Indonesian Journal of Chemical Science and Technology (IJCST)

State University of Medan, https://jurnal.unimed.ac.id/2012/index.php/aromatika

IJCST-UNIMED 2026, Vol. 09, No. 2 Page; 461 – 470

Received : April 18th, 2026 Accepted : Jun 12th, 2026 Web Published : July 31st, 2026

From Biowaste to Buffering Agent: Chicken Eggshell Filtrate in Controlling pH and Acid–Base Equilibrium Based on Eggshell Thickness

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ABSTRACT

In weak acid tissue culture system, chicken eggshell biowaste containing 95% $CaCO_3$ could serve as an economical and green buffering agent. This study investigates the influence of eggshell filtrate thickness (1 cm, 2 cm and 3 cm) on pH improvement and acid–base balance in acetic acid (vinegar) and citric acid (lime juice) solutions. The filtrate media were prepared by cleaning, drying and crushing eggshells which organize the egg shell in columns with different thickness. Then, each acid solution was applied to the filtrate, using a range of pH values recorded before and after treatment. Filtrate with greater thickness consistently yielded a higher pH, regardless of the samples, and the 3 cm medium produced the highest rise in both samples. This is due to the higher interaction between acid solutions and $CaCO_3$, which allows for neutralization and shifting the chemical equilibrium toward less acidic conditions. The findings confirm that eggshell thickness significantly affects buffering efficiency. Therefore, eggshell-derived filtrate can serve as a sustainable and effective material for pH control in weak acid systems.

Keywords: Chemical equilibrium, Eggshell, Calcium carbonate, Filtration, pH enhancement

1. INTRODUCTION

Water quality is a key factor in ensuring environmental sustainability and protecting human health, especially in areas where water sources are generally acidic. Acidic water which contains dissolved organic substances (humic and fulvic acids), is generally characterized by low pH values, greatly limiting the usability of water in domestic and industrial applications.[1] In addition to natural water sources, weak acid solutions such as acetic acid (vinegar) and citric acid (lime juice) also exhibit low pH values, typically ranging from 2.4–3.4 for vinegar and 2.0–2.6 for lime juice depending on concentration.[4,12] These acidic characteristics require appropriate treatment methods to increase pH and improve water quality. Therefore, the development of effective, low-cost, and environmentally friendly materials for pH control is highly necessary.

The use of biowaste products especially the chicken eggshells which are abundant and underutilized is one of the promising alternatives. Eggshells are mostly constituted by calcium carbonate (CaCO 3), which is an alkaline compound with the ability to neutralize acidic solutions.[5] Moreover, eggshells can be refined into fines or filtration media to increase their reactivity and surface area thereby increasing their effectiveness in chemical reactions.[8] Past research has established that natural filtration systems have a profound effect on the parameters of water quality (pH, total dissolved solids (TDS), and conductivity).[11] Furthermore, , it was demonstrated that the addition of eggshell powder to other natural adsorbents, e.g., zeolite, enhances the level of filtration, with the mass of the adsorbent increasing the effectiveness of the filtration process and the pH leveling.[9]

Eggshells have also been reported extensively to be effective in pH increase in peat water treatment. Peat water in eggshell-based filtration media had a significant pH increase with increased filter thickness and that the eggshell-based filtration media had a significant effect on the pH increase in the water.[6] This observation is guided by the fact that the thicker the filtration media the greater the amount of contact time and contact between the solution and the reactive material.[10] Also, research on eggshell-derived materials has shown that the calcium compounds formed by the processing of eggshells including calcium oxide (CaO) have high reactivity, as they have a porous structure, and their particles are small, which further justifies their use in acid neutralization.[8]

Based on these previous findings, this study aims to investigate the effect of eggshell filtrate thickness (1 cm, 2 cm, and 3 cm) on pH enhancement and acid–base equilibrium in weak acid systems, specifically acetic acid and citric acid solutions. The hypothesis which is given is that with the increase of the thickness of the eggshell filtrate the pH will be higher because of the increase in the availability of CaCO3 and the contact of the solution of acidic nature and the filtration media. The experimental approach consists of the preparation of eggshell filtrate by cleaning, drying, and crushing procedures and then the material is placed in filtration columns of different thickness levels. The media are then treated with acidic solutions and the pH values monitored before and after treatment. The main reaction expected in this system is the neutralization of acid by calcium carbonate.[2,7]

$$CaCO_3\,(s) + 2H^+\,(aq) \rightleftarrows Ca^{2+}\,(aq) + Co_2(aq) + H_2O\,(l)$$

This reaction is coupled with the carbonate equilibrium system in aqueous solution, where carbonate ions (CO_3^{2-}) are progressively protonated to bicarbonate (HCO_3^-) and carbonic acid (H_2CO_3), which then decomposes into CO_2 and H_2O. According to Le Chatelier's principle, the addition of $CaCO_3$ shifts the equilibrium toward product formation by consuming H^+ ions, thereby reducing acidity and increasing pH. The release of CO_2 gas also drives the reaction forward, enhancing the neutralization process.

