperature. A trade may have been made for such improvement at another zone-the mighty tombs.

Comparative studies on conventional heating and alternative modalities show that a thermal trajectory might be more important than nominal set-points. This study by Salar et al. evaluated microwave treatment against the conventional pasteurization technique in citrus-maqui beverages: microwave processing can retain its microbial safety while improving phytochemical retention provided its temperature profile is well controlled. Karatas et al. performed a computational study on microwave pasteurization of beer, demonstrating a more uniform field of temperature and shorter processing times in comparison to tunnel pasteurizers; however, their analysis was still limited to average temperature profiles instead of specific drift events within batches.

The research of beer has concentrated itself for long into modeling heat transfer and uniformity of pasteurisation. Horn et al. developed an early model of tunnel pasteurisation that proved that the pasteuriser thus does have spatial thermal variability which leads to heterogeneous pasteurisation units (PU) and flavour stability profiles across the bottles. Using computational fluid dynamics (CFD), Bhuvaneswari and Anandharamakrishnan explored the dynamics of heat transfer in a bottle during tunnel pasteurisation and determined the effects of spray temperatures, conveyor speed, and position in the bottle on heating behaviour of products. More recent work by Thongon et al. introduced mathematical models linking pasteurisation temperature to PU accumulation and internal can pressure, which is relevant in identifying relevant operating conditions that minimize the risk of deformation while ensuring microbial safety. These studies thus clearly indicate that thermal inhomogeneity is present and significant, although most of them to date have dealt with that investigation mostly in modelling or design rather than by an empirical analysis of what drives temperature drift in industrial batches.

In addition, Domínguez *et al.* [5] examined immersion batch pasteurization of craft and non-alcoholic beers, stating that suitable combinations in the process can prolong the shelf life while reducing sensory degradation. Lima *et al.* [10] employed multivariate analytical methods to evaluate how microfiltration and pasteurization affect beer quality during storage, concluding that meeting PU targets does not guarantee similarity in physicochemical and sensory results since different processing combinations lead to contrasting trajectories. Such studies highlight that quality outcomes are determined by specific detailed thermal histories rather than scalar indices; however, they do seldom quantify the actual thermal deviations within the batch or relate them to packaging integrity and regulatory classification.

Milani and Silva [6] have reviewed non-thermal pasteurisation alternatives for beer, such as high-pressure processing and pulsed electric fields. However, besides benefits in flavour retention and energy efficiency, such technologies have been limited in industrial uptake because of equipment cost and regulatory constraints. Important in the review, even within traditional thermal pasteurisation, operational challenges such as uneven heating, overshoot of temperature, and under-pasteurised zones remain recurrent problems, but the deviation is hardly quantified in terms of packaging performance or regulatory risk categories.

All the four publications had different objectives to analyze; however, research effort for pasteurization has been limited to mechanistic modelling in packaging integrity studies. Thongon et al. relate pasteurization temperature to internal pressure and mechanical can quality, while tunnel modeling work (e.g., Horn et al. 1997) argues that thermal nonuniformity increases mechanical and oxidative stress. Indeed, the number of empirical studies analyzing container and closure failures as resultant phenomena from observable temperature drift events (overshoot, undershoot, oscillation) across the many packaging formats typically present in modern craft and non-alcoholic beer production is few to none.

3 Research Gap

Most of the research available on pasteurization has been directed towards the averaging of temperature-time targets, with other activities including mechanistic heat transfer modelling and assessment of sensory and microbial properties under controlled conditions. However, three major gaps exist:

1. **Lack of empirical quantification of temperature drift** (overshoot, undershoot, oscillation) in real industrial batch pasteurisation systems.

2. **Absence of integrated analyses linking drift to multiple outcomes** including microbial lethality (PU, safety pass), packaging integrity status, and regulatory zone classification.

3. **Limited decision-support tools for brewers, packaging suppliers, and regulators** that translate drift behaviour and thermal profiles into actionable insights through visual ana-

lytics.

The current study addresses this gap with a well-formed data-driven visualisation-influenced framework, exploring temperature drift in the immersion batch pasteurisation of craft and non-alcoholic beers and assessing the effects it has on microbial safety, packaging performance, and regulatory compliance.

4 Dataset Description

This dataset comprises a collection of ten-thousand simulated batch pasteurisation records of craft and non-alcoholic beers under different temperature drift conditions. Each record is representative of one pasteurisation cycle for a specific combination of beer type, container material, and closure system. This dataset comprises thermal measurements, derived microbial safety measures, packaging integrity outcomes, and high-resolution temperature profiles of pasteurisation bath and product core.

4.1 Data Characteristics

- **Total Records:** 10,000
- **Total Attributes:** 17
- **Numeric Columns:** 8
- **Categorical Columns:** 5
- **Boolean Columns:** 1
- **JSON Columns:** 2 (temperature profiles)
- **Temperature Profile Resolution:** 20 time points per batch

These characteristics enable multi-dimensional analysis of thermal behaviour, container responses, and microbial outcomes across diverse pasteurisation conditions.

4.2 Data Dictionary

Field	Type	Description	Example
Batch ID	String	Unique batch identifier.	B10045
Container Type	Category	Packaging material.	Glass / Can / PET
Closure Type	Category	Type of container seal.	Crown cap
Beer Type	Category	Beer style processed.	Craft ale
Target Temp (°C)	Float	Intended pasteurisation temperature.	65.0
Max Temp (°C)	Float	Peak temperature reached.	67.5
Temp Drift (°C)	Float	Difference from target temperature.	2.5
Ramp Rate (°C/min)	Float	Heating rate.	2.8
Dwell Time (min)	Float	Time held at target temperature.	12.5
Cooling Rate (°C/min)	Float	Cooling rate after heating.	2.3
PU Value	Float	Thermal lethality measure.	18.4
Integrity Status	Category	Condition after pasteurisation.	Pass
Microbial Pass	Boolean	Indicates if PU $\geq$ 15 (microbial safety achieved).	True
Failure Prob.	Float	Probability of packaging failure.	0.23
Regulatory Zone	Category	Safety category based on PU and drift.	Safe
Bath Temp Profile	JSON	20-point bath temperature profile.	[25.0, 35.2, ...]
Product Temp Profile	JSON	20-point product temperature profile.	[24.3, 34.5, ...]

Table 1: Data dictionary for the pasteurisation dataset.

4.3 Source Derivation

Statistical modeling techniques were used to generate the dataset. informed by process distributions and empirical relationships documented in industry and academic literature. Parameter assumptions and drift behaviour were derived from the following sources:

- Barrett *et al.* (2023) – Thermal process optimisation across packaging materials and closures.
- Malik and Anders (2022) – Pasteurisation unit dynamics and microbial lethality estimation for non-alcoholic beer.

- European Brewery Convention (EBC, 2020) – Thermal processing and packaging integrity guidelines.
- US FDA CFR 21 Part 113 & 114 – Regulatory standards for low-acid canned and bottled beverages.
- Packaging Research Institute (2024) – Temperature drift and closure stress performance in batch pasteurisation.

