

REGULAR ARTICLE

SHELF LIFE EVALUATION OF APPLE FLAVOR BEVERAGE USING ACCELERATED SHELF LIFE TESTING (ASLT) ARRHENIUS MODEL AT PT. XYZ*Isma Roudhotun Nadhiroh^{1*}, Jariyah², Muhammad Rosyid Wardianto³***Address:**^{1,2,3} Departement of Food Technology, Faculty of Engineering and Science, Universitas Pembangunan Nasional "Veteran" Jawa Timur, Surabaya 60294. East Java.

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ABSTRACT

Indonesia's fruit-flavored beverage industry has grown rapidly in response to increasing consumer demand for practical, hygienic, and long-lasting packaged drinks, yet many shelf life claims printed on product labels remain scientifically unverified. PT. XYZ was selected as the object of this study because its apple flavored beverage, marketed under the "Siipiah" brand, carries a 12-month label expiration date while the company applies a 9-month product return policy, creating a 3-month discrepancy that requires scientific justification. This study aimed to estimate the shelf life of PT. XYZ's apple flavored beverage using the Accelerated Shelf Life Testing (ASLT) Arrhenius method based on three physicochemical quality parameters, namely pH, total soluble solids (TSS, °Brix), and total titratable acidity (TTA, %), and to evaluate whether the company's 9-month return policy is scientifically justified relative to the 12-month label claim. Samples were stored at three temperatures (25°C, 30°C, and 40°C) and analyzed weekly for four weeks. Results showed that all three parameters followed first-order reaction kinetics. The activation energy (E_a) was highest for pH (7,295.5 kcal/mol), followed by TSS (7,195.1 kcal/mol) and TTA (3,925.4 kcal/mol), indicating pH as the most temperature-sensitive quality parameter. At 30°C, representing the maximum normal distribution temperature under tropical conditions, the estimated shelf life based on pH and TTA was 12 months, while TSS yielded 16 months. These findings confirm that the 12-month label claim is scientifically valid and that the 9-month return policy provides a justified 3-month safety buffer to accommodate temperature variability during distribution.

Keywords: apple flavored drink, Arrhenius, ASLT, return policy, shelf life**INTRODUCTION**

Indonesia's fruit-flavored beverage industry has experienced rapid growth driven by rising consumer demand for practical, hygienic, and long-lasting packaged drinks. The ability to maintain product quality throughout the distribution chain is a major challenge, especially given the diverse geographic conditions and environmental temperatures across the country (Jaelani *et al.*, 2025). PT. XYZ is one company that produces apple flavored beverages marketed under the "Siipiah" brand, with a labeled shelf life of 12 months from the date of production. A discrepancy exists between the 12-month expiry claim on the label and the company's 9-month product return policy, whereby products are withdrawn from distribution 3 months before the labeled expiry date. This gap raises the question of whether the 12-month label claim is scientifically valid and whether the 9-month return policy is justified based on actual product quality data.

The discrepancy between the labeled shelf life and the company's distribution policy highlights the need for a more comprehensive scientific evaluation. It remains unclear whether the 9-month return policy is based on evidence of product quality deterioration before the labeled expiry date or is merely a preventive strategy for inventory management and distribution efficiency. Investigating the actual shelf life of the product is therefore essential to verify the accuracy of the expiration date, ensure that quality is maintained throughout the distribution chain, and provide consumers with reliable product information. Such an evaluation can also serve as a scientific basis for optimizing the company's shelf life labeling and product return policy.

Indonesian food regulations, including Law No. 18 of 2012 on Food and Government Regulation No. 69 of 1999 on Food Labels, require that expiration dates be based on validated scientific testing rather than estimation. The most efficient method for rapid shelf life determination is the Accelerated Shelf Life Testing (ASLT) approach using the Arrhenius model, which accelerates quality degradation through elevated storage temperatures and extrapolates the results mathematically to normal distribution conditions (Anggraini *et al.*,

2019). The objective of this study was to evaluate the shelf life of apple flavored beverages produced by PT. XYZ using the ASLT Arrhenius method, based on changes in pH, total soluble solids (TSS), and total titratable acidity (TTA), and to assess the alignment between the 12-month label claim and the 9-month return policy using actual shelf life data.

