



(RESEARCH ARTICLE)



## Mathematical modeling of beer fermentation with grape seed enrichment

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### Abstract

This article presents a comprehensive study on the biochemical kinetics of beer fermentation, specifically comparing standard beer with beer enriched with grape seed pomace. Utilizing differential equations, the research employs a logistic model to quantify alcohol growth and first-order kinetics to model extract reduction. The fermentation process was monitored over a five-day period, collecting experimental data on alcohol concentration, original and real extracts, and bioactive compound accumulation. The results indicate that the addition of grape seed pomace significantly accelerates the fermentation process. The growth rate constant ( $k$ ) was found to be approximately 60% higher in the enriched samples compared to the control group. Furthermore, the lag phase was reduced by nearly half, decreasing from 3.31 days to 1.67 days. The enriched beer also demonstrated a superior nutritional profile, characterized by enhanced polyphenol content and increased antioxidant activity. The mathematical models showed high reliability, validating their use for process optimization. The study concludes that grape seed enrichment offers a viable strategy for developing functional beverages while optimizing production efficiency.

**Keywords:** Beer Fermentation; Grape Pomace; Mathematical Modeling; Logistic Model; Polyphenols; Antioxidant Activity

### 1. Introduction

The modern brewing industry is increasingly focusing on two pivotal areas: the development of functional beverages that offer health benefits beyond basic nutrition, and the implementation of sustainable practices through the circular economy. In this context, the utilization of byproducts from the wine industry, such as grape pomace, represents a significant opportunity. Grape pomace is rich in bioactive compounds, including polyphenols and antioxidants, which can enhance the nutritional profile of beer.

Recent research has begun to explore this potential [1] demonstrated the application of white grape pomace in brewing technology, highlighting its impact on the chemical composition of the final product. Similarly, [3] investigated craft beer production using immobilized yeast cells with grape pomace seed powder, noting improvements in fermentation stability. Further studies by [2] and [4] have reinforced the viability of incorporating purple grape pomace into craft beers, reviewing the transition of bioactive compounds from the vineyard to the brewery.

However, despite these advances, there remains a significant gap in the literature regarding the mathematical quantification of these processes. While the chemical effects are becoming better understood, the specific kinetic changes induced by grape seed enrichment have not been adequately modeled. The goal of this study is to develop and validate differential equation models that accurately describe the fermentation kinetics, specifically alcohol growth and extract reduction, to optimize the brewing process for functional beverages.

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## 2. Materials and methods

### 2.1. Experimental Data

The fermentation process was monitored over a five-day period under controlled laboratory conditions. Samples were collected daily to measure key physicochemical parameters. Alcohol content (v/v %) was determined using distillation methods, while original extract, real extract, and apparent extract were measured to track the consumption of sugars. The fermentation rate was calculated as a percentage of attenuation. Additionally, diacetyl levels were monitored as an indicator of beer maturation quality.

To assess the functional properties of the beer, bioactive compounds were analyzed. Total polyphenol content was measured using spectrophotometric methods, and antioxidant activity was quantified using the Ferric Reducing Antioxidant Power (FRAP) assay. The presence of specific phenolic acids and flavonoids was also recorded to correlate kinetic changes with compositional shifts.

**Mathematical Models.** Two primary differential equations were employed to model the fermentation kinetics. The growth of alcohol concentration over time was modeled using the Logistic Model, which accounts for the carrying capacity of the system:

$$DA/dt = k \cdot A \cdot (1 - A/A_{max})$$

Where A represents the alcohol concentration at time t, k is the specific growth rate constant, and A<sub>max</sub> is the maximum potential alcohol concentration. To model the consumption of substrate, First-order kinetics were applied to the reduction of extract:

$$DE/dt = -r \cdot E$$

Where E is the extract concentration and r are the reaction rate constant. Parameter estimation was performed using the non-linear least squares method via the Python SciPy library.

### 2.2. Statistical Analysis

Model validity was assessed using the coefficient of determination (R<sup>2</sup>). The normality of residuals was tested using the Shapiro-Wilk test to ensure that error terms followed a Gaussian distribution. The Akaike Information Criterion (AIC) was utilized to evaluate model parsimony, preventing overfitting. Comparison between the control and enriched groups was performed using T-tests, with statistical significance defined as p < 0.05.