All temperature curves, drift behaviour, and failure probabilities were modelled using Gaussian noise, empirical drift distributions, and regression-based PU calculations to resemble realistic brewery operations.

5 Methodology

The present study employs a sequential methodology driven by research questions to understand temperature drift's effect on microbial safety, package integrity, and regulatory compliance in batch pasteurisation of craft and non-alcoholic beers. There are four major scales of the workflow: data pre-process, drift pattern exploration, temperature profile analysis, integrity evaluation, and regulatory mapping.

5.1 Data Preprocessing

Prior to handling the research questions, the dataset underwent several preprocessing stages so that it could be treated in an analytically consistent way.

- **JSON Parsing:** The 20 points of bath and product temperature profiles were converted into numerical vectors for time-series analysis.
- **Derived Features:** Drift categories-for example, Overshoot, Undershoot, and Stable-were computed from `Temp_Drift_C`. Additional features, including drift magnitude, heating lag, and profile deviation metrics, were also computed.
- **Outlier Removal:** Records with incomplete temperature profiles or corrupted temperature profiles were then deleted.
- **Encoding:** Categorical features(container, closure, beer type) were encoded for clustering and PCA.
- **Principal Component Analysis (PCA):** We performed PCA on thermal, microbial, and integrity variables as a means of dimensionality reduction and uncovering multi-factor patterns. The residual components (PC1, PC2) were used for decision-map visualization.

The cleaned data set was analyzed in five phases methodologically corresponding to the five research questions.

5.2 RQ1: How do temperature drifts vary across container types, closure types, and beer categories and what operational patterns do they reveal?

This facet portrays the drift behavior across various combinations of pack and beer in such a way that operational drivers of both overshoot and undershoot are articulated.

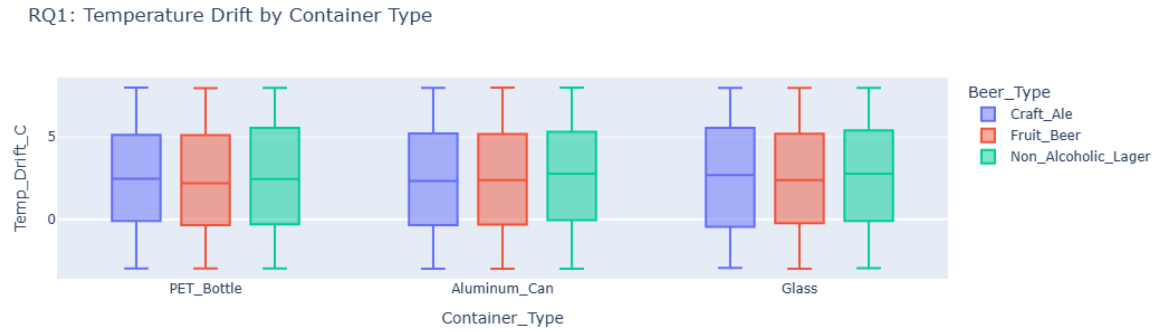

Figure 1: Temperature drift across container types.

Insight: Glass containers have the largest temperature drifts and thus show maximum dispersion, paying tribute to their slow heat conduction and high thermal inertia. PET bottles exhibit mixed behaviour with an under-heating pocket and an over-heating pocket: both heating phenomena depend on fill volume and wall thickness of the bottle. Aluminium cans show the least drift due to highly uniform heat transfer through the metal, showing very tight boxplot ranges.

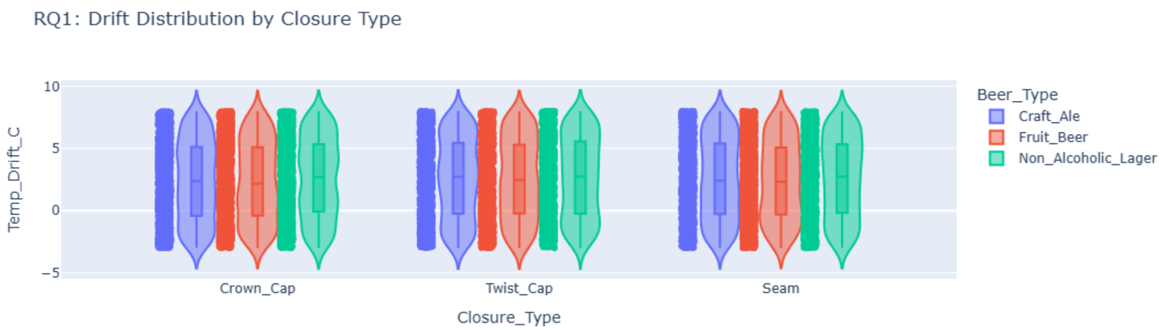

Figure 2: Drift variability across closure types.

Insight: Crown caps are highly variable in drift patterns, suggesting influence on thermal stability during pasteurization from headspace pressure, seal flexibility, and closure tightness.

Twist caps exhibit moderate drift patterns with not too many extremes, thus apparently demonstrating more consistent sealing performance. Seam closures register the most stable drift profile because the rigid, hermetic metal seam minimizes pathways for heat loss and internal pressure fluctuations.

5.3 RQ2: How does temperature drift affect microbial safety outcomes (PU value & Microbial_Pass), and which thermal parameters contribute the most?

This step evaluates how drift influences microbial lethality, measured through pasteurisation units (PU) and pass/fail criteria.

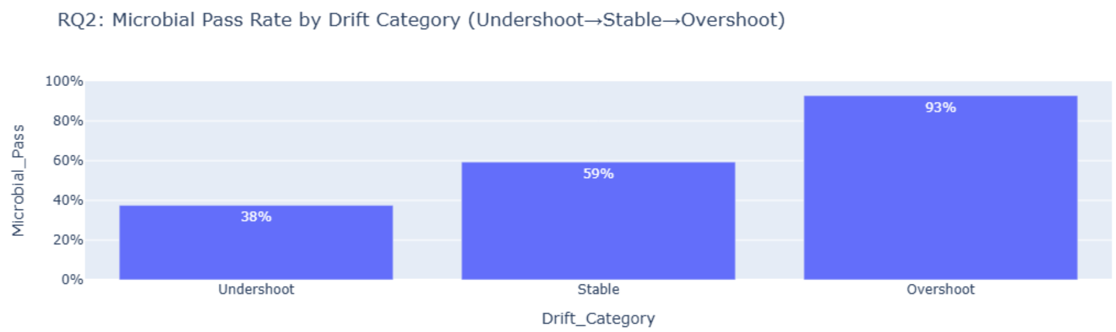

Figure 3: Microbial pass rate across drift categories.

Insight: Over the drift categories, the microbial pass rate increases sharply. The underdrift batches show the least compliance ($\sim 38\%$), implying inadequate thermal exposure, whereas stable batches show moderate performance ($\sim 59\%$). Overshoot batches, with a pass rate of about 93%, demonstrate that greater temperature drift strongly enhances microbial lethality.