MATERIAL AND METHODS

Material

Apple flavored beverage samples (Siipah brand, formulated with water, refined sugar, and stabilizers, packaged in 120 mL polypropylene (PP) cups) were obtained directly from the production line at PT. XYZ, located in Batu City, East Java, Indonesia. All samples were collected from the same production batch to ensure uniformity of the initial quality characteristics prior to storage.

Methods

The Accelerated Shelf Life Testing (ASLT) method was conducted by storing apple flavored beverage samples at three accelerated temperatures: 25°C (refrigerated), 30°C (ambient), and 40°C (incubator) for 4 weeks, with physicochemical analyses performed at weekly intervals (weeks 0, 1, 2, 3, and 4). These storage conditions were selected to simulate distribution environments ranging from controlled storage to elevated temperatures that may occur during transportation. Three quality parameters were evaluated, namely pH, measured using a calibrated digital pH meter; total soluble solids (TSS, °Brix), determined using a hand refractometer; and total titratable acidity (TTA), determined by titration with 0.1 N NaOH and expressed as percentage acid equivalent. All measurements were performed in triplicate at each sampling interval.

For each quality parameter, the mean value was plotted against storage time (weeks) to determine the reaction order. A zero-order plot was constructed with storage time (weeks) on the x-axis and the mean decrease in the quality value on the y-axis, while a first-order plot was constructed with storage time (weeks) on the x-axis and the natural logarithm (ln) of the mean decrease in the quality value on the y-axis. From each plot, a linear regression equation of the form $y = a + bx$ was derived, together with its coefficient of determination (R^2). The reaction order for each quality parameter was determined by comparing the R^2 values of the zero-order and first-order kinetic models, with the model exhibiting the higher R^2 selected as the best fit (Li *et al.*, 2025). The gradient (slope) of the regression line corresponding to the selected order was then used as the reaction rate constant (k) for each storage temperature.

Shelf Life Calculation

The reaction order was determined by plotting the mean value of each quality parameter (pH, TSS, and TTA) during storage on the y-axis, and storage time (weeks) on the x-axis, at three different storage temperatures. Linear regression (Equation 1) and non-linear regression (Equation 2) analyses were used to determine the reaction order of each quality parameter of the apple flavored beverage (Li *et al.*, 2025).

$$C_t = C_0 - kt \quad [1]$$

$$\ln C_t = \ln C_0 - kt \quad [2]$$

Once the reaction order was determined based on the highest R^2 value, the slope of the linear or non-linear regression equation was obtained for each quality parameter observed. This slope value represented the reaction rate constant (k). To determine the effect of temperature on the reaction rate, the $\ln k$ values were plotted against $1/T$ (K^{-1}), resulting in Equation 3:

$$\ln k = \ln k_0 - (E_a/R)(1/T) \quad [3]$$

The intercept of Equation 3 represented the value of $\ln k_0$, while the slope represented the value of E_a/R . The activation energy (E_a) for each quality parameter observed was calculated by multiplying the slope value by the ideal gas constant (R), which is 1.986 cal/mol.K. The k_0 value obtained from the intercept of Equation 3 was substituted into the Arrhenius equation (Equation 4):

$$k = k_0 \cdot e^{-E_a/RT} \quad [4]$$

From the Arrhenius equation, the reaction rate constant (k) at any given storage temperature (T) could be calculated. The shelf life of the apple flavored beverage under each storage temperature treatment was then estimated using Equation 5, if the parameter followed zero-order kinetics, or Equation 6, if the parameter followed first-order kinetics:

$$t = \frac{(C_0 - C_t)}{k} \quad [5]$$

$$t = \frac{(\ln C_0 - \ln C_t)}{k} \quad [6]$$

The quality parameter yielding the shortest predicted shelf life was identified as the critical parameter determining the overall shelf life of the product (Fikry *et al.*, 2026).

RESULTS AND DISCUSSION

pH

pH monitoring is one of the key parameters in the Accelerated Shelf Life Testing (ASLT) method, as it reflects changes in product quality during storage. The pH value represents the level of acidity of the product, which is closely related to the chemical and microbiological stability of the apple flavored beverage throughout its shelf life. The results of pH measurements for the apple flavored beverage over four weeks are presented in Figure 1.

