Mathematical analysis and modelling of respiration rate of tropical climacteric produces during storage under various temperatures

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**Abstract.** Many tropical agricultural products belong to climacteric group which need more attention to be able to extend or maintain their shelf life during storage. One of the most important phenomenon of climacteric produce is about the respiration rate of that produce. The following research was intended to investigate the rate of respiration of tropical climacteric products under various treatments including low temperature and the type of products. This research had developed respirometer device made from glass and thick plastic jar equipped with some needed sensing devices such as air temperature and humidity, product temperature sensing devices, and a tap for O\(_2\) and CO\(_2\) measurement. The respiration rate of banana, guava, and mango was succeeded measured by using a closed system method. It was found that storage temperature, fruit type, and interaction between them were significantly affect the respiration rate. The changes in gas composition inside the respirometer were found to vary for each fruit studied. This could be referred to an internal composition for every fruit was different. The fastest rate of O\(_2\) consumption and CO\(_2\) evolution belong to banana and mango, respectively. The effect of temperature on respiration rate could be modeled using Arrhenius equation with a satisfactory results.

1. Introduction

In tropical countries such as Indonesia, there are various and abundant agricultural products. Indonesia is also known as one of the largest producers for tropical fruits in the world. In the range of three years, from 2014, there has been a rapid increase tropical products at a rate of 24.48% became 2.5 million tonnes in 2017. As for banana, Indonesia becomes the sixth banana producer in the world, as well as for guavas and mangoes, Indonesia is the fourth top producers in the world [1]. A good postharvest handling is needed to keep those product quality always in a good condition and also to increase the fruit shelflife during the storage. However, banana, guavas, mangoes and more other tropical fruits are known belong to climacteric fruits and also have chilling injury properties, so they need much more attention to maintain their quality after being harvested.

In climacteric fruits, the ripening process continued even the fruit has already been harvested, and during this ripening process it is marked by climacteric peak of the respiration rate. If that climacteric peak has been reached, the fruit will experience a senescence then the fruit will damage. There are many researches have been done to know when is the time for climacteric peak occurred and try to postpone that process to lengthen shelflife of the fruits, so it can be stored for a longer time. Temperature and gas concentrations inside the storage room can be modified differ with the ambient condition. Low room...
temperature has been known to be better to maintain fruit quality for longer storage time. Concentration of O\textsubscript{2} and CO\textsubscript{2} in various combinations have also been known to give a good effect in fruits storage. Where in general, decreasing O\textsubscript{2} concentration to some extend are capable to slow down respiration rate of the fruit.

Some researches have been done to known the influence of temperature and gas concentration on the respiration rate of fruits. Respiration rate of banana decrease along with decreasing storage temperature [2], similar cases are also found in mango, guava, and litchi [3–5]. Those research are carried out in a modified atmosphere storage (MAS) in 21% O\textsubscript{2} concentration. Respiration rate of a golden papaya declines significantly with reducing O\textsubscript{2} concentration [6]. Modelling respiration rate is also another important information which is needed in the development of some facilities to maintain fruit quality during storage. As has been known that respiration rate is affected by temperature and gas concentration inside the storage room. There are various mathematical modelling that has already been developed to predict the change of respiration rate[7]. To study the effect of temperature on the respiration rate, an Arrhenius equation is commonly used in the modelling development. Respiration rate model for mango, banana, and litchi have been done using the Arrhenius equation [2,3,5]. However, those researches are only conducted in one kind of fruit.

In the developed countries, there are many facilities that can be used to do research dealing with maintaining quality of fresh products. However, in Indonesia there are still very limited facilities to carried our research in the filed of postharvest handling of fresh products. The need of an adequate facilities are an important requirement to be able to develop a more qualified postharvest technology of fresh products. It can be started from the development of some simple apparatus needed to carry out research such as respirometer, cold storage room, modified atmosphere storage or even a simple controlled atmosphere storage. The objective of this study was to construct respirometer for measuring respiration rate of several climacteric fruits under different storage room temperatures and to develop the prediction model based on Arrhenius equation.