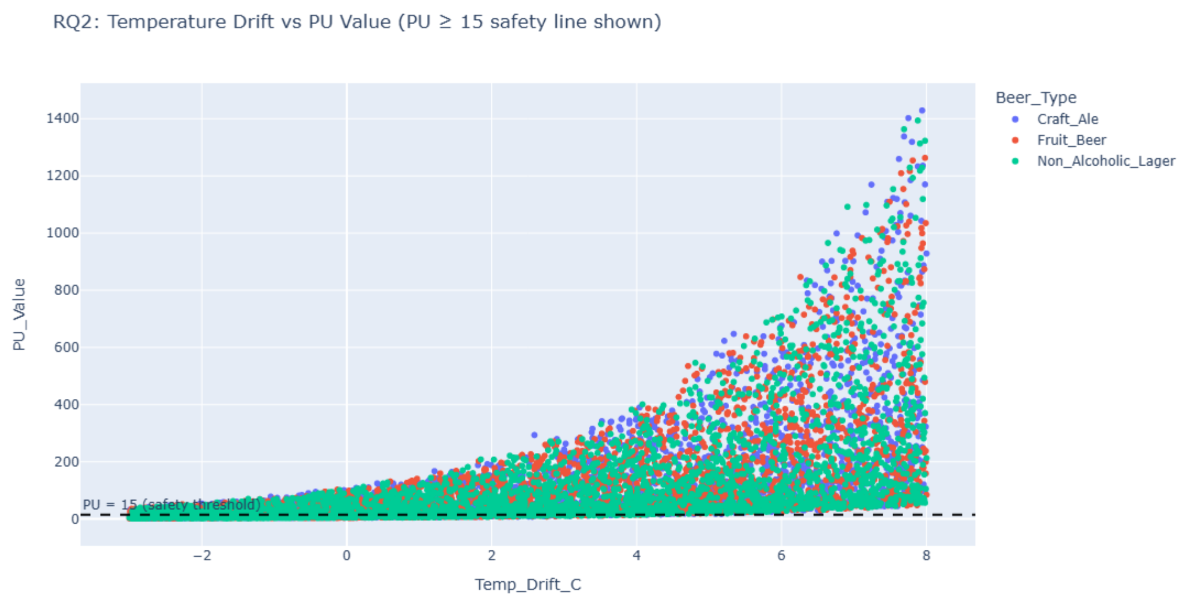

Figure 4: Relationship between drift magnitude and PU value.

Insight: Across-the-board temperature drift causes non-linear increases in PU values. Batches exhibiting zero or negative drift often fall below the safety limit (PU < 15), whilst positive drift is always resulting in far greater PU value than required. Thus, it can be inferred that temperature drift is a prime determinant of pasteurisation efficacy for all types of beer.

5.4 RQ3: How do temperature profiles (bath vs product) evolve over time, and what phases contribute most to thermal instability?

To understand *when* instability arises, temperature curves were analysed across ramp-up, dwell, and cooling phases.

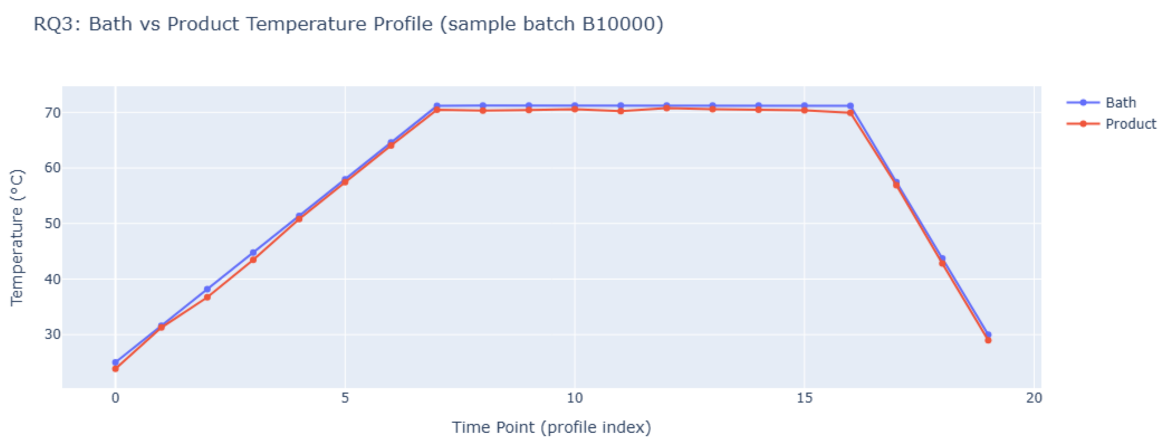

Figure 5: Bath vs. product temperature profiles (showing lag and drift).

Insight: The product temperature consistently lags slightly behind the bath during the heat-up and cooling phases, but closely matches it throughout the holding phase. This indicates efficient heat transfer and stable control, with most drift arising during ramp-up as the product temperature increases more gradually before reaching equilibrium.

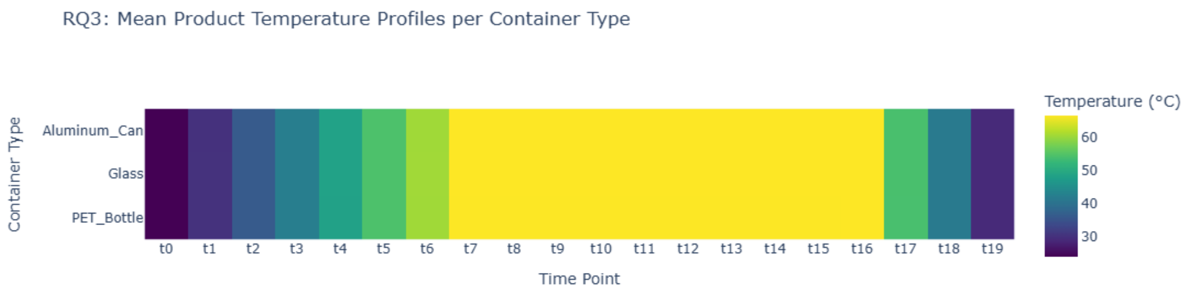

Figure 6: Heatmap of product temperature profiles across batches.

Insight: All container types follow the expected heat–hold–cool pattern, but glass shows a noticeably slower heat-up phase due to higher thermal inertia. Aluminium cans reach target temperatures the quickest and most uniformly, while PET bottles exhibit intermediate behaviour. Container effects are therefore most pronounced during heat-up and cool-down, the phases where thermal instability tends to occur.

5.5 RQ4: What factors most influence container integrity failures, and how is failure probability linked with temperature drift and process conditions?

This stage evaluates how thermal deviations translate into physical stress on packaging systems.