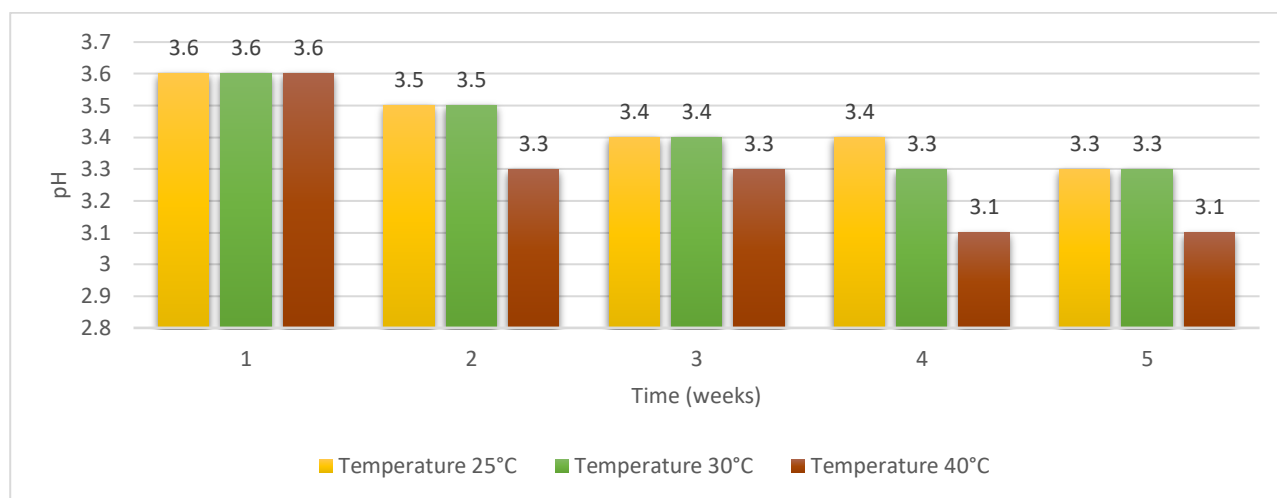


Figure 1 pH of apple flavored beverage at different storage temperatures and times

All samples began with the same pH value of 3.6 at Week 0, then experienced a consistent decline as storage time progressed across all three temperature treatments. The most pronounced pH decrease occurred at 40°C, where pH dropped from 3.6 to 3.1 by Week 3, compared to storage at 25°C, which only reached 3.3 by Week 4. This pattern indicates that higher storage temperatures significantly accelerate the rate of pH decline.

According to Prayitno *et al.* (2025), storage at elevated temperatures accelerates reactions within food materials, thereby increasing the migration of substances that degrade food quality. This is consistent with the observed results, in which the 40°C treatment consistently showed the fastest rate of pH decline compared to 25°C and 30°C. This pH decline phenomenon is in line with the findings of Li *et al.* (2016), who reported that pH decline in fruit beverages during storage is primarily driven by the degradation of ascorbic acid into intermediate compounds that shift the acid-base equilibrium of the product. The higher the storage temperature, the faster these reactions proceed, resulting in a more rapid pH decrease.

In addition to ascorbic acid degradation, the decline in pH may also be attributed to an increase in lactic acid produced through the metabolic activity of *Lactic Acid Bacteria* (LAB) over the storage period. Lactic acid generated from carbohydrate metabolism lowers the pH of its growth environment and produces a sour taste (Pratiwi *et al.*, 2025). This indicates that the pH changes observed during storage are not solely the result of non-microbiological chemical reactions, but may also be influenced by the activity of residual microorganisms still capable of metabolizing under the acidic pH conditions of the apple flavored beverage. Overall, these findings confirm that storage temperature is a critical factor affecting pH stability, consistent with the conclusion that elevated temperatures during distribution represent a critical risk factor for pH-based quality degradation.

Total Soluble Solid (TSS)

Total soluble solid serves as an important quality indicator in beverage products because it primarily reflects the sugar content responsible for sweetness, one of the key sensory attributes consumers use to judge product acceptability. Beyond its sensory relevance, changes in total soluble solid during storage can also indicate underlying chemical degradation processes occurring within the product, making it a useful parameter

for tracking quality loss over time. The results of total soluble solid measurements for the apple flavored beverage over four weeks are presented in Figure 2.