Based on these findings, the proposed study will apply the use of chicken eggshell filtrate with different thickness (1 cm, 2 cm, and 3 cm) in order to regulate the pH and chemical equilibrium in acidic media. The hypothesis is that an increase in the thickness of the eggshell will lead to an increase in the pH values because the neutralization capacity will be increased. The experimental procedure includes the preparation of eggshell filtrate, its application to acidic samples, and measuring pH variations, and it is anticipated that the equilibrium shifts would be more pronounced with the increase of the quantity of CaCO3.

e-ISSN : 2622-4968, p-ISSN : 2622-1349

2. EXPERIMENTAL

2.1. Chemicals, Equipment and Instrumentation

The chemicals that are used in this experiment are chicken eggshells (calcium carbonate, $CaCO_3$, natural biowaste), a vinegar solution (acetic acid, CH 3COOH, commercial grade), and lemon juice (citric acid, $C_6H_8O_7$ fresh extract). The level of acidity of the solutions before and after treatment was determined using universal pH indicator paper (pH range 114).

The quipment to be used would be plastic containers, polyethylene terephthalate (PET) bottles and used as filtration columns, scissors, and tissue paper as a supportive filter layer. The instrument of measurement was a universal pH indicator and it yields semi-quantitative pH values, depending on the change in color.[11]

2.2. Research Procedure

Chicken eggshells were washed properly to get rid of impurities and dried at room temperature until they were dry. The shells were dried and made into fine powder to augment the surface area and reactivity since the bigger the surface area the more the chemical interaction is efficient.[8] Vinegar (acetic acid) and lemon juice (citric acid) were made into two acidic solutions and the pH values of the solutions were recorded. Weak acids like acetic acid and citric acid have low PH levels because of the presence of hydrogen ions in solution.[2,4]

Filtration devices were constructed using cut plastic bottles with perforated caps to allow liquid flow. Tissue paper was placed inside the column to retain the eggshell powder. The eggshell powder was added into the columns with thickness variations of 1 cm, 2 cm, and 3 cm. Increasing the thickness increases contact time and interaction between the solution and the filtration medium, thus improving treatment efficiency.

The acidic solutions were then emptied into the filtration columns and filtrate collected and its pH measured with the help of a universal pH indicator. The experiment was also repeated with the same thickness variation and on both acid samples and all the results were recorded to be analyzed. Natural filtration was known to affect the water quality parameters and in particular the pH, as a result of the chemical interactions between the solution and the filtration medium. Foam was also formed on the top of the eggshell layer during the filtration process. This is because a reaction of calcium carbonate with the hydrogen ions comes about and the carbon dioxide gas is produced in the form of bubbles or foam.

2.3. Reaction Mechanism

The main reaction occurring during the filtration process is the neutralization of acid by calcium carbonate present in the eggshell.[2,7]

$$CaCO_3\,(s) + 2H^+\,(aq) \rightleftarrows Ca^{2+}\,(aq) + CO_2\,(g) + H_2O\,(l)$$

This reaction reduces the concentration of hydrogen ions in the solution, resulting in an increase in pH and a shift toward less acidic conditions.

e-ISSN : 2622-4968, p-ISSN : 2622-1349

2.4. Experimental Design

The experimental design that was employed in this study has one independent variable, that is, the thickness of the eggshell filtration media (1 cm, 2cm, and 3cm) and one dependent variable, that is, the pH of the solution after filtration. Test samples were two weak acids, namely acetic acid and citric acid.