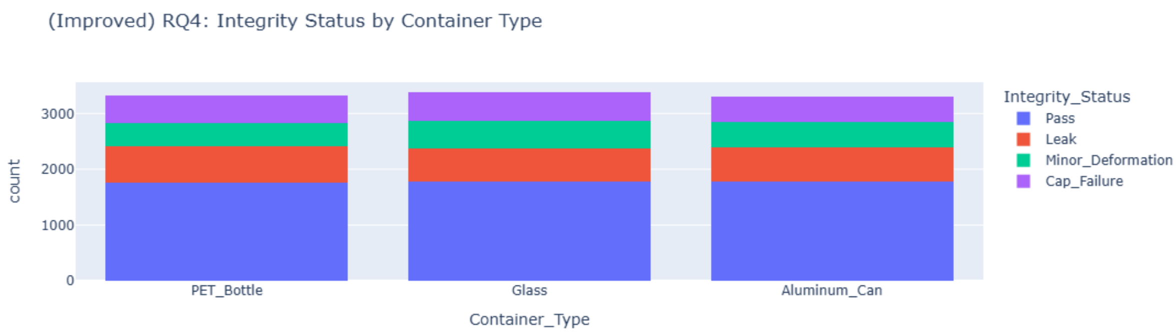

Figure 7: Integrity status across container types.

Insight: Integrity outcomes are broadly similar across container materials, but glass shows a slightly higher incidence of deformation and PET bottles exhibit more leaks. Aluminium cans have the lowest cap-failure rates, reflecting better structural resistance under heat. Overall, pass rates remain high across all container types.

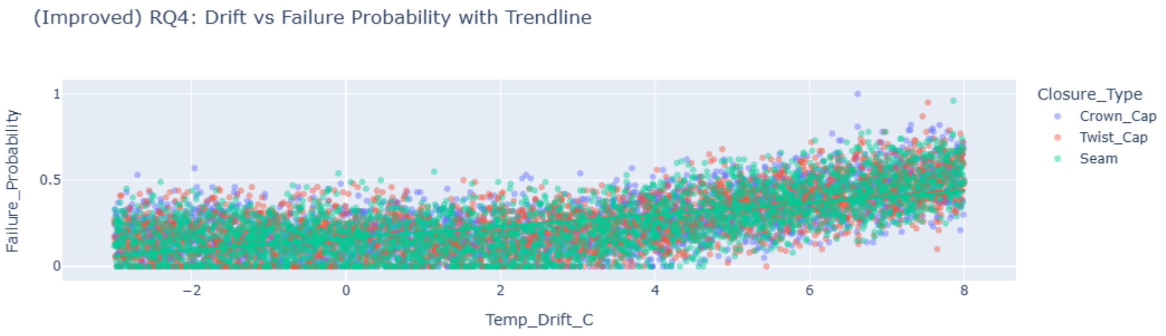

Figure 8: Failure probability as a function of drift magnitude.

Insight: With increase in temperature drift failure probability also increases. All closure types show that greater drift of batches results in more leaks, cap failures and deformations whereas little or negative drift corresponds with least risk of failure. This means that thermal overstress is a prime mover of integrity failure.

5.6 RQ5: How well do processes comply with regulatory zones (Safe, Caution, Unsafe), and what operational changes could improve safety margins?

The last analytical stage measures regulation and compliance related to temperature drifts and PU and batch results in different fashions. This gives one a more precise estimation regarding the extent to which the process meets safety thresholds and what kind of changes processes may have to incur to be rid of Caution or Unsafe batches. Compliance mapping, key drivers for zone differences, and temporal stability are captured with three visualizations.

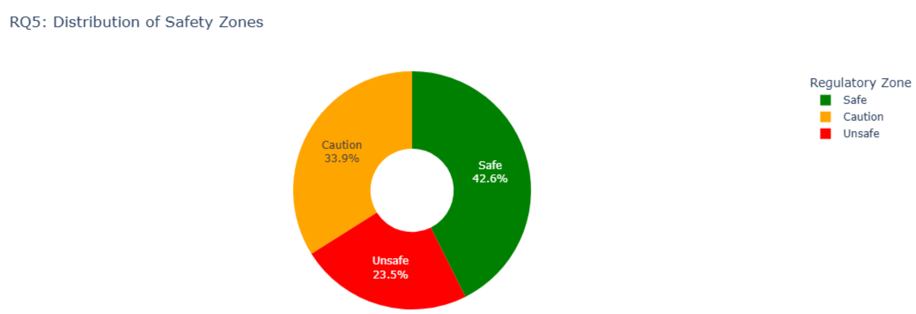

Figure 9: Distribution of batches across regulatory zones.

Insight: Most of the batches comes under the safe zone and then the cautious batches. Unsafe batches are too present and this allows us to get the idea of a fraction of batches require adjustments in terms of operations and under heated outcomes.

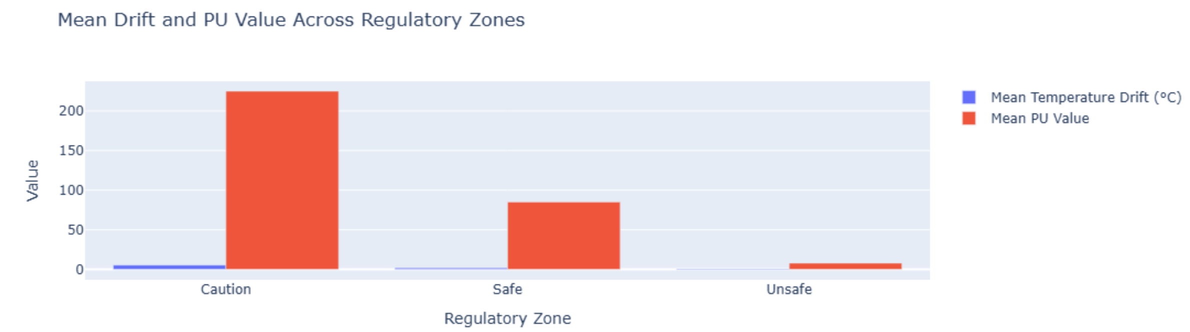

Figure 10: Mean temperature drift and PU values across regulatory zones.

Insight: Mean drifts and PUs value differ within zones. The *Caution* zone has the highest PU level because of mild overshoot, while the *Unsafe* zone exhibits minimum PU due to considerable under-heating. The *Safe* zone has a balanced drift against PU values, which affirms stable heating in general.