2. Methodology

2.1. Equipment  
The experiment started by constructing respirometer apparatus to be used for measuring the change of O\textsubscript{2} and CO\textsubscript{2} concentrations. A statics or closed system measurement method was chosen as this was the easiest method. Constructed respirometer consisted of a thick glass jar of 3300 ml, equipped several sensors and holes for gas flushing. The lid of the jars were made airtight using rubber gasket, glue, and adhesive tape. A thermo-hygrometer sensor was mounted into the lid of a respirometer to measure the temperature and relative humidity inside respirometer. To homogenize the air inside the jar, a small fan 3 – 4 cm in diameter was set in the inside of the lid. At the outside of the lid, there were two holes as inlet-outlet equipped with small cap and also a small hole covered with rubber sheet for injecting the needle to facilitate the measurement of O\textsubscript{2} and CO\textsubscript{2}. A schematic sketch of the respirometer is represented in Figure 1.
2.2. Sample materials
Banana (*Musa paradisiaca* L.), guava (*Psidium guajava* L.), and mango (*Mangifera indica* L.) were chosen for the samples to represent climacteric fruit products. These samples were bought from local market at Yogyakarta, Indonesia, one day after being harvested. Mass and volume of every samples were taken before they were inserted into the respirometer. The weight of these samples varied from 92 – 115 gram, 170 – 195 gram, and 172 – 200 gram, for the banana, guava, and mango, respectively.

2.3. Gas exchange measurement and respiration rate
Each respirometer filled with two fruit samples were stored in 15°C and room temperature (28°C) for 3 weeks. These two temperature levels were chosen to represent the temperature of refrigerator and room air conditions. Total respirometers used for this study were 18 respirometers, which was three replication for every treatment in factorial 3x2, completely randomized design. Changes in O₂ and CO₂ concentration were measured periodically (every 6-8 hours for the first day, 12 hours for the second day, and every 24 hours after that) for totally 3 weeks. The initial gas concentration was 21% (O₂) and 0.03% (CO₂). Measured O₂ and CO₂ inside the respirometer were done using a Gas Analyser O₂ and CO₂ (Quantek, Model 902D DualTrak) and these values were used to calculate respiration rate for each fruit. Table 1 shows some of measured parameter which were needed in the following research.

Table 1. Weight of banana, guava, and mango and free volume of respirometer

| Storage Temperature (°C) | Parameters | Fruits          |             |        |
|--------------------------|------------|----------------|------------|-------|
|                          |            | Banana         | Guava      | Mango |
| 15 °C                    | Weight (kg)| 0.115 ± 0.0015 | 0.278 ± 0.0174 | 0.383 ± 0.0193 |
|                          | Vf (ml)    | 3127.5 ± 17.078 | 2790 ± 52.915 | 2520 ± 20 |
| 28 °C                    | Weight (kg)| 0.095 ± 0.001  | 0.324 ± 0.00078 | 0.380 ± 0.021 |
|                          | Vf (ml)    | 3256.667 ± 40.414 | 2763.33 ± 47.258 | 2520 ± 20 |

2.4. Modelling and data analysis
The respiration rate for each fruit sample at specified storage temperatures was calculated from concentration changes of O₂ and CO₂, free volume, fruit weight, and time difference using the following equations:

\[
R_{O_2} = \frac{\left(t_f \cdot y_{O_2} - t_i \cdot y_{O_2}ight) \times V_f}{100 \cdot M \left(t_f - t_i\right)}
\]  

(1)
\[ R_{CO_2} = \frac{\left( y_{CO_2}^f - y_{CO_2}^i \right) \times V_f}{100 \times M (t_f - t_i)} \tag{2} \]

where subscripts \( O_2 \) and \( CO_2 \) refer to \( O_2 \) and \( CO_2 \), \( R \) = respiration rate, (ml\( O_2 \)/kg.h) or (ml\( CO_2 \)/kg.h), \( y \) = concentration of gas (%), \( V_f \) = free volume of respirometer (ml), \( M \) = mass of the product inside the jar (kg), and \( t_i \) = initial time (h) or (hour), \( t_f \) time at final (hour), \( t_f - t_i \) mean the interval between initial and the final measurement in a certain period of time. Those respiration rates were then used to calculated the respiratory quotient (RQ) using following equation:

\[ RQ = \frac{R_{CO_2}}{R_{O_2}} \tag{3} \]

2.4.1. Mathematics modelling. Based on the calculated respiration rates a mathematics model was developed by using Arrhenius equation as shown below (4).

\[ k = A \cdot e^{-\frac{E_a}{R \cdot T}} \tag{4} \]

Where \( k \) = rate constant, in this study \( k \) is respiration rate of \( O_2 \) or \( CO_2 \), \( A \) = frequency factor, \( E_a \) activation energy, \( R \) = universal gas constant, 8,314 J/mol K, \( T \) = temperature (K). Those equation has another form as follows.

\[ k = k_{ref} \cdot e^{\left[ -\frac{E_a}{R \cdot \left( \frac{1}{T} - \frac{1}{T_{ref}} \right)} \right]} \tag{5} \]

where \( k_{ref} \) is rate constant at the reference temperature and \( T_{ref} \) is the reference temperature.

3. Results and Discussion

3.1. Change in gas concentration and respiration rate

The changes in gas concentration for \( O_2 \) and \( CO_2 \) during storage were different for each fruit and temperature observed (Figure 2). In the respiration process, \( O_2 \) was consumed, the complex compounds such as carbohydrates, proteins, lipids, and organic acids were breakdown into simple organic molecules with the release of \( CO_2 \), water, and energy [9]. This process depended on the fruits characteristics, this was suggested to be the reason of those difference. In this study, the phenomenon clearly reflected in banana, guava, and mango, as they had a very different nutrient composition [10–12]. As for example, for the same storage temperature, mango consumes \( O_2 \) more of among the other, similar trend also shown for \( CO_2 \) evolution. Banana and guava produce \( CO_2 \) fewer than mango.
Storage temperature was also had strong effect, respiration rate slower along with the lower temperature. According to the Van’t Hoff Rule, for every 10°C temperature increase, the velocity of a biological reaction will rise two to threefold [9]. For all of investigated samples, respiration rates on O
2 and CO
2 at 28°C were two to three times faster than at 15°C storage temperature. In the point of view of the respiration rate, low temperature commonly used to postpone the respiration peak for climacteric fruits. In this study, banana, guava, and mango that were stored in 15°C took a longer time to reach the respiratory peak compared to 28°C storage temperature (data not shown).

Comparing the R
O
2 and R
CO
2 within the same time interval (40-50 hours storage time) for each fruit, it was clear that the respiration rate in 15°C had a smaller value rather than in 28°C storage temperature. Using banana as a sample, R
O
2 in 28°C (13.5 mlO
2 / kg h) were almost two times faster than R
O
2 in 15°C (7.6 mlO
2 /kg h). In addition, R
CO
2 at 28°C increases by about twofold from R
CO
2 at lower temperature (10.7 mlCO
2/kg h from 4.5 mlCO
2/kg h, respectively). In Guava, R
O
2 and R
CO
2 at 15°C storage temperature were 4.6 mlO
2/kg h and 3.1 mlCO
2/kg h rose by 57.01% and 65.56% at room storage temperature, respectively. As for mango, the respiration rate for O
2 (7.7 mlO
2/kg h) and CO
2 (5.6 mlCO
2/kg h) at 15°C were increased around twofold in 28°C storage temperature. However, for all sample studied, over a period of time, the respiration rate for both temperature gradually slow down. As an example in mango fruit, the trend is clearly reflected in Figure 3.

The respiratory quotient for all samples were ranged between 0.67 to 0.95 as presented in Table 2, which meant all sample mostly have good RQ based on [8], a good RQ is in the range of 0.7 - 1.3 for
aerobic respiration. In the case of banana, guava, and mango RQ at room temperature had a larger value than at 15°C storage temperature, in addition, mango had the highest RQ among the other.

**Table 2. Respiratory Quotient.**

| Storage Temperature (°C) | Fruits          |
|--------------------------|-----------------|
|                          | Banana | Guava | Mango |
| 15 °C                    | 0.67    | 0.73   | 0.73  |
| 28 °C                    | 0.95    | 0.98   | 1.10  |

### 3.2 Mathematical modelling

By using equations (6) it could be found the new Arrhenius constants model for each fruit investigated.

\[
R_{O_2}^{(banana)} = 18,3018 \cdot e^{\left[\frac{48823.9}{8,314} \left(\frac{1}{T} - \frac{1}{T_{ref}}\right)\right]} 
\]

(6)

\[
R_{CO_2}^{(banana)} = 15,1333 \cdot e^{\left[\frac{68411.7}{8,314} \left(\frac{1}{T} - \frac{1}{T_{ref}}\right)\right]} 
\]

(7)

\[
R_{O_2}^{(guava)} = 10,6856 \cdot e^{\left[\frac{42751.4}{8,314} \left(\frac{1}{T} - \frac{1}{T_{ref}}\right)\right]} 
\]

(8)

\[
R_{CO_2}^{(guava)} = 8,9611 \cdot e^{\left[\frac{53924.6}{8,314} \left(\frac{1}{T} - \frac{1}{T_{ref}}\right)\right]} 
\]

(9)

\[
R_{O_2}^{(mango)} = 16,7366 \cdot e^{\left[\frac{42294.1}{8,314} \left(\frac{1}{T} - \frac{1}{T_{ref}}\right)\right]} 
\]

(10)

\[
R_{CO_2}^{(mango)} = 12,2856 \cdot e^{\left[\frac{50284.7}{8,314} \left(\frac{1}{T} - \frac{1}{T_{ref}}\right)\right]} 
\]

(11)

The newly developed constants model then used to predict the respiration rate of O\(_2\) and CO\(_2\) for banana, guava, and mango in different temperature range between 15°C to 28°C. Figure 4 depicts the respiration rate against temperature of those three fruits. It can be seen that all of the predicted respiration rate increased with respect to the temperature, and follows Van’t Hoff Rule.
Figure 4. Respiration rates prediction, (a) $R_{O2}$ prediction of banana, (b) $R_{CO2}$ prediction of banana, (c) $R_{O2}$ prediction of guava, (d) $R_{CO2}$ prediction of guava, (e) $R_{O2}$ prediction of mango, and (f) $R_{CO2}$ prediction of mango.

3.3 Statistical analysis

Table 3 shows the results of statistical analysis for gas composition inside the respirometer chamber during 50-60 hours storage time. It was found that storage temperature, fruit type, and interaction between them were significantly affect the respiration rates of O$_2$ and CO$_2$ for the same time period. The result showed that storage temperature had a significantly influence the velocity of the respiration rate. Higher temperature makes fruit respire faster rather than in a lowest temperature. In addition, considering fruit as a factor for gas composition alteration for closed system respirometer. The changes in gas composition will influence the respiration rate of each fruit. Furthermore, the interaction between storage temperature and fruit types give a significant result for respiration rates of O$_2$ and CO$_2$. Interaction between banana and 28°C storage temperature gives the most affected to accelerate O$_2$ respiration rates, conversely, interaction factor between guava and 15°C storage temperature yields the slowest rate to produce CO$_2$ among other treatment. Meanwhile, $R_{CO2}$ was most influenced by interaction between mango and 28°C storage temperature.

| Factors | Respiration rates (ml/kg h) |
|---------|-----------------------------|
| Storage Temperature (°C) | Fruits | O$_2$ Consumption | CO$_2$ Evolution |
| 15 | Banana | $7,600 \pm 0,984^{ab}$ | $4,533 \pm 1,159^{a}$ |
| | Guava | $5,000 \pm 0,954^{a}$ | $3,100 \pm 0,794^{a}$ |
| | Mango | $7,733 \pm 4,101^{ab}$ | $4,800 \pm 2,500^{a}$ |
| 28 | Banana | $13,467 \pm 1,258^{b}$ | $8,967 \pm 0,153^{b}$ |
Guava 10,667 ± 0,416ᵇᶜ 9,900 ± 1,868ᵇ
Mango 12,067 ± 1,882ᵇᶜ 10,733 ± 1,050ᵇ

ᵃᵇᶜ Different superscripts within the same column corresponding to a factor indicate that the means differ significantly (p ≤ 0,05);

4. Conclusion

The respiration rate of banana, guava, and mango was succeeded measured by using a closed system method. It was found that storage temperature, fruit type, and interaction between them were significantly affect the respiration rate of O₂ and CO₂. The changes in gas composition inside the respirometer were found to vary for each fruit studied. This could be referred to an internal composition for every fruit was different. Banana had the fastest rate of O₂ consumption rather than guava and mango, while the fastest RCO₂ belong to mango. In addition, guava had the slowest R O₂ and R CO₂. Moreover, respiration rate was increasing together with rising the storage temperature. The effect of temperature on respiration rate could be modeled using Arrhenius equation with a satisfactory results.

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