Optimizing induction sealing for milk bottles at different conveyor speeds

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Abstract. Optimal sealing helps reduce milk spoilage amid rising temperatures caused by climate change. One potential solution is the use of alufo plastic on the bottle mouth with an induction sealing machine. This study aimed to evaluate the effectiveness of alufo plastic in sealing 200 mL milk bottles at different sealing speeds. The experiment used a completely randomized design with three treatments: 10, 15, and 20 rpm, each with three replications. The study was conducted at the Teaching Factory (Tefa) Milk, Jember State Polytechnic. The results showed that the average sealing time ($P < 0.05$) was 7.88 seconds at 10 rpm, 6.01 seconds at 15 rpm, and 5.28 seconds at 20 rpm. The physical leak test revealed that samples sealed at 10 and 15 rpm showed no leakage, whereas those sealed at 20 rpm exhibited leakage ($P < 0.05$). The vacuum test further confirmed that bottles sealed at 10 rpm had better sealing integrity compared to the others ($P<0.05$). In conclusion, sealing 200 mL milk bottles using aluminum plastic at a speed of 10 rpm for 7.88 seconds provides the most effective sealing performance. This method can help improve the safety and shelf life of milk products.

1 Introduction

Fresh milk consumption in 2024 experienced a decline compared to the previous two years, amounting to 824,273.20 tons in 2022, 837,223.20 tons in 2023, and 808,352.84 tons in 2024 [1]. Meanwhile, the Indonesian population continues to increase, with an average population of 281,579,600 people over the last three years [2]. This condition creates an imbalance, as milk production should ideally be proportional to population growth to meet the recommended intake of animal-based protein. One of the efforts to address this issue is by increasing the production of processed dairy products. Politeknik Negeri Jember, as an institution implementing industry-based learning, operates a teaching factory known as Tefa Milk that supports the production of processed milk products. One important factor in maintaining product quality is the development of appropriate bottle packaging. However,

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several findings indicate that some bottles still experience leakage due to asymmetry in the bottle neck.

Leakage in the bottle may lead to contamination risks, causing the final product to fail to meet quality standards. The risks that may arise when a milk product bottle leaks include potential microbial contamination, reduced product quality, compromised safety, and a shorter shelf life [3]. One potential solution is the application of an aluminum foil seal on the bottle mouth. Optimal sealing performance is also crucial in the context of climate change, as higher environmental temperatures increase the risk of milk spoilage, making secure and reliable packaging an important strategy to reduce food waste and enhance product safety. The type of packaging currently used for Tefa Milk liquid products is made of High Density Polyethylene (HDPE). High Density Polyethylene (HDPE) is selected because it possesses characteristics that meet food-safety requirements, including impact resistance, stability at low temperatures, non-reactivity with milk components, and relatively good permeability to water vapor. However, the semi-crystalline molecular structure of HDPE can lead to variations in its physical form, including the potential for irregularities in the bottle neck area [4]. These dimensional inconsistencies can increase the likelihood of leakage when the capping process does not produce a tight and uniform seal.

In the context of liquid product packaging, one increasingly adopted approach is the application of an additional sealing layer in the form of an aluminum foil (foil seal) on the bottle opening [5]. This layer functions as a barrier that provides extra protection against microbiological contamination, oxidation, and physical damage during distribution [6]. Although aluminum foil sealing technology has been widely applied to several types of plastics such as PET and PP, studies evaluating its effectiveness on HDPE bottles—particularly for liquid milk or other microbiologically sensitive products—remain relatively limited. This condition highlights the importance of assessing foil performance on HDPE surfaces to ensure material compatibility and consistent sealing adhesion [7].

In addition, climate change has intensified temperature fluctuations and increased the risk of microbial growth in perishable products such as fresh milk. These environmental changes make packaging integrity even more critical to prevent spoilage and ensure product safety during distribution. Therefore, optimizing sealing performance becomes an important strategy to reduce food loss under climate-related stress conditions.

The sealing of aluminum foil on HDPE bottles generally utilizes an induction sealing machine, a technology that employs an electromagnetic field to melt the polymer layer on the inner side of the foil, allowing it to adhere firmly to the bottle rim. The quality of the resulting seal is strongly influenced by several process parameters, particularly the conveyor speed. Variations in speed affect the duration of heat exposure, which directly determines the strength and uniformity of the seal. To date, studies examining the effect of different induction sealing speeds on the effectiveness of aluminum foil sealing on HDPE bottles for milk products have been limited, leaving a notable research gap. Therefore, this study aims to determine the effect of different induction sealing machine speeds on the leakage level of aluminum-foil–sealed milk bottles.

2 Materials and Method

This study was conducted at the Teaching Factory Milk, Politeknik Negeri Jember, Jember, East Java, Indonesia, and was carried out in July 2025. The materials and equipment used included 200-ml HDPE bottles (nine units), aluminum foil seals adjusted to fit the bottle mouth diameter, and an induction sealing machine. The research procedure began with inserting the aluminum foil into the bottle caps, manually filling the HDPE bottles, capping them, and performing the sealing process using the induction sealing machine according to each treatment (P1: 10 rpm, P2: 15 rpm, and P3: 20 rpm).