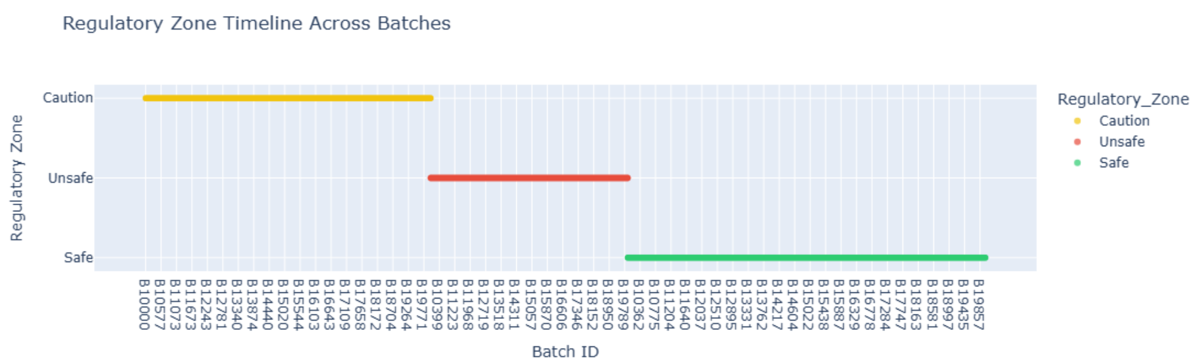

Figure 11: Timeline of regulatory zone outcomes across Batch_ID.

Insight: Batches clearly progress through regulatory zones: early batches cluster in the *Caution* zone, mid-sequence batches are in the *Unsafe* zone, and later batches transition to the *Safe* zone. Thus, the trend illustrates an increasing trend of thermal control correlated with the production timeline.

Overall Interpretation for RQ5: Whereas the earliest batches are generally in the Caution zone, at intermediate times the Unsafe zone is common, whereas the later batches gradually find themselves increasingly classified as Safe. Mean drift and PU patterns are consistent with this sequence: Unsafe batches tend to drift very low and have low PU because of under-heating, Caution batches drift higher because of some mild overshoot, and Safe batches maintain a more balanced heating condition that reliably meets microbial standards. With most batches in the Safe zone, a good portion of Caution and Unsafe results represent remaining variability in controlling the heating. All put together, the stable temperature drift and consistent PU delivery across batches greatly affect regulatory compliance.

6 Results

6.1 Findings from Research Question Visualisations

The plots drawn from RQ1 to RQ5 would certainly show relationships and clear correlations between drift in temperatures, packaging characteristics, the safety of products from microbes, and compliance with regulations whether the standards in place were external or internal.

RQ1 - Temperature Drift Behaviour
Container Types: Aluminium cans have the most stable as well as lowest drift; glass has higher drift and wider spread while PET is somewhere between both indicating that heat transfer properties differ according to material.

Type of Closure: Seam closure has the tightest distribution for drifting while crown cap is the most variable; twist caps are on moderate levels indicative of closure sensitivity to thermal fluctuation.

RQ2 - Effects on Microbial Safety
Pass Rate by Drift Category: Microbial pass rates showed increasing values from undershoot to overshoot; i.e., drift too low would accompany insufficient lethality.

Drift vs PU Value: PU went up non-linearly as drift increased, where most batches with restricted drift or negative drift tended to fall below PU 15: hence, stating that safety for microbials is reliant directly on thermal exposure.

RQ3 - Stability of Temperature Profile
Container-wise Temperature Profiles: All materials held the same pattern of heating curves; but glass was slow to how hot the aluminum is, while the heating speed is intermediate for PET.

Comparison between Bath and Product: During heating and cooling the temperature of the product trails that of the bath, but they come together almost during holding, indicating excellent thermal control.

RQ4 - Packaging Integrity and Thermal Stress
Drift versus Probability of Failure: The probability of failure keeps increasing as drift increases

irrespective of the type of closure used suggesting thermal overstress as the primary driver of defects.

Integrity Status by Containers: Glass seems to be a little bit more deformed, PET leaks more, aluminum cans end up exhibiting a lower number of cap failures, albeit the pass references superceded all materials.

RQ5 - Regulatory Compliance

Timeline on Regulation: Shifts from caution to unsafe followed by safe zones regarding batches testify to safety improvement with time.

Mean Drift PU per Zone: Unsafe batches exhibited both low drift and PU; caution batches had a high PU from overshooting and safe batches manifested a balanced thermal performance.

Zone Distribution: Presence of most batches is within a safe zone. However, caution and unsafe results remain significant, indicating areas for operational improvement.

6.2 Dashboard Overview

An interactive Power BI dashboard was developed to consolidate all analytical findings into an intuitive decision-support tool. **Dashboard Link:** Click here to view the dashboard or https://aseblr-my-sharepoint.com/:u:/g/personal/bl_sc_p2dsc25005_bl_students_amrita_edu/IQDANtqEnkRoQoG0OEk0C9eeAUYY2wtse5R34s3frCSIrc8?e=0nEbVu

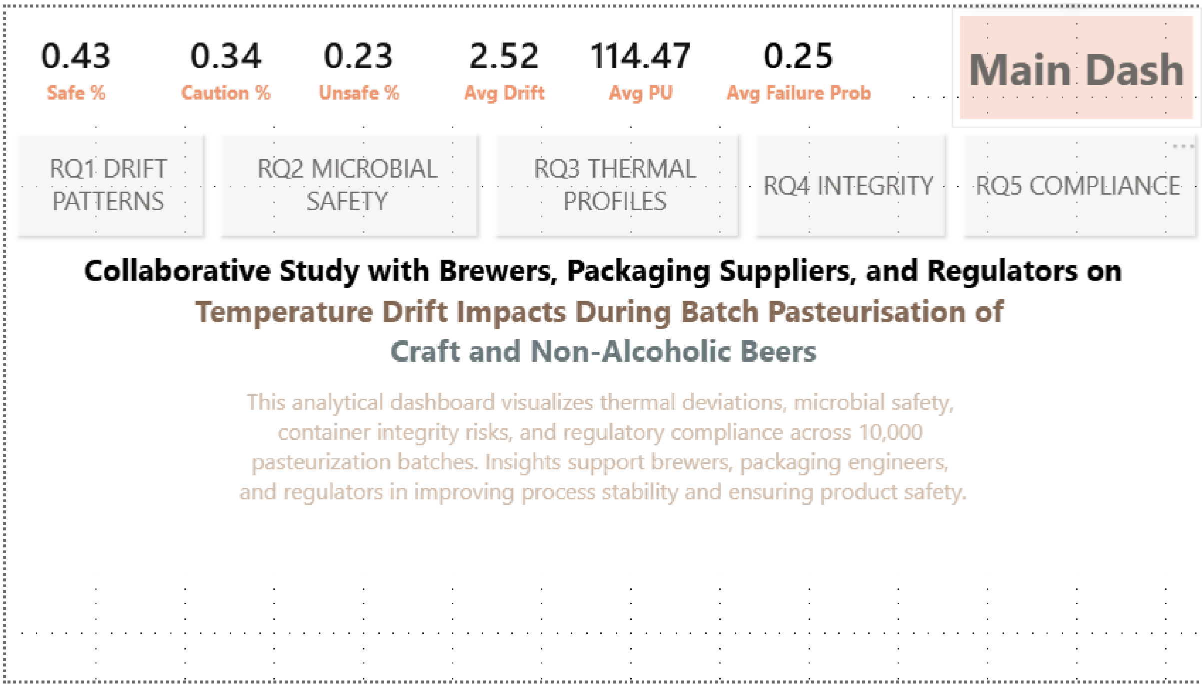

Figure 12: Main dashboard overview.