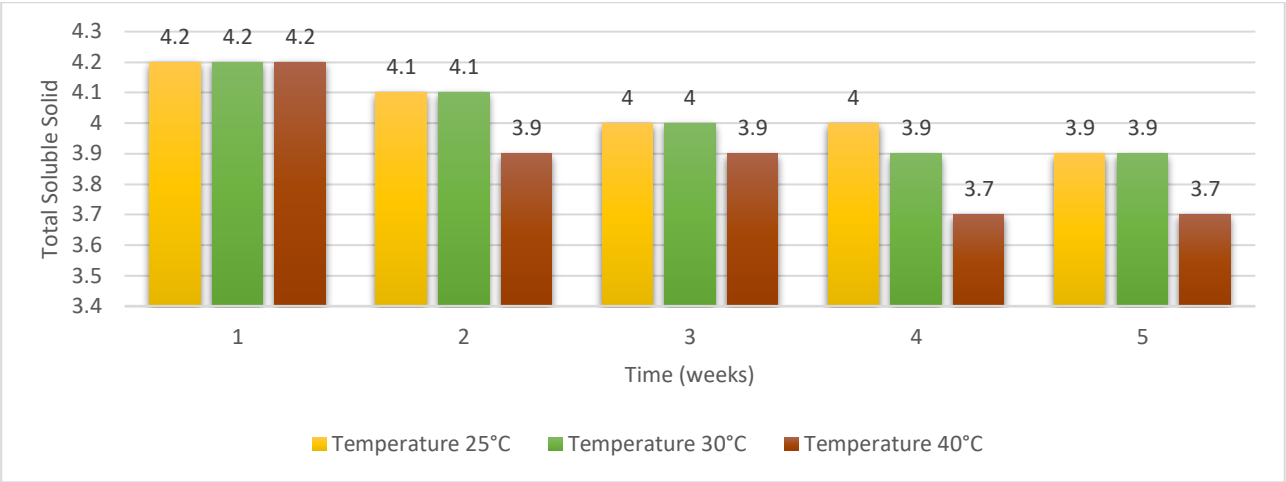


Figure 2 Total soluble solids (°Brix) of apple flavored beverage at different storage temperatures and times

All treatments began at an identical total soluble solid value of 4.2 at Week 0 and exhibited a consistent downward trend throughout the four week storage period. The rate of decline, however, was not uniform across treatments: samples subjected to more intense thermal exposure showed an earlier and steeper drop, with a noticeable reduction already evident by Week 1, whereas the decline in less severely stressed samples remained more gradual and only became comparably pronounced toward the end of the storage period. This divergence in decline rate indicates that the underlying degradation reactions are thermally accelerated rather than time dependent alone.

The reduction in total soluble solid is attributed to the hydrolysis of sucrose into glucose and fructose (invert sugar), a reaction that alters the refractive properties of the solution and is subsequently followed by Maillard reactions between reducing sugars and amino acids. Potential fermentation by residual microorganisms that consume sugar as an energy source may further contribute to the depletion of soluble solid over the storage period. These findings align with **Fang et al. (2020)**, who also reported a consistent decline in total soluble solid in commercially produced apple flavored beverages stored under multiple thermal conditions, linking this phenomenon to the acceleration of saccharide decomposition reactions driven by elevated storage temperature.

Total Titratable Acidity (TTA)

TTA monitoring is another essential parameter in the Accelerated Shelf Life Testing (ASLT) method, as it captures the accumulation of organic acids that occurs as a product undergoes chemical and microbiological degradation during storage. Unlike pH and total soluble solid, which decreased over time, TTA values showed an upward trend, reflecting the progressive formation of free acids as the product's quality declines. The results of TTA measurements for the apple flavored beverage over four weeks are presented in Table 1.

Table 1 Total titratable acidity (TTA, %) of apple flavored beverage at different storage temperatures and times

Storage Time (Week)	Temperature		
	25°C	30°C	40°C
0	0.0067	0.0067	0.0067
1	0.0074	0.0074	0.0080
2	0.0080	0.0074	0.0101
3	0.0080	0.0094	0.0101
4	0.0094	0.0094	0.0101

All treatments began at an identical TTA value of 0.0067% at Week 0 and exhibited a consistent upward trend throughout the four week storage period. The rate of increase, however, was not uniform across

treatments: samples subjected to more intense thermal exposure reached higher TTA values earlier in the storage period, plateauing at 0.0101% by Week 2, whereas the increase in less severely stressed samples proceeded more gradually and only approached comparable levels toward the end of storage. This divergence indicates that the mechanisms driving acid accumulation are accelerated by thermal stress rather than progressing at a fixed rate over time.

The increase in TTA reflects the accumulation of free organic acids as products of oxidation reactions, including ascorbic acid degradation and decomposition of other organic compounds during storage. In addition, the rise in TTA is closely associated with increasing yeast activity, as these microorganisms metabolize sucrose and other carbon sources through fermentation, producing organic acids such as acetic acid as byproducts, particularly under osmotic stress conditions (Mendes & Mendes, 2020). The faster accumulation observed under more intense thermal exposure confirms that elevated temperatures accelerate acid formation reactions, directly influencing the beverage's flavor stability.

Reaction Order and Arrhenius Parameters

Determination of reaction order aims to identify the kinetic model that most accurately describes the pattern of quality change in a product during storage, so that the resulting equation can be reliably used to predict shelf life. This is done by comparing the coefficient of determination (R^2) of the zero-order model, which assumes that the increase or decrease in a quality parameter progresses linearly with time, against the first-order model, which assumes that the rate of quality change is proportional to the amount of the parameter remaining at a given time (Le et al., 2025). The model exhibiting the higher R^2 value is selected as the best-fitting kinetic model, since an R^2 closer to 1 indicates a stronger goodness of fit between the observed data and the linear regression line, making the resulting equation more valid for predicting quality changes under other storage conditions (Li et al., 2025).

Table 2 summarizes the reaction order analysis for each parameter. All three quality parameters followed first-order reaction kinetics at all storage temperatures, as the R^2 values for the first-order models were consistently higher than those for the zero-order models.

Table 2 Reaction order and regression parameters for quality indicators of apple flavored beverage

Parameter	Temperature (°C)	Order 0		Order 1		Selected Order
		Slope (k)	R ²	Slope (k)	R ²	
pH	25°C	0,07	0,9423	0,0203	0,9442	1st
	30°C	0,08	0,9412	0,0233	0,9431	
	40°C	0,12	0,8571	0,0362	0,8659	
TSS	25°C	0,07	0,9423	0,0173	0,944	1st
	30°C	0,08	0,9412	0,0198	0,9424	
	40°C	0,12	0,8571	0,0306	0,8646	
TTA	25°C	0,0006	0,9091	0,0755	0,9233	1st
	30°C	0,0007	0,8676	0,0916	0,8785	
	40°C	0,0009	0,7985	0,1054	0,7937	

First-order kinetics indicate that the rate of quality decline is proportional to the remaining quality level at any given time the closer the product approaches its critical limit, the slower the absolute rate of decline. This kinetic behavior is typical for beverage products undergoing chemical changes such as pH reduction from organic acid accumulation and oxidation of phenolic compounds (Adebo et al., 2021). The R^2 values ranged from 0.79 to 0.94 for first order models, indicating an acceptable model fit, though the lower R^2 observed at 40°C reflects the more complex simultaneous degradation reactions occurring under extreme thermal conditions.

To evaluate the effect of temperature on the reaction rate constant (k) of each quality parameter, the ln k values obtained at each storage temperature were plotted against 1/T, from which the Arrhenius equation and activation energy (Ea) for each parameter were derived. Table 3 presents the Arrhenius equations and activation energy (Ea) values for each parameter.

Table 3 Arrhenius equations and activation energy (Ea) for quality parameters of apple flavored beverage

Parameter	Arrhenius Equation	-Ea/R	Ea (kcal/mol)
pH	y= -367,5x + 8.04042	-3673.5	7,295.5
TSS	y= -3623x + 8.07460	-3623	7,195.1
TTA	y= -1976.6x + 4.0823	-1976.6	3,925.4

The activation energy for pH was the highest (7,295.5 kcal/mol), followed by total soluble solid (7,195.1 kcal/mol) and TTA (3,925.4 kcal/mol). A higher Ea value indicates greater sensitivity of the reaction to temperature change. Therefore, pH degradation in this product is the most temperature dependent quality

parameter. The relatively lower E_a of TTA suggests that acid accumulation is less inhibited by moderate temperature increases, though it still occurs at a faster absolute rate, as reflected by its consistently higher k values across all temperatures Table 4.