**Results and discussion.** The experimental data collected over the five-day period revealed distinct differences between the regular and grape seed-enriched beers. The enriched samples demonstrated a more rapid onset of fermentation and a higher final attenuation within the observed window.

**Table 1** Kinetic parameters during 5-day fermentation

Parameter	Day 2	Day 3	Day 4	Day 5
Alcohol (v/v %)	3.84	4.45	4.92	5.18
Real Extract (%)	7.12	6.25	5.40	4.93
Apparent Extract (%)	5.73	4.50	3.65	3.07
Fermentation Rate (%)	55.41	64.20	71.15	75.96

The alcohol concentration steadily increased from 3.84% on Day 2 to 5.18% on Day 5, indicating a robust fermentation. Concurrently, the Real Extract decreased from 7.12% to 4.93%, confirming efficient substrate utilization.

### 2.3. Model Parameters

The application of the logistic model revealed significant kinetic advantages in the enriched beer. For regular beer, the growth rate constant (k) was determined to be 2.06 day<sup>-1</sup>. In contrast, the grape seed-enriched beer exhibited a k value of 3.29 day<sup>-1</sup>, representing a 60% increase in fermentation speed. Furthermore, the lag phase (t<sub>0</sub>) was drastically

reduced. While regular beer required 3.31 days to exit the lag phase effectively, the enriched variant achieved this in only 1.67 days.

The statistical fit of the models was excellent, with  $R^2$  values approaching 1.000 for both alcohol growth and extract reduction curves. The AIC analysis supported the parsimony of the chosen models, yielding a value of -18.2 for the enriched alcohol model, which indicates a high quality of fit relative to the number of parameters used.

#### 2.4. Bioactive Compounds and Physical Characteristics

The addition of grape pomace significantly altered the biochemical profile of the beer (Table 2). The addition of pomace during the boil stage yielded the highest concentrations of bioactive compounds.

**Table 2** Comparison of Bioactive Compounds

Sample Type	Polyphenols (mg/L)	Antioxidant Activity (FRAP mg/L)
Classic Beer (Control)	326	18.04
Pomace Added to Boil	401	22.83
% Increase	23%	27%

Statistical analysis confirmed that these increases were significant ( $p < 0.05$  for polyphenols and  $p < 0.001$  for antioxidant activity). Physically, the enriched beer showed increased sedimentation (up to 3.7% at 25°C) and a reduction in bitterness to 15–16.6 IBU when purple grape pomace was used, suggesting a smoother flavor profile despite the high polyphenol content.

### 3. Results and Discussion

The experimental observations obtained during the five-day fermentation period demonstrated clear kinetic and biochemical differences between the control beer and the beer enriched with grape seed pomace. Monitoring of alcohol formation and extract reduction showed that the enriched system entered the active fermentation stage more rapidly and achieved higher attenuation within the same time frame.

#### 3.1. Fermentation Kinetics

Table 1 summarizes the principal physicochemical indicators measured during the fermentation process. Alcohol concentration increased steadily from 3.84% (v/v) on the second day to 5.18% (v/v) on the fifth day. At the same time, the real extract decreased from 7.12% to 4.93%, confirming the progressive consumption of fermentable sugars by yeast metabolism. The apparent extract followed the same downward trend, decreasing from 5.73% to 3.07%.

The fermentation rate increased from 55.41% on day 2 to 75.96% on day 5, indicating that yeast cells maintained high metabolic activity throughout the monitored period. Such behavior is characteristic of an efficient fermentation system where nutrient availability and environmental conditions support continuous yeast growth and substrate utilization.

#### 3.2. Mathematical Modeling of Alcohol Formation

Application of the logistic growth model provided a quantitative description of alcohol accumulation. The estimated growth rate constant ( $k$ ) for the control beer was  $2.06 \text{ day}^{-1}$ , while the grape seed-enriched sample exhibited a significantly higher value of  $3.29 \text{ day}^{-1}$ . This corresponds to an increase of approximately 60% in the fermentation rate constant.

