An Analysis of Acid-Base Reaction and Fermentation Induced Leavening Agents in in Bread Making

Authors: Sally Liu, Joe Song, May Sun & Yolanda Sun

sallyliu1188@gmail.com
songchengzuo@gmail.com
maysun1999@gmail.com
yolandasun07262@gmail.com

Abstract:

Leavening is used to describe the culinary process in which an agent is added to raise bread during baking. Leavening agents release air bubbles inside the dough, and this creates the fluffy texture of well-raised bread. For example, yeast (*Saccharomyces cerevisiae*) is a common leavening agent used in baking, which produces carbon dioxide (CO_2) during fermentation by converting sugar into CO_2 gas and ethanol (C_2H_5OH) (Miller 523). On the other hand, chemical leavening agents depend on the phenomenon of acid-base reaction to produce CO_2 for leavening in baking (Miller 523). The two popular chemical leavening agents were brought into our attention: baking powder and citric acid and baking soda. In this experiment, we showed equivalent amounts of chemical leavening agents cannot substitute the same amount of yeast as leavening agents, and we discovered baking powder was a slightly better leavening agent compared to citric acid and base mixture, as the mean volume of baking powder leavened bread was 42% less than the volume of bread baked with yeast, while the volume of citric acid and baking soda leavened bread was 46% less than the volume of bread baked with yeast.

Introduction:

Half a century ago, the rise of industrial food production dramatically increased productivity and cut back the cost of commercial baked goods (Cauvain & Clark). Store-bought bread became the more convenient option and is preferred by society over homemade bread. However, due to the pandemic of COVID-19, the option of baking at home has been reinvigorated, and the stock of essential baking ingredients, such as baker's yeast, is regularly depleted in supermarkets as a consequence (Cholowsky).

Yeast is the most used leavening agent in baked products. Yeast metabolize sugar to produce carbon dioxide gas (CO_2), alcohol, flavor compounds, and water continuously during fermentation (Miller 523). This enlarges air bubbles captivated in dough during mixing and ultimately increasing the volume of the dough and improving the texture and taste of the end baked product (Miller 523). The expansion of the dough is described as the leavening process (Miller 523). Other than yeast, there are alternative leavening agents as well. For example, studies have shown baking powder can be just as effective as yeast in the leavening process via chemical leavening reactions (Manthy). Baking powder consists of mostly baking soda, or sodium bicarbonate ($NaHCO_3$), and a small amount of ammonium bicarbonate (NH_4HCO_3) and potassium bicarbonate ($KHCO_3$), as well as a weak acid premixed in proportion by manufacturers. During chemical leavening, only a small amount of CO_2 is produced by NH_4HCO_3 during heating and $KHCO_3$ and baking soda resting in dough, most of the CO_2 is produced by the acid reacting with baking soda (Brodie & Godber). Additionally, online articles have suggested using orange juice, containing citric acid, and baking soda as an alternative leavening agent will also achieve the same leavening effect fermentation by yeast (Huffstetler). In chemical leavening reactions, baking soda determines the amount of CO_2 produced because it supplies CO_2 formation, and the type of acid controls the rate of CO_2 production (Brodie & Godber). Since both chemical leavening agents contain baking soda, if enough acid is added for the complete reaction of baking soda, enough CO_2 should be produced to leaven bread. Here, we want to assess the leavening ability of yeast by fermentation in comparison to chemical leavening agents by acid-base reaction to determine whether the chemical leavening agents can substitute yeast in bread baking. We hypothesized, if using the same proportion of baking powder or acid and base mixture (citric acid and baking soda) can substitute yeast as a leavening

agent, then the volume of bread baked with different leavening agents will be comparatively similar. The leavening efficiency is assessed by comparing the volume (L) of the final bread baked using each leavening agent. The result is statistically analyzed using one-way ANOVA and Tukey-Kramer test by Graphpad Prism 9.

Methods:

In this experiment, each group member baked three different types of bread using the identical bread recipe ("Basic Homemade Bread") but with different types of leavening agents: yeast (bread Y), baking powder (bread BP), and acid-base mixture (bread BA). We used an equal amount of each leavening agent to bake the corresponding bread for an amount-irrelevant comparison between different leavening agents. Every group member calibrated their oven to the actual temperature of 350°F before baking. For bread Y, we used 2 ¼ tsp of dry yeast, for bread BP, we used 2 ¼ tsp of baking powder, and for bread BA, we used 160 mL of orange juice and 1 ⅛ tsp of baking soda. The volume of orange juice was calculated for full reaction of citric acid contained in the juice with baking soda by stoichiometry (refer to Appendix: Sample Calculation A). We measured the length, width, and height for the end baked products. We calculated and collected the volume (L) of each loaf of bread (refer to Appendix: Sample Calculation B). We then calculated the mean volume of each group of bread (refer to Appendix: Sample Calculation C).

Lastly, we used Prism 9 Graphpad software version 9.1.0 (216) to conduct one way-ANOVA statistical test to determine the overall p-value. Before we determine the overall p-value, we used Y=Log(Y) to transform our data to meet the statistical assumptions. We also used

Tukey-Kramer test to assess the p-value between specific groups. Finally, we used the calculated p-value to determine significant mean differences among pairs of treatment groups.