All the solutions were subjected to identical conditions, and all of them were filtered through the columns of various thicknesses. The obtained results of each variation were compared to assess the influence of the thickness on the change of pH and the neutralization effectiveness. Thickening is supposed to enhance the buffering performance because of increased supply of CaCO 3 and increased time of interaction between the acid and the filtration media.[6,9]

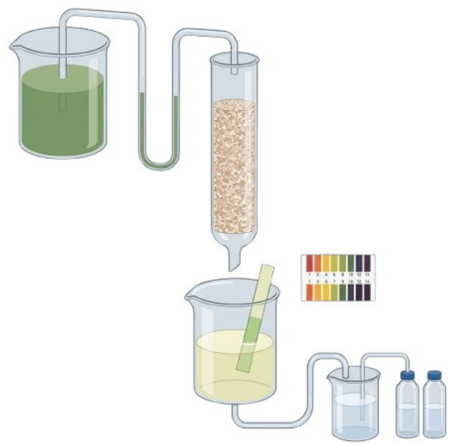

Figure 1. *Simple Eggshell Filtration Process.*

2.5. Chemical Equilibrium and Mathematical Modeling

The filtration process in this study involves both acid–base neutralization and chemical equilibrium phenomena. Weak acids such as acetic acid (CH_3COOH) and citric acid ($C_6H_8O_7$) partially dissociate in aqueous solution according to the following equilibrium reaction:

$$CH_3COOH \rightleftharpoons H^+ + CH_3COO^-$$

The equilibrium of weak acids is characterized by the acid dissociation constant (Ka), which can be expressed mathematically as:

$$Ka = \frac{[H^+][A^-]}{[HA]}$$

Where Ka is the acid dissociation constant, $[H^+]$ is the concentration of hydrogen ions, $[A^-]$ is the concentration of conjugate base, and [HA] is the concentration of the undissociated acid.[2,3] During the filtration process,

e-ISSN : 2622-4968, p-ISSN : 2622-1349

calcium carbonate ($CaCO_3$) reacts with hydrogen ions (H^+), reducing their concentration in the solution. This reaction can be represented as:

$$CaCO_3\,(s) + 2H^+\,(aq) \rightarrow Ca^{2+}\,(aq) + CO_2\,(g) + H_2O\,(l)$$

This reduction in concentration of [H^+] leads to a change in equilibrium in accordance with the principle of Le Chatelier of which the system reacts by creating additional H + ions through the dissociation of the weak acid. Nonetheless, progressive elimination of [H^+] by CaCO3 leads to an overall rise in pH.[2] The pH of the solution is mathematically related to hydrogen ion concentration as:

$$pH = -\log\,[H^+]$$

As the concentration of hydrogen ions decreases due to the neutralization reaction, the pH value increases logarithmically. This explains why even small changes in [H^+] can produce significant changes in pH.Furthermore, the effectiveness of the filtration process can be qualitatively related to the thickness of the eggshell layer. A thicker filtration medium provides a greater amount of $CaCO_3$ and increases the contact time between the solution and the reactive surface. This can be conceptually modeled as:

$$\Delta\, pH \propto m\ CaCO_3 \times t\ contact$$

Where ΔpH represents the change in pH, $m_{(CaCO_3)}$ is the mass of calcium carbonate (related to thickness), and $t_{(contact)}$ is the contact time between the solution and the filtration media.[6,9] This mathematical relationship supports the hypothesis that increasing the thickness of the eggshell filtrate enhances the neutralization process, leading to higher pH values and improved buffering performance.

3. RESULTS AND DISCUSSION

3.1. Analysis of Characterization Results

The identification of acetic acid solution was done by testing the pH of the solution prior to and after filtration procedure through the use of eggshell media of varying thickness. The starting pH is a baseline level of acidity of the solution before treatment and the final pH values are the indicators of the success of the filtration process in decreasing the acidity. Besides this, the pH difference (ΔpH) is also determined to measure the degree of neutralization that takes place in the course of filtration. According to Table 1, there is a constant rise in pH with an increase in the thickness of the filtration media. The pH increases 3 to 6 at 1 cm thickness, which means that a significant fraction of hydrogen ions is neutralized even at the lowest level of thickness. The pH further rises to 7 and 8 respectively as the thickness increases to 2 cm and 3 cm respectively, which shows a gradual decrease in acidity. The gradual change in the ΔpH values between 3 and 5 indicates that the effectiveness of the neutralization process increases with the value of the thickness. Reaction wise, this trend implies that hydrogen ions [H^+] are constantly used up in the process of interacting with the eggshell material. The fatter the thickness, the more reactive material can be used and the reaction can go further and give higher pH values.