Table 4 Rate constants (k) for quality parameters of apple-flavored beverage at each storage temperature

Parameter	K at 25°C	K at 30°C	K at 40°C
pH	0.019782	0.024245	0.035714
TSS	0.016855	0.020599	0.030183
TTA	0.078036	0.087062	0.107237

Shelf Life Estimation

Following the determination of the reaction rate constant (k) and activation energy (E_a) for each quality parameter, the Arrhenius equation was subsequently used to estimate the shelf life of the apple flavored beverage at each storage temperature. Table 5 summarizes the estimated shelf life for each parameter at each storage temperature.

Table 5 Estimated shelf life of apple flavored beverage based on three quality parameters at three storage temperatures

Parameter	Temp (°C)	t (weeks)	t (months)	Label Claim (months)
pH	25°C	59	14	12
	30°C	48	12	
	40°C	30	7	
Brix	25°C	79	19	12
	30°C	65	16	
	40°C	42	10	
TTA	25°C	55	13	12
	30°C	49	12	
	40°C	38	9	

At 30°C, representing the maximum likely distribution temperature in tropical Indonesia, the estimated shelf life based on the most conservative parameters pH and TTA was 12-months (48 and 49 weeks respectively). This directly validates the 12 month label claim printed on the product packaging. Total soluble solid yielded a longer estimate of 16 months, confirming it is not the critical limiting parameter under these conditions.

According to **Fikry et al. (2026)**, the shelf life of a product should be determined by the parameter that reaches its critical limit first. In this study, that parameter is pH and TTA at 30°C, both converging on 12 months as the scientifically supportable shelf life under normal distribution conditions. At 25°C (ideal controlled storage), estimated shelf life extends to 13-14 months, indicating a modest safety buffer under optimal conditions. These results are consistent with **Calligaris et al. (2024)**, who demonstrated that ASLT Arrhenius outcomes are highly sensitive to the selection of the critical parameter and storage temperature in the estimation.

Evaluation of the 9 Month Return Policy

With a validated shelf life of 12 months at 30°C, the company's 9 month return policy results in a 3-month safety buffer. This gap is scientifically defensible and serves multiple quality management functions.

First, the buffer compensates for temperature uncertainty during distribution. At 40°C representing extreme exposure during transport in non refrigerated vehicles or outdoor storage in hot weather the estimated shelf life drops to only 7 months for pH and 9 months for TTA. Products that experience prolonged high temperature exposure during distribution could approach their critical quality limits even before the 9-month return deadline. **De Bouillé and Beeren (2016)** demonstrated that for a similar product category, a temperature difference of just 10°C (from 30°C to 40°C) resulted in a shelf life reduction of nearly half. This confirms that the 3-month buffer is a practical and necessary safety margin.

Second, the return policy aligns with common supply chain quality practices. In fast moving consumer goods (FMCG) distribution, a sell-by or best-before date set well before the label expiration is standard practice to ensure consumers receive products with adequate remaining shelf life (**Kuzminskiy et al., 2020**). **Wallace et al. (2018)** noted that this conservative approach is recommended by food safety regulations as a buffer against storage condition variability. Furthermore, **Akkas and Honhon (2023)** demonstrated that setting

maximum shipping age requirements can reduce food waste by up to 14.7% and increase profitability by approximately 8.7% across the supply chain.

Third, the policy protects consumer experience and brand reputation. Products consumed close to their expiration date may already show perceptible changes in flavor, color, or aroma due to accumulated pH decline and acid build up, even if they remain technically within label limits. **Llorente et al. (2024)** emphasized that shelf life encompasses not only safety aspects but also sensory characteristics, and that when these sensory values are compromised, consumer purchasing decisions are significantly affected. By returning and withdrawing products at 9 months, the company ensures that consumers receive the beverage at an acceptably fresh quality level throughout its commercial life.

CONCLUSION

The shelf life of apple flavored beverages from PT. XYZ was estimated using the ASLT Arrhenius method, based on pH, total soluble solids, and TTA. The shortest predicted shelf life of 12 months at 30°C is supported by scientific data, while it drops to 7–9 months at 40°C. The 9-month return policy offers a 3-month safety margin, ensuring product quality during distribution and supporting the company's current labeling practices.

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