Results:

The mean volume (L) of bread Y, bread BA, and bread BP was 2.86, 1.54, and 1.66, respectively. The mean volume of bread baked with baking powder was 42% smaller than the mean volume of bread baked with yeast. The mean volume of bread baked with citric acid and baking soda was 46% smaller than the mean volume of bread baked with yeast. Statistical analysis was conducted using Graphpad Prism 9, and the data was transformed using Y=Log(Y) to meet statistical assumptions for ANOVA. From a one-way ANOVA test, the p-value was approximately 0.02. Then a Tukey-Kramer test was applied and showed a significant difference between bread Y and bread BA (p-value =0.03).

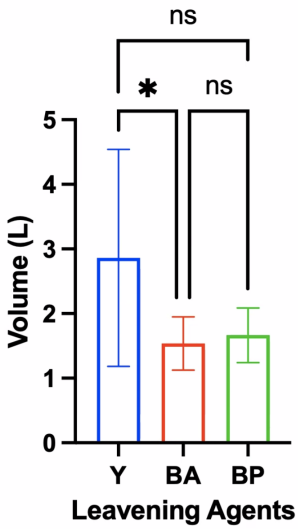

*Figure 1. Volume (L) of bread using different leavening agents with means and 95% confidence intervals shown. Types of leavening agents tested were as follows: (Y) yeast (n=4); (BA) citric acid and baking soda (n=4); (BP) baking powder (n=4). The height of the bar indicated the mean volume (L) of bread using different leavening agents. The error bars represented the 95% confidence interval. * indicated pair of means that was significantly different from each other (Tukey-Kramer method, p <0.05). Statistical analysis by one-way ANOVA by Graphpad Prism 9 (p<0.05).*

Discussion:

In this experiment, we investigated whether chemical leavening agents can substitute yeast as leavening agents for bread making. We hypothesized if the equal proportions of citric acid and baking soda and baking powder can substitute yeast as leavening agents, then the volume of every loaf of bread will be similar. However, the result showed chemical-leavened breads had a 43% reduction of mean volume compared to fermentation-leavened breads, where the volume of bread BP was 42% smaller and the volume of bread BA was 46% smaller than bread Y. The statistical results from one-way ANOVA revealed an overall p-value of 0.02 ($p<0.05$). This implies that there were differences between treatment groups, so we rejected the null hypothesis of there being no significant differences between the mean volume of bread baked with different leavening agents. We also performed Tukey-Kramer test in order to identify the significant difference between pairs of treatment, and the result showed only the mean volume of bread Y and bread BA had a significant difference, with a p-value of 0.03 ($p<0.05$).

According to the Tukey-Kramer test, baking powder could substitute yeast fermentation as a leavening agent for bread making. Similar studies have also shown baking powder leavens baked products to a higher volume than citric acid and base mixture (Manthey). This could be ascribed to the double-acting ability of baking powder. Double acting means having two rounds of CO_2 gas production and thus two stages of the leavening process ("Baking Powder vs. Yeast vs. Baking Soda"). The first stage occurs during the addition of water, and the second stage occurs during the heating process ("Baking Powder vs. Yeast vs. Baking Soda"). When water is combined with baking powder, the monocalcium phosphate ($Ca(HPO_4)$) and sodium bicarbonate ($NaHCO_3$) in baking powder react with water, releasing CO_2 gas ("Baking Powder vs. Yeast vs. Baking Soda"). The second round of CO_2 gas production occurs during the heating process when

water and sodium bicarbonate($NaHCO_3$) react with sodium acid pyrophosphate ($Na_2H_2P_2O_7$) or sodium aluminum sulfate ($NaAl(SO_4)_2 \cdot 12H_2O$), leavening the dough again as it bakes ("Baking Powder vs. Yeast vs. Baking Soda"). This unique property enables bread leavened with baking powder to possess a slightly closer volume to bread leavened using yeast than bread leavened with citric acid and baking soda. Moreover, studies have shown citric acid and baking soda yield the best leavening effect when used in "quick bake recipes", such as pancakes and muffins, which are baked immediately after the combination of ingredients ("Baking Powder vs. Yeast vs. Baking Soda"). This is because baking powder reacts with citric acid as soon as water is added, producing most CO2 gas rapidly at once (Miller 524, 526). This results in products leavened by citric acid and baking powder to be prone to losing more CO2 during long term preparation. In the case of bread making, the process of kneading exacerbates the lost CO2 provides an opportunity for CO2 to escape the dough as we press the air bubbles out of the dough. This weakens the leavening efficiency since citric acid and baking powder does not have a second round of CO2 production to compensate for the loss of CO2 escaped.