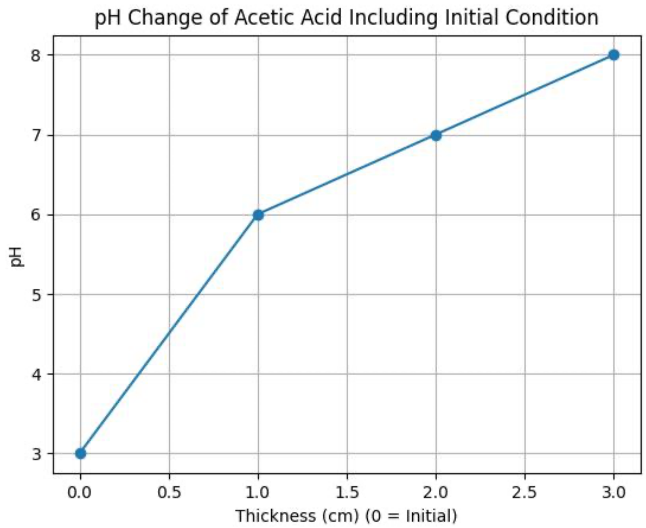

Figure 2. Curve of pH change of acetic acid with eggshell thickness

Table 1. pH values of acetic acid before and after filtration

Thickness (cm)	Initial pH	Final pH	ΔpH
1	3	6	3
2	3	7	4
3	3	8	5

3.1.2. pH Change of Citric Acid (Lime Juice)

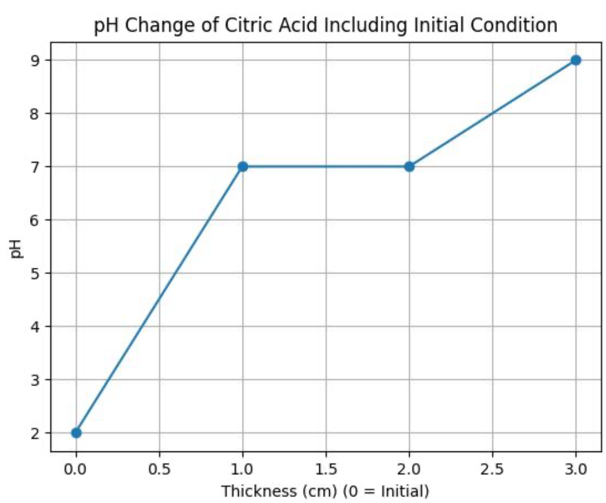

Figure 2. Curve of pH change of citric acid with eggshell thickness

The characterization of citric acid solution was performed using the same approach, where pH values were measured before and after filtration. The initial pH indicates the inherent acidity of the solution, while the final pH reflects the impact of the filtration process. The ΔpH value is used to represent the magnitude of pH change as an indicator of reaction extent. The experimental results are presented in Table 2. Table 2 demonstrates that the pH of citric acid is considerably higher after filtration. The pH value at a depth of 1 cm rises and reaches 7, showing that it is highly neutralized at the first stage. The ΔpH mean of 5 indicates a significant decrease in the concentration of hydrogen ions. The pH at 2 cm of thickness is 7 and this indicates that there is a temporary stabilization in the system where further increase in filtration thickness does not immediately lead to further rise in pH.

Table 2. pH values of citric acid before and after filtration

Thickness (cm)	Initial pH	Final pH	ΔpH
1	2	7	5
2	2	7	5
3	2	9	7

Nevertheless, the pH increases rapidly at the 3 cm thickness to 9 with a ΔpH of 7 which means that the reaction continues to take place as long as additional filtration media is available. Reaction wise, the higher values of ΔpH mean that there is a greater consumption of hydrogen ions. The non-linear pattern indicates that the reaction does not have a constant rate but may have stages whereby the reaction decelerates and later accelerates again. To evaluate the relative effectiveness of eggshell filtration on different acidic solutions, a comparison of ΔpH values between acetic acid and citric acid was conducted. This comparison highlights differences in the response of each solution to the same treatment conditions. The comparative data are presented in Table 3.

Table 3. Comparison of pH changes between acetic acid and citric acid

Thickness (cm)	ΔpH Acetic Acid	ΔpH Citric Acid
1	3	5
2	4	5
3	5	7

The comparison reveals that citric acid always has high 0pH values than acetic acid at all the levels of thickness. Citric acid at the same 1 cm thickness increases much more, which suggests that it responds more initially to the filtration process. Acetic acid keeps on increasing at 2 cm of thickness and citric acid does not show any change, which means that there is a difference in the reaction behavior. At 3 cm of thickness, the changes in both solutions are further increased, however, citric acid has a higher change. All in all, a better increase in pH can be observed in citric acid, whereas acetic acid has a more gradual and consistent pattern. This means that the degree and trend of the response varies according to the nature of the solution being addressed.