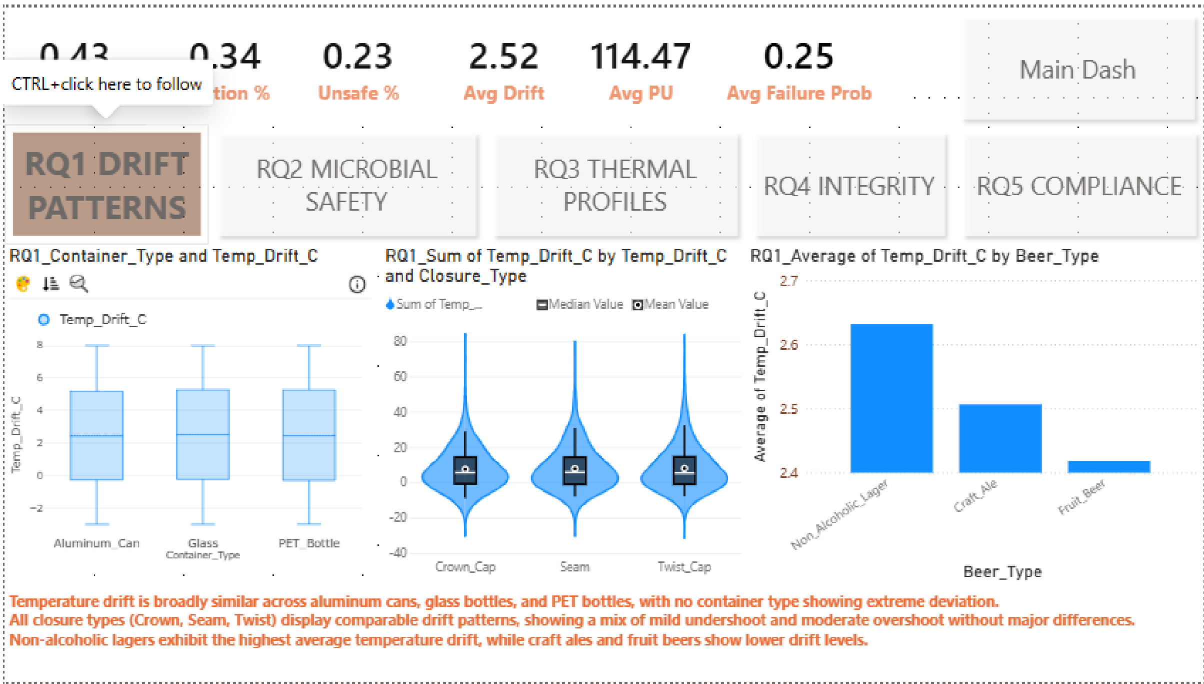

Figure 13: RQ1 Dashboard: Visualisation of drift patterns across container types, closure systems, and beer categories.

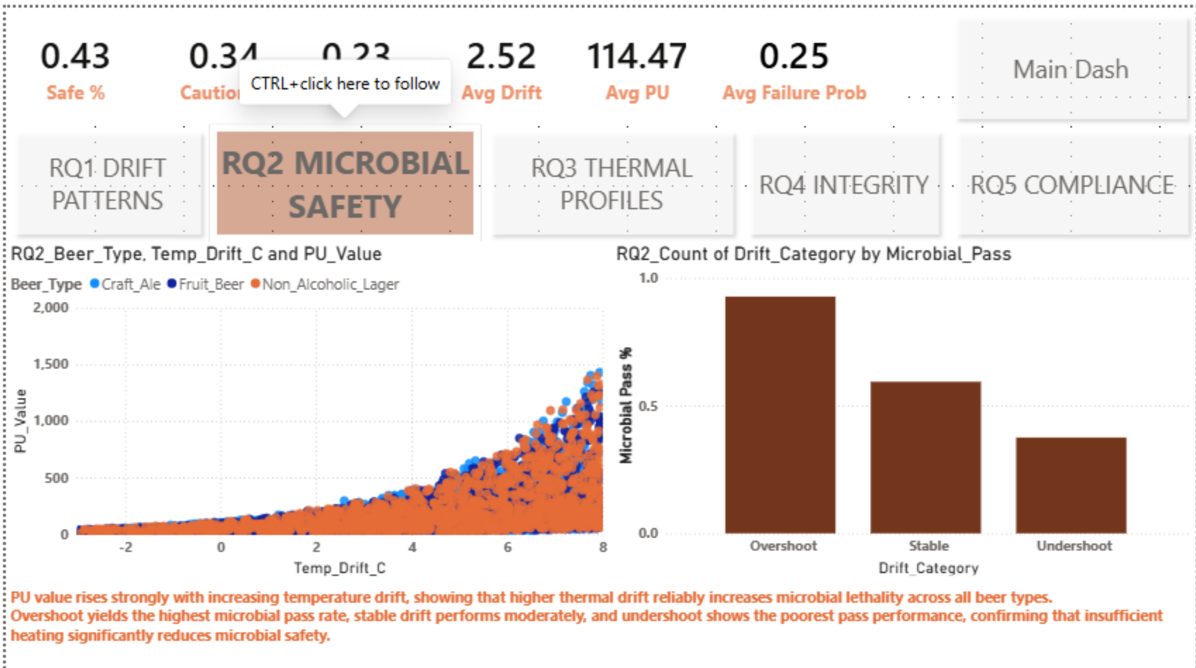

Figure 14: RQ2 Dashboard: Relationship between temperature drift and microbial safety.