In addition, yeast is a better leavening agent compared to the chemical leavening agents in general because its leavening process is based on fermentation. During fermentation, yeast metabolizes sugar to produce CO_2 and ethanol continuously, compensating for the loss of CO_2 from kneading (Miller 523). As well, the ethanol produced during the heating process assists the development and strengthening of gluten molecules in dough ("Baking Powder vs. Yeast vs. Baking Soda"). Gluten acts as a key structural component in dough. It is a heterogeneous mixture composed of gliadin and glutenin protein in flour that assembles together when in contact with water((Jekle and Becker 375). A stronger gluten network leads to greater dough extensibility and gas retention property (Jekle and Becker 376). On the other hand, chemical

leavening agents do not provide this strengthening property. In fact, the base in chemical leavening agents increases the pH of dough, which weakens the strength of gluten networks ("What Does Baking Soda Do?"). The biological reaction of yeast and strengthening of gluten improves the performance of leavening efficiency in yeast and sets it apart from the other leavening agents ("Baking Powder vs. Yeast vs. Baking Soda").

Lastly, throughout this experiment, certain improvements could be accomplished to achieve more optimal results. We can reduce the kneading process for the chemical leavened bread to reduce loss of CO2 gas. Additionally, we can increase our sample size to reduce possible sampling errors. Finally, we can increase the precision of measurement using more sophisticated lab equipment than rulers in order to prevent variation in measurements between each member for a more accurate result.

Conclusion:

The volume of bread produced by fermentation was much larger than those produced by chemical leavening agents, and baking powder seemed to be a better leavening agent than citric acid and baking soda. One-way ANOVA test showed there was a significant difference between the volume of each type of bread, suggesting there was a difference in the leavening efficiency of leavening agents. Furthermore, Tukey-Kramer test showed that the significant difference was between bread Y and bread BA. We rejected the null hypothesis that there is no significant difference between the mean volume of bread baked with different leavening agents. Thus, we concluded equal amounts of chemical leavening agents cannot substitute yeast for bread making, and baking powder processes greater leavening efficiency than citric acid and baking soda.

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Appendix:

Sample Calculation:

A.) Calculation of orange juice volume containing citric acid for full reaction with baking soda

$C_6H_8O_7 + 3NaHCO_3(aq) \rightarrow 3CO_2(g) + 3H_2O(l) + Na_3C_6H_5O_9(aq)$

Citric acid content in tropicana orange juice=16.9%=16.9g/L

Acid + base mixture = 0.25oz=7.081g

Baking powder = 7.081/2=3.5435g

The amount of acid to fully react with base:

3.5435g(baking soda)*1mol/89.006g*1mol citric acid/3mol baking soda=0.014 mol

0.014mol citric acid*192.123g/mol=2.7013g citric acid

2.7013g*L/16.9g=0.1598L orange juice=159.8mL = 160mL

B.) Calculation of volume of bread

Cylindrical pan:

$$V = \pi * r^2 * H$$

The height of the bread are 6.3cm (Bread Y), 4.55cm (Bread BA) ,6.1cm (Bread BP)

So the volumes of the bread are:

Bread Y: V = π*r^2*H = 3.14*(10cm)^2*6.3cm=1979cm^3=1979ml=1.98L

Bread BA: V = π*r^2*H = 3.14*(10cm)^2*4.55cm=1429cm^3=1429ml=1.43L

Bread BP: V = π*r^2*H = 3.14*(10cm)^2*6.1cm=1913cm^3=1913ml=1.91L

Squared pan:

$$V = L * W * H$$

Bread Y :V = L*W*H = 10cm*31.5cm*12cm = 3980cm^3 = 3.98L

Bread BP :V = L*W*H = 9.7cm*32.2cm*6cm = 1.87L

Bread BA :V = L*W*H = 9.8cm*31.5cm*5.8cm = 1.79L

C.) Calculation of mean volume of each type of bread

Mean volume of bread Y = (1.92+3.87+1.98+3.67)/4 = 2.86 L

Raw Data:

The volume of bread baked with different leavening agents that are measured in Liters(L). Y(n=4) is baked with active dry yeast. BA(n=4) is baked with sodium bicarbonate and citric acid. BP (n=4) is baked with baking powder.

Y	BA	BP
1.92	1.22	1.47
3.87	1.79	1.87
1.98	1.43	1.91
3.67	1.70	1.40

Transformed volume Y=Log(Y) of each bread measured in Liters(L); Y(n=4), BA (n=4), BP(n=4).

Y	BA	BP
0.283	0.086	0.167
0.588	0.253	0.272
0.297	0.155	0.281
0.565	0.230	0.146

Transformed data (Y=Log(Y)) using One-way ANOVA to obtain the overall p-value of Y(n=4), BA (n=4), and BP(n=4). The overall p-value obtained is less than 0.05, therefore, there is a significant difference among means.

ANOVA summary	
P-Value	0.0234
Significant diff. among means (P < 0.05)?	Yes

Tukey-Kramer test with transformed data (Y=Log(Y)) to compare means of each bread (Y(n=4),BA (n=4), and BP(n=4)) to obtain the p-value. The p-value for Y vs BA is less than 0.05, therefore, there is a significant difference among means. While p-value for Y vs BP and BA vs BP the p-value is greater than 0.05. Thus, there is no significant difference among means.

Tukey-Kramer test	P-Value
Y vs. BA	0.0280

Y vs BP	0.0560
BA vs BP	0.8983