Physical observations were carried out by inverting and pressing the bottles; if no liquid escaped, the bottle was categorized as having no physical leakage. This observation was coded as 1 and 2 (1: No Leakage, 2: Leakage). Vacuum observations were performed by placing the bottles inside a desiccator containing water, which was then connected to a vacuum pump at a pressure of 2 bar for 20 seconds. The presence of air bubbles indicated leakage and was coded according to the physical leakage criteria. The condition of the aluminum foil was evaluated by inspecting whether the foil adhered perfectly to the bottle mouth or whether any paper layer remained attached to the foil or cap. This observation was coded as 3 and 4 (3: Paper Detached, 4: Paper Adhered to the plastic on the bottle neck). The observation data were analyzed using Analysis of Variance (ANOVA) with a Completely Randomized Design consisting of three treatments and three replications. Data processing was conducted using SPSS software.

3 Result and Discussion

The results of this study present the effects of different induction sealing speeds on sealing time, physical leakage, vacuum leakage, and aluminum foil condition in HDPE milk bottles. The observations were conducted to assess how variations in sealing speed influence the integrity and performance of the aluminum foil seal as an additional protective layer. Overall, the findings highlight clear differences among treatments, indicating that sealing speed plays a crucial role in determining heat exposure, sealing strength, and the final condition of the foil on the bottle mouth. A summary of the results for each parameter is presented in Table 1.

Table 1. Effects of Aluminum Foil Application at Different Induction Sealing Speeds.

Treatment	Sealing Time (second)	Physical Leakage	Vacuum Leakage	Aluminum Foil Condition
P1	7.88^{a}	1^{b}	1^{b}	3
P2	6.01^{b}	1^{b}	$1,67^{a}$	3
P3	5.28^{c}	2^{a}	2^{a}	3.67

Note: P1: 10 rpm, P2: 15 rpm, P3: 20 rpm; 1: No Leakage, 2: Leakage, 3: Paper Detached, 4: Paper Adhered to the plastic on the bottle neck.

3.1 Sealing Time

The sealing time showed a significant decrease with increasing induction sealing speed. Treatment P1 (10 rpm) produced the longest sealing time (7.88 s), followed by P2 (15 rpm) at 6.01 s, and P3 (20 rpm) at 5.28 s. This pattern is consistent with the principle that higher conveyor speeds reduce the exposure duration of the aluminum foil to the electromagnetic field, thereby shortening the heat absorption period [8]. The longer sealing time observed in P1 indicates greater thermal penetration into the polymer layer, which generally contributes to better adhesion potential. Conversely, the shortest sealing time in P3 suggests insufficient heat transfer, which may compromise the sealing integrity. These findings confirm that sealing speed directly influences the duration of heat activation, which is critical for forming a strong bond between the aluminum foil and the HDPE bottle mouth. Heat sealing using contact-based equipment, such as seal bars and sealing bands relies on the interaction of temperature, pressure, and sealing duration. These factors are essential in initiating the melting of the sealant layer and ensuring proper fusion between the molten surfaces. The resulting seal quality depends on product sensitivity, packaging design, and user-friendly performance requirements [9].

The results of this study clearly demonstrate that sealing time determined by the induction sealing speed plays a crucial role in achieving optimal sealing performance in HDPE bottles with aluminum foil. Treatments with longer effective sealing times (P1: 7.88 s) produced better sealing outcomes, indicated by the absence of both physical and vacuum leakage. As sealing speed increased (P3: 20 rpm), the effective sealing time decreased (5.28 s), leading to incomplete heat transfer, insufficient polymer melting, and ultimately leakage and poor foil adhesion. This finding is consistent with established principles of heat sealing, which emphasize that the sealing process depends on sufficient temperature, pressure, and time to enable proper fusion of the sealing layer [6].

Shorter sealing times reduce the duration of heat exposure at the interface, delaying or preventing the sealant layer (in this case, the polymer coating on the aluminum foil) from reaching its melting point. Similar conclusions were reported by Mihindukulasuriya and Lim, who observed that inadequate holding time results in lower seal strength due to incomplete heat transfer. Research on multilayer films also shows that optimal sealing strength is achieved only when the heat exposure time is sufficient for the sealant layer to soften and bond evenly across the sealing surface.

3.2 Physical Leakage

In terms of physical leakage, treatments P1 and P2 showed no leakage (coded as 1), whereas P3 exhibited leakage (coded as 2). The absence of leakage in P1 and P2 suggests that the thermal energy generated at lower speeds (10–15 rpm) was adequate to ensure a complete and uniform seal. Meanwhile, physical leakage in P3 indicates that the sealing process was insufficient due to the higher speed (20 rpm), which reduced the induction heating time and inhibited optimal bonding. These results highlight that excessive conveyor speed may compromise sealing strength, increasing the risk of mechanical failure during handling or transportation.