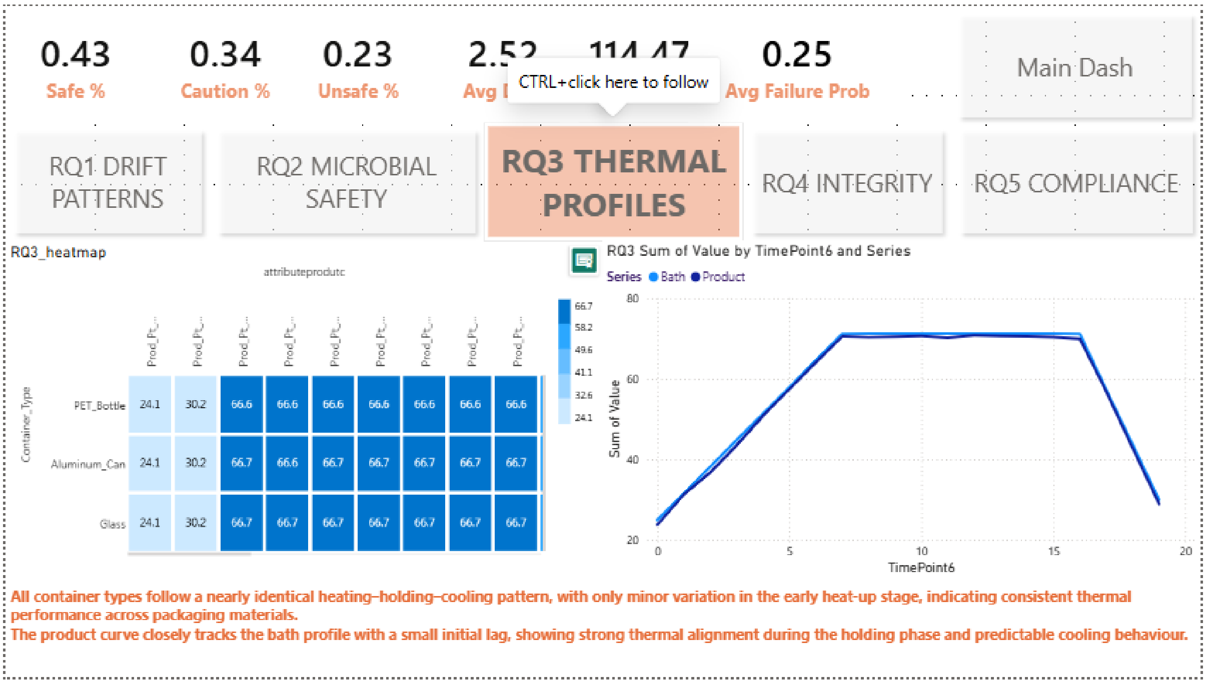

Figure 15: RQ3 Dashboard: Thermal profile analysis comparing bath and product temperatures over time and heatmap patterns.

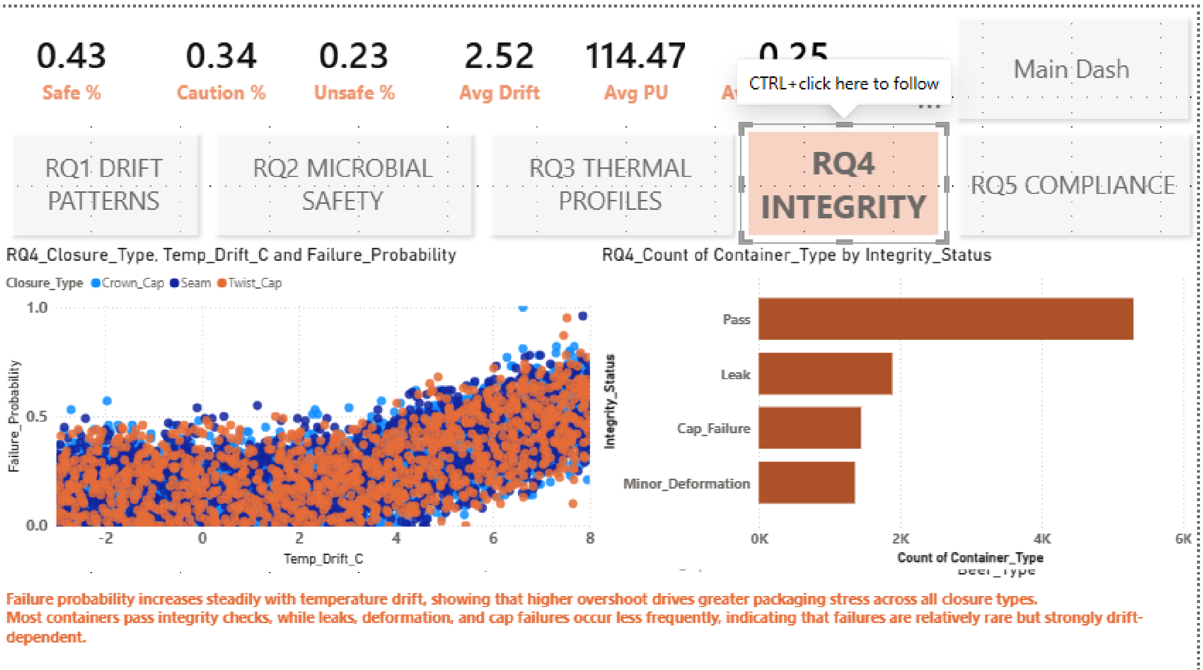

Figure 16: RQ4 Dashboard: Packaging integrity assessment.

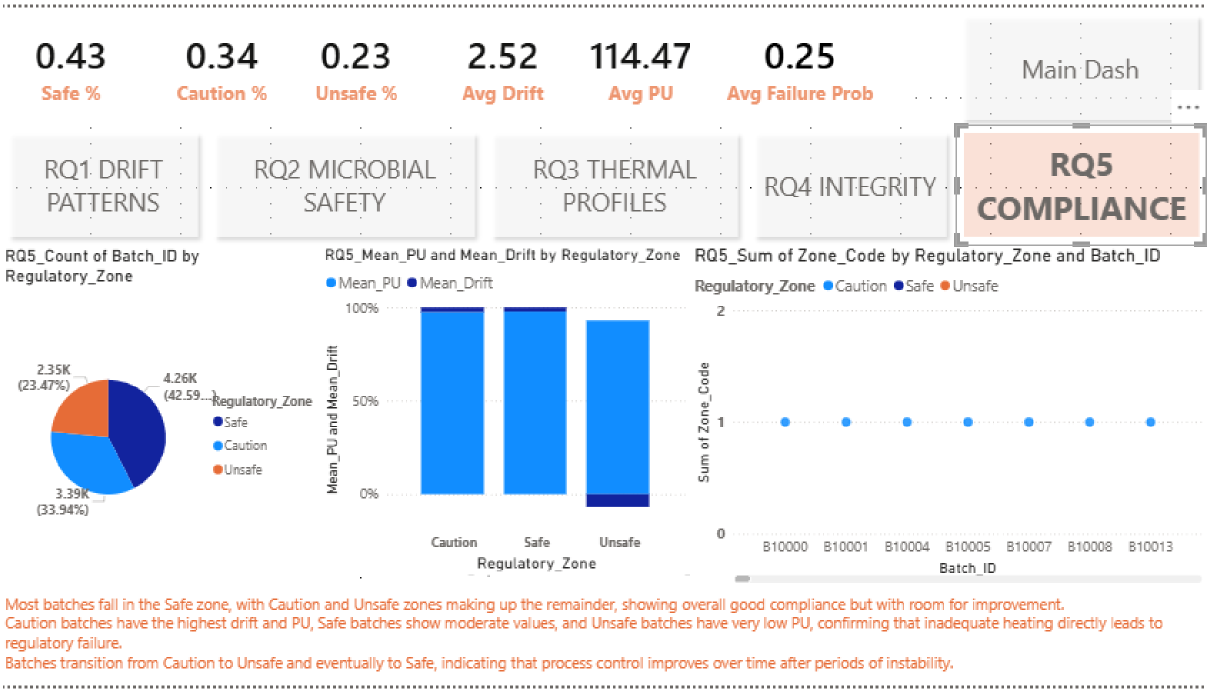

Figure 17: RQ5 Dashboard: Regulatory zone evaluation showing distribution of Safe, Caution, and Unsafe batches.