3.2 Overall Trend Including Initial Condition

To provide a comprehensive representation of pH changes, including the initial condition, the data from both solutions are combined and presented in Table 4. This allows visualization of the full progression of pH throughout the filtration process.

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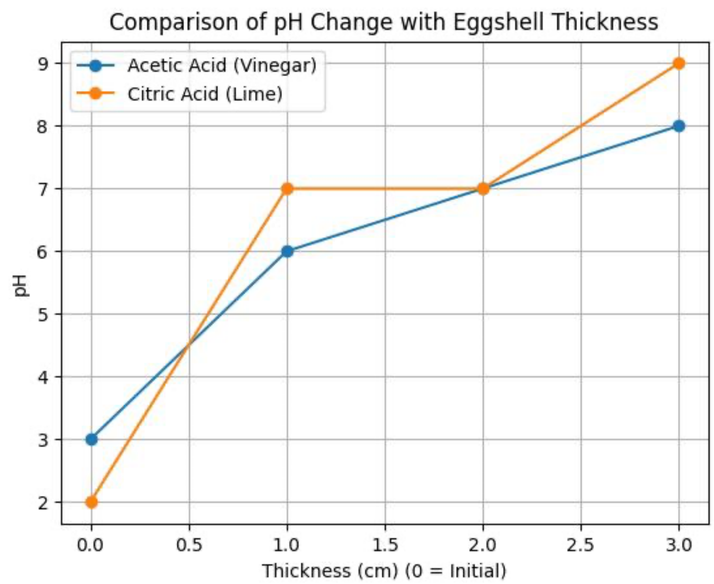

Figure 4. Combined curve of pH change with eggshell thickness

Table 4. *Overall pH values including initial condition*

Thickness (cm)	Acetic Acid pH	Citric Acid pH
0 (Initial)	3	2
1	6	7
2	7	7
3	8	9

The data show that both solutions experience an increase in pH as the thickness increases. However, the rate and pattern of increase differ. Citric acid shows a steeper increase, especially at the initial and final stages, while acetic acid shows a more gradual progression.

3.1.5. *Observation of Reaction Indicators During Filtration*

Visual observations were made during the filtration process in order to detect physical changes that might be used to determine the presence of chemical reactions. The most striking observation was the development of bubbles or foam on the top of the eggshell filtration media. The formation of bubbles indicates that a gas is formed in the process of reaction between the acidic solution and the eggshell substance. This observation facilitates the presence of a chemical reaction in the process of filtration. During the early stages, the formation of foam is more evident as the concentration of the hydrogen ions is greater meaning that the rate of the reaction is greater at this stage.

3.1.6. *Reaction-Based Interpretation of pH Increase*

The pH rise in both solutions can be directly related to the chemical reaction that took place in the course of the filtration process. The reaction of the acidic solution with the eggshell material causes a decline in the concentration of hydrogen ions, and the pH increases.

The magnitude of this reaction is quantified by the values of ΔpH. The presence of larger ΔpH values means that the hydrogen ions were used more and that the reaction was more extensive. The difference in ΔpH at various levels of thickness indicates that the reaction is dependent on the quantity of filtration media and the conditions of interaction. Also, trends between the two solutions are different, which implies that the behavior of the reaction is not the same. The pattern of the reaction of acetic acid is steady and continuous, whereas citric acid demonstrates a more complicated pattern with periods of active growth and subsequent levels. All in all, the findings show that filtration process is a dynamic chemical reaction that decreases acidity and increases pH and the degree of the reaction varies with the thickness of the eggshell media and the type of acidic solution.

4. CONCLUSION

Based on the results, eggshell filtration is effective in increasing the pH of both acetic acid and citric acid solutions. The acidity of the media reduces with the increase in the thickness of the eggshell media, indicating that thicker filtration is more effective at neutralizing.There is a gradual, steady increase in the pH of acetic acid, whereas citric acid increases more significantly but irregularly. It means that the various kinds of acids react differently to the same treatment. In general, eggshells are a low-cost, environmentally-friendly, and simple material that can be used to reduce acidity. The thickness of the eggshell media increases the effectiveness of the eggshell media in increasing pH.

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