Physical leakage in this study was influenced by the duration of the sealing process, which was determined by the induction sealing speed. Treatment P3 (20 rpm) resulted in leakage due to insufficient heating time, which led to incomplete polymer melting and fusion. This observation is consistent with [10], who emphasized that successful heat sealing depends on adequate heat, pressure, and dwell time to achieve strong adhesion between the sealing layers. In contrast, treatments P1 and P2, which had longer sealing times, allowed more effective heat transfer and polymer fusion, producing a more homogeneous seal and preventing physical leakage. dditional reinforcement of this finding is supported by the principles outlined in [11], which describe that insufficient sealing energy often leads to weak seal formation, incomplete bonding, and increased susceptibility to mechanical failure. The study highlights that when the heat exposure is too low or the sealing duration is shortened, the polymer layer fails to reach its optimal melting state, resulting in voids, micro-leaks, and non-uniform seal morphology—all of which contribute to physical leakage.

3.3 Vacuum Leakage

Vacuum leakage data also support the trend observed in physical leakage. Treatments P1 and P2 recorded lower leakage levels (1 and 1.67), demonstrating strong vacuum integrity. In contrast, treatment P3 showed the highest leakage score (2), indicating compromised seal performance under pressure differentials. The presence of air bubbles during vacuum testing suggests that micro-gaps or incomplete fusion occurred at the bottle–foil interface. This reinforces the conclusion that sealing speed notably influences the overall sealing integrity, with P3 failing to achieve sufficient thermal bonding to maintain vacuum resistance.

These findings are strongly supported by [12], who explains that effective seal formation requires sufficient conductive and electromagnetic heat transfer to soften and melt the sealant layer uniformly. When the heating duration is too short, the polymer layer does not reach the required melt flow state, leading to micro-gaps, uneven fusion, and reduced sealing strength. Under vacuum conditions, these weak points become failure sites where air can escape, which corresponds with the presence of air bubbles observed during the vacuum test in P3. Seals produced under insufficient thermal energy often fail under stress-induced deformation or rapid pressure changes—mechanisms that clearly align with the leakage behavior detected in this study. The stronger performance of P1 and P2 can be attributed to their longer effective sealing times, which allowed better heat penetration, more uniform melting, and improved wetting of the bottle surface by the sealant layer. Extended heating provides the necessary conditions for achieving interfacial diffusion and polymer chain entanglement, both of which contribute to the formation of a seal resistant to vacuum-induced stress.

3.4 Aluminum Foil Condition

The condition of the aluminum foil across treatments shows that P1 and P2 maintained a consistent rating of 3 (paper detached), while P3 recorded a higher value (3.67), indicating partial adhesion of the paper layer to the bottle neck. Foil adhesion defects in P3 are likely caused by insufficient heat penetration, preventing complete separation of the paper layer from the laminate. This further supports the interpretation that the sealing energy at 20 rpm was inadequate. A proper foil condition where the paper layer detaches cleanly—is an essential indicator of optimal sealing temperature and uniform polymer melt. Therefore, the condition observed in P3 confirms suboptimal sealing performance at the highest speed.

In addition to the leakage results, the condition of the aluminum foil also provides important evidence regarding seal integrity at different induction sealing speeds. Treatments P1 and P2 consistently showed a foil condition score of 3, indicating clean paper detachment after sealing, which suggests adequate heat penetration and uniform polymer melt. By contrast, treatment P3 exhibited a higher score (3.67), characterized by partial adhesion of the paper layer to the bottle neck. This defect reflects insufficient thermal activation of the heat-seal laminate, preventing complete separation of the paper backing from the polymer layer. Similar observations have been reported in studies on heat-seal performance, where incomplete melting and non-uniform heat transfer generate weak interfacial bonding and poor laminate release [9]. Furthermore, Marsh & Bugusu (2007) highlighted that inadequate sealing temperature or dwell time results in the formation of heterogeneous seal zones, often manifested as partial paper adhesion or tearing during post-seal evaluation [13]. Therefore, the foil condition observed in P3 reinforces the conclusion that sealing at 20 rpm did not deliver sufficient heat energy to promote uniform polymer flow and proper laminate separation, ultimately confirming the suboptimal sealing performance at the highest speed

4 Conclusion

This study demonstrated that different induction sealing speeds significantly affected the leakage level of HDPE milk bottles sealed with aluminum foil. The results showed that lower sealing speeds, particularly 10 rpm, produced the strongest sealing performance with no leakage, optimal vacuum resistance, and proper foil adhesion, whereas 20 rpm resulted in incomplete sealing and higher leakage. These findings confirm the research aim by identifying the optimal sealing speed required to minimize leakage and ensure packaging integrity for Tefa Milk products. In a broader context, reliable sealing is essential for maintaining food safety, especially as rising temperatures associated with climate change increase the risk of milk spoilage and contamination. Therefore, optimizing sealing conditions contributes to both product quality and the reduction of food waste.

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