The lag phase parameter ( $t_0$ ) also showed substantial differences between the systems. The control fermentation required approximately 3.31 days to transition from the lag phase to active growth, whereas the enriched fermentation reached this stage in only 1.67 days. The reduction in lag time suggests that compounds present in grape seed pomace may stimulate yeast metabolism or provide additional micronutrients that accelerate the adaptation of yeast cells to the fermentation environment.

The logistic model produced an excellent statistical fit to the experimental data. The coefficient of determination ( $R^2$ ) approached 0.99–1.00 for alcohol growth curves, indicating that the model accurately describes the observed kinetics.

In addition, Akaike Information Criterion (AIC) values supported the parsimony of the selected model, confirming that the logistic equation provides an optimal balance between explanatory power and parameter simplicity.

### 3.3. Extract Reduction Dynamics

The reduction of extract during fermentation was effectively described using a first-order kinetic model. The gradual decline in extract concentration reflects the enzymatic conversion of fermentable sugars into ethanol and carbon dioxide. The estimated reaction rate constants were higher for the enriched system, further confirming that the presence of grape seed components accelerates substrate utilization.

The improved extract consumption may also be associated with enhanced yeast vitality. Grape seeds contain various micronutrients and phenolic compounds that may act as metabolic stimulants, indirectly influencing yeast activity and fermentation efficiency.

### 3.4. Bioactive Compounds and Functional Properties

One of the most significant advantages of grape pomace enrichment is the improvement in the nutritional and functional properties of the final beverage. Analysis of total polyphenols and antioxidant activity demonstrated a substantial increase in the enriched samples. Polyphenol concentration increased from 326 mg/L in the control beer to 401 mg/L in the enriched beer, representing an increase of approximately 23%.

Similarly, antioxidant activity measured by the FRAP assay increased from 18.04 mg/L to 22.83 mg/L, corresponding to an improvement of nearly 27%. Statistical analysis confirmed that these differences were significant ( $p < 0.05$  for polyphenols and  $p < 0.001$  for antioxidant activity). These findings are consistent with previous studies reporting that grape pomace is a rich source of phenolic compounds capable of enhancing the antioxidant potential of fermented beverages.

### 3.5. Physical Characteristics of the Enriched Beer

In addition to biochemical changes, the enrichment also influenced several physical characteristics of the beer. The presence of grape pomace increased sedimentation levels, reaching approximately 3.7% at 25°C. This phenomenon is likely associated with insoluble plant particles and the formation of polyphenol–protein complexes during fermentation.

Another notable observation was a moderate reduction in bitterness when purple grape pomace was used, with bitterness values ranging between 15 and 16.6 IBU. This effect may result from the interaction of polyphenols with iso-alpha acids, leading to partial masking of bitterness and contributing to a smoother flavor profile.

### 3.6. Overall Interpretation

Taken together, the results demonstrate that grape seed pomace enrichment significantly modifies the kinetics and composition of beer fermentation. The enriched system shows faster fermentation, reduced lag phase, improved substrate utilization, and enhanced functional properties due to increased polyphenol content and antioxidant activity.

These findings highlight the dual technological and nutritional advantages of incorporating winery by-products into brewing processes. From an industrial perspective, the acceleration of fermentation could shorten production cycles and improve process efficiency, while from a consumer perspective the resulting beverage offers increased health-related value.

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## 4. Conclusion

The mathematical modeling of beer fermentation enriched with grape seed demonstrates clear advantages for industrial application. The addition of seeds act as a bio stimulant, significantly accelerating the fermentation process by increasing the growth rate constant by 60% and reducing the lag phase by approximately 50%. These kinetic improvements allow for shorter production cycles and potentially lower energy consumption.

Moreover, the resulting beverage possesses a superior nutritional profile, with significantly higher levels of polyphenols and antioxidant activity. This supports the development of functional beers that appeal to health-conscious consumers. The validated differential equation models serve as robust tools for brewers to predict and control the fermentation process under these enriched conditions. Future research should focus on optimizing the timing and quantity of grape seeds addition to balance sedimentation rates with sensory characteristics.

## **Compliance with ethical standards**

### *Disclosure of conflict of interest*

No conflict-of-interest to be disclosed.

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