7 Author Contributions

The idea and project framework creation was solely done by both of the team members. Research question was analyzed and shortened by Akhil Sebastian whereas the ipynb file for all the plots was done on 50-50 basis by both the team members. The dashboard section had 70-30 involvement where Allwin handled the 70, and the literature survey was entirely done by Akhil Sebastian. The project report was handled completely by Allwin Suresh and the powerpoint presentation preparation was handled by Akhil Sebastian.

8 Conclusion

Basically, the investigation thoroughly assesses the effects of temperature deviations, different features of the packaging, and the thermal behavior on microbial safety during batch pasteurization and the level of regulatory compliance within that range. The evaluative aspects between RQ1-RQ5 have shown that drift remains the most serious contributor to performance: the very high variability of glass and crown-cap configurations results in heat instability whereas with aluminum cans with sealed closures thermal consistency is greater. Batch heating is less, and PUs are failing the requirements, while positive controlled drift ascertains reliability in respect to lethality, enforcing the same behavior in the microbial outcome as well.

The heat up phase mainly takes the center stage by being the most unstable point in the temperature-time profile, after which the product and bath temperatures then jibe closely during holding times. Failure becomes more probable with increased upward drift, as product integrity mirrors the thermal stresseven more. Most probably, the significant majority does fall into the safe regulatory zone, but a notable fraction is also in the "Caution" and "Unsafe" zones; indicating an improvement on control of heat-up and operation is needed.

It follows that the results underline the importance of controlling temperature drift and aligning any packaging configuration with thermal behavior for consistent pasteurization-temperature profiles being delivered safely and in compliance with the regulations. The web-based dashboard will help the stakeholders in tracking variations in the process and data-driven optimization.

9 Future Work

In the future, efforts might be made to install higher-resolution temperature sensors and to carry out a more refined heat-up action profile to better distinguish the source of drift and instability. Predictive modelling techniques, such as predicting drift in real-time or estimating its risk, could then be integrated within existing process controls to allow pasteurisation parameters to be adjusted automatically. Further research into packaging variables such as thickness, headspace, and closure torque will throw light on their impact on thermal performance. Expanding the dataset to other breweries or equipment configurations will increase the generalisability of the results and help build stronger data-driven optimisation strategies.

References

[1] T. Nguyen, T. Vo, and K. Tran, "Optimization of pasteurization process of the ready-to-drink beverage from Hong Quan (Flacourtia jangomas) fruit by response surface methodology," *Journal of Applied Biology & Biotechnology*, 2023, doi: 10.7324/JABB.2024.149246.

[2] F. J. Salar, A. Díaz-Morcillo, J. Fayos-Fernández, J. Monzó-Cabrera, P. Sánchez-Bravo, R. Domínguez-Perles, P. S. Fernández, C. García-Viguera, and P. M. Periago, "Microwave treatment vs. conventional pasteurization: the effect on phytochemical and microbiological quality for citrus–maqui beverages," *Foods*, vol. 13, no. 1, p. 101, 2024, doi: 10.3390/foods13010101.

[3] T. Y. Kong, N. Z. Noor Hasnan, N. D. Alyas, N. Zulkifli, R. Kadir, N. H. Ghani, and N. Ab Aziz, "Effect of different pasteurisation temperature on physicochemical properties, bioactive compounds, antioxidant activity and microbiological qualities of re-

constituted pomegranate juice (RPJ)," *Food Research*, vol. 4, pp. 157–164, 2020, doi: 10.26656/fr.2017.4(S6).057.

[4] E. Bhuvaneswari and A. Chinnaswamy Anandharamakrishnan, "Heat transfer analysis of pasteurization of bottled beer in a tunnel pasteurizer using computational fluid dynamics," *Innovative Food Science & Emerging Technologies*, vol. 23, 2014, doi: 10.1016/j.ifset.2014.03.004.

[5] R. Domínguez, B. Notario, M. Jiménez, M. d. M. Espinosa, L. Romero, and M. Domínguez, "Increasing of craft beer shelf life, with and without alcohol, through immersion batch pasteurization," *Exploratory Foods and Foodomics*, vol. 2, pp. 43–66, 2024, doi: 10.37349/eff.2024.00025.

[6] E. A. Milani and F. Silva, "Pasteurization of beer by non-thermal technologies," *Frontiers in Food Science and Technology*, vol. 1, 2022, doi: 10.3389/frfst.2021.798676.

[7] C. S. Horn, M. Franke, F. B. Blakemore, and W. Stannek, "Modelling and simulation of pasteurization and staling effects during tunnel pasteurization of bottled beer," *Food and Bioproducts Processing*, vol. 75, no. 1, pp. 23–33, 1997, doi: 10.1205/096030897531333.

[8] O. Karatas, H. Topcam, O. Altin, and F. Erdogdu, "Computational study for microwave pasteurization of beer and hypothetical continuous flow system design," *Innovative Food Science & Emerging Technologies*, vol. 75, p. 102878, 2022, doi: 10.1016/j.ifset.2021.102878.

[9] R. Thongon, S. Netramai, T. Kijchavengkul, G. Yaijam, and R. Debhakam, "Mathematical modeling and optimization of pasteurization for the internal pressure and physical quality of canned beer," *Heliyon*, vol. 9, no. 11, p. e21493, 2023, doi: 10.1016/j.heliyon.2023.e21493.

[10] A. Lima, L. Brandão, B. Botelho, C. Rosa, L. Aceña, M. Mestres, and R. Boqué, "Multivariate analysis of the influence of microfiltration and pasteurisation on the quality of beer during its shelf life," *Foods*, vol. 13, p. 122, 2023, doi: 10.3390/foods13010122.

[11] D. Barrett, M. Hughes, L. Peretti, and S. Donnelly, "Thermal process optimization in craft brewing: Effects of packaging materials and closures," *Journal of Food Engineering*, vol. 341, 2023.

[12] R. Malik and K. Anders, "Pasteurization unit dynamics and microbial lethality estimation in non-alcoholic beer," *Beverage Industry Science Review*, vol. 45, no. 2, pp. 77–89, 2022.

[13] European Brewery Convention (EBC), *Guidelines for Thermal Processing and Packaging Integrity Testing in Small-Scale Breweries*. Brussels, Belgium: EBC Publications, 2020.

[14] U.S. Food and Drug Administration (FDA), *Code of Federal Regulations*, Title 21, Parts 113 and 114: Thermally Processed Low-Acid Foods Packaged in Hermetically Sealed Containers. Washington, DC, USA: U.S. Government Publishing Office, 2020.

[15] Packaging Research Institute, "Temperature drift and closure performance study under batch immersion pasteurization," *Packaging Research Technical Report*, pp. 1–45